Multi-Objective Optimization in Urban Design

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ABSTRACT
Urban Design is a multi-objective task. Traditionally, urban spaces are designed hierarchically; organizational inputs are idealized uniquely, and negotiated through sequential overlay. In our investigation, parametric modeling (with the software application Catia) and evolutionary optimization employing genetic algorithms (with the software application Mode Frontier) enable the exploration of a non-linear design space whereby multiple objectives may be optimized concurrently. This paper describes an experiment that builds from prior research in multi-objective optimization of architectural design and applies that workflow to multi-objective optimization in urban design. The experiment employs given constraints, custom procedural algorithms and genetic algorithms to examine a wide design space and identify designs that perform well in multiple arenas. Design, data and latent influences are exposed and negotiated quantitatively to render topological variation through optimization. By using multi-objective optimization we define and apply quantitative metrics in order to examine the potential for a new workflow in urban design.

Keywords: Optimization, Catia, Mode Frontier

1. INTRODUCTION

The context of our research elaborates on the recent work of David Benjamin and Ian Keogh in Multi-Objective Optimization in Architectural Design (Keough and Benjamin 2010). Benjamin and Keough created an automated workflow that linked parametric modeling (*Catia*), structural analysis through a custom-designed software (Catbot) and a multi-objective *optimization* engine (*Mode Frontier*). Their workflow was used to compute multiple architectural design permutations and aid as a tool to evaluate those designs. Building on their investigations and gained knowledge, we hope to broaden the potential influence of this workflow to include urban design. Our research does not integrate the structural analysis loop but uses parametric software and a multi-objective *optimization* at the scale of the city. Our experiment abstracts buildings to basic geometric primitives such as cylinders in order to study programmatic and spatial relationships. We outline the importance of the definition of metrics for the success of the experiment and discuss how explicit metrics could influence current practices in urban design.

Urban design concerns the arrangement, design and functionality of cities. The discipline traverses many fields and interests such as architecture, urban planning, construction, politics, economics, real estate development, environmental systems and social theory. In some cases, urban design is influenced disproportionately by one or more of these fields, or by a particular stakeholder. In other cases, early decisions may have a much stronger influence than later decisions. In yet other cases, decisions may be made to satisfy each objective in sequence, which rules out some possible design results. As an alternative to these examples, we propose a workflow of multi-objective optimization in which many design criteria are evaluated simultaneously, with relatively equal influence.

Optimization software computes a parametric model through its range of possible permutations to find a set of high-performance designs. The application of this technique is novel in the context of urban design. In engineering, architecture and product design, *optimization* is often tied to simulation software such as finite element analysis (Kicinger et al. 2005). Inputs are identifiable and quantifiable; permitted tolerances are determined specific to the project, or are taken from known rules of thumb. Using primarily known materials, practices and tolerances for inputs, the workflow often produces designs that are both novel and high performance (Koza et al. 2003).

Often in urban design, projects are developed hierarchically; organizational inputs are idealized uniquely, and negotiated through sequential overlay. Complex problems in urban design may present multiple primary design factors to multiple invested parties (Galster et al. 2001). The strength of the computational process is the software's ability to evaluate multiple objectives concurrently and render a range of high-performance designs.

There are many quantitative factors to be considered in the urban design process. Zoning; program; density; solar gain; shadow projections; wind velocity, location to city service points for energy, water, and waste collection; traffic flow and projected economic revenue are just a few of the factors involved in the process. Furthermore, there are often qualitative factors that are addressed in urban design; they can include quality of life, cultural distinction and aesthetics. These qualitative factors require metrics for design and critical evaluation. Urban design lays the foundation for the new buildings, public spaces and services that shape our lives.

New technologies enable new workflows to address the complexity of urban design projects. Automated genetic algorithms have been used to exploit parametric permutations by generating, evaluating and improving the performance of possible design options (Keller 2006). This workflow is not geared toward a specific task; it is a tool to aid reflective, responsible design practice.

2. WORKFLOW

Our workflow begins with a set of constraints, generates design permutations through custom procedural algorithms and evolves high-performing designs through genetic algorithms. Beginning with design constraints is a familiar launching point for architects and urban designers. Given constraints can include the site, existing infrastructures, services, budgets and legal parameters. Identifying and drawing the given constraints create the initial environment in which to operate.

Inputs are identified through conversation with involved parties. An input is any quantifiable factor, specified by an acceptable range that would support a desired state or objective. For example: Input: building height range 50'–75'. Ideal building height = 75'. Objective: maximize building height. Once given constraints and inputs have been identified, they may be drawn or modeled digitally using parametric software (*Catia*). The custom procedural algorithm is the *Catia* script. The architect or urban designer writes this script. In doing so, he or she sets up the relationships between the inputs and the parameters that can affect their values. The designer may also set up rules to further articulate relationships between design parameters (example: when x is 2, y is 0.5x). The role of the designer is to identify and create the morphological identity of the inputs. Using the custom procedural script, the designer builds the domain of influence of the genetic algorithm, setting the breadth of the potential design space (Figure 1).

The design of a good experiment establishes clear design metrics, bases input parameters upon valid data, is procedural in its modeling techniques and enables the genetic algorithm to explore a wide design space through the custom procedural script.

Connected to scripting is the notion of State Change. State Change is a function of an If/Then condition. That is to say that if x is true, proceed with State A, if y is true, proceed with State B, etc. The State can effect morphological or topological changes in the design. State Change widens design space in that it enables the algorithm to explore possible relationships and design permutations that would not necessarily occur to the independent designer.

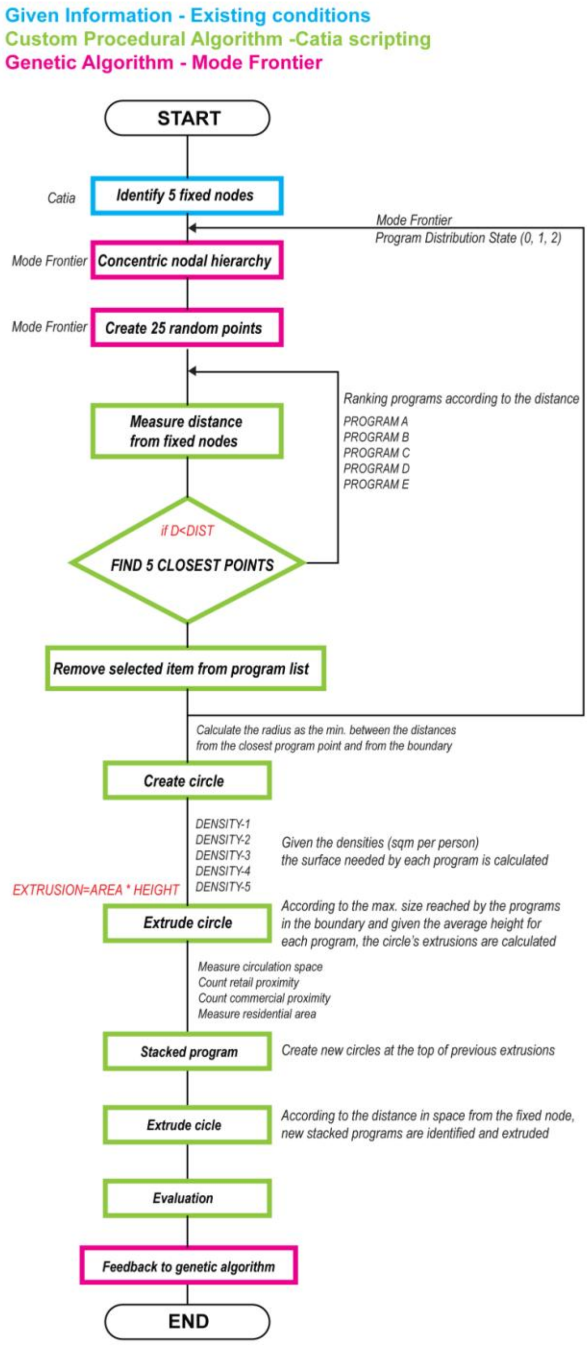

Figure 1. Workflow diagram specifying each agent's role in the process.

Once the model, parametric relationships and script are set, the *Catia* file is linked to the *optimization* software, *Mode Frontier*. *Mode Frontier* is an evolutionary computational software that employs a genetic algorithm as a search heuristic to generate multiple design permutations. It differs from stochastic search in that it learns from ratings of previous permutations. Specifically, our experiment employed the MOGA-II. MOGA-II is a scheduler based on a multi-objective genetic algorithm (MOGA) designed for fast Pareto convergence. MOGA II supports directional crossover, implements elitism, enforces user-defined constraints and allows Steady State evolution. *Mode Frontier* starts initially with a random population of input parameters. Through generational growth, it evaluates the results of each cycle to ultimately reach a set of designs that offer the best possible outputs for the objectives. For each permutation, *Mode Frontier* generates data sets that the designer can then evaluate and compare with other permutations of the experiment.

Within *Mode Frontier*, objectives are set for the experiment. An objective is a value to which the outputs should be optimized. It can be set to "minimize" or "maximize" global parameters, or at specific target. The objectives articulate the purpose of the experiment. When defining metrics for the objectives, it is possible to create conditions that produce competing objectives. Competing objectives are ones where the conditions champion the maximum performance of one objective and diminish the performance of another. Establishing the objectives involves design decisions that are as crucial as the design of the inputs.

In setting up the experiment, it is the role of the designer to clearly construct the metrics by which the inputs are evaluated. In the case of urban design, objectives can be based on known rules of thumb. Objectives may also be developed as a way of quantifying less mathematical inputs such as quality of life or aesthetics. Often both types of metrics play a role in the experiment (DeLanda 2002). Defining metrics to evaluate design creates a new workflow and design culture in many ways:

1. Each design must begin with the question: what are the necessary inputs for urban design? What does it take to plan a great city?
2. It challenges the architect or designer to set a range of acceptable parameters for each possible case, identifying and expanding the definition of what makes a "good" design.
3. The explicit definition of metrics lessens the importance of subjective preconceptions in the design process. Once rules are established, design evaluation can be more critical and thorough. This novel approach could identify high-performance designs that reach beyond established practices.
4. By re-programming design methodology, this new workflow opens up conversation with representative stakeholders, designers, engineers, investors and community members early on.

To adequately address the numerous variables involved in urban design, the initial setup of experiment is paramount.

For our experiment, we decided to focus on five inputs that we believe to be influential for the urban design of Masdar, UAE: program, density, proximity and mixed-use quality.

In terms of computational resources, we have found that with a PC computer (Intel® Core™ Quad CPU, 4GB RAM) running for 24 hours, with 5 inputs, we can evolve 1,500 design permutations. Increased inputs, model complexity and wider parameter ranges could warrant longer computation times, networked processing or the organization of multiple experiments.

3. MASDAR 2.0 (BETA)

Masdar is a new city being constructed 17 km east-southeast of Abu Dhabi. Masdar aims to be a highly efficient, sustainable, zero-carbon, zero-waste ecology development, relying entirely on solar energy and renewable resources (Adrian Smith and Gordon Gill Architecture 2010). Beginning Tabula Rasa, the design of the city invites not only questions of efficient operational practices but also an optimistic interrogation into the factors involved in creating an 21st century city. We hope to develop programmatic distribution for Masdar that not only can be evaluated by measurable criteria but also to create a new workflow and design culture.

This case study involves the use of two existing software applications: *Catia* and *Mode Frontier*. The morphology of the experiment is abstracted: points, circles, cylinders and color are used diagrammatically to represent relationships of program, density, proximity and mixed-use quality (Figure 2).

The procedure starts with a set of fixed nodes as given constraints. For this test the fixed nodes are based on the existing transportation system. These nodes are transit stations that have already been planned and constructed in Masdar. The previous master plan also used these hubs as a primary factor of influence.

In *Catia*, as part of the custom procedural algorithm, we generated a field of potential program locations. We used 100 possible locations. The spacing and number of nodes in this field are influential for the overall design output. It is the responsibility of the designer to set these constraints during the experiment.

The genetic algorithm in *Mode Frontier* creates 25 random points at the possible locations. The distance from all the points to all the nodes is measured through the custom procedural algorithm, and points are ranked in accordance with their node proximity. A list is generated for each node of its sequentially adjacent five points.

For the identified five programs or inputs, a nodal hierarchy is established by the designer (Figure 3). This determines which program should be placed closest to its node and thereon. This hierarchy can determine the conceptual base for the city. For our case study we defined three nodal hierarchies that were of interest to us.

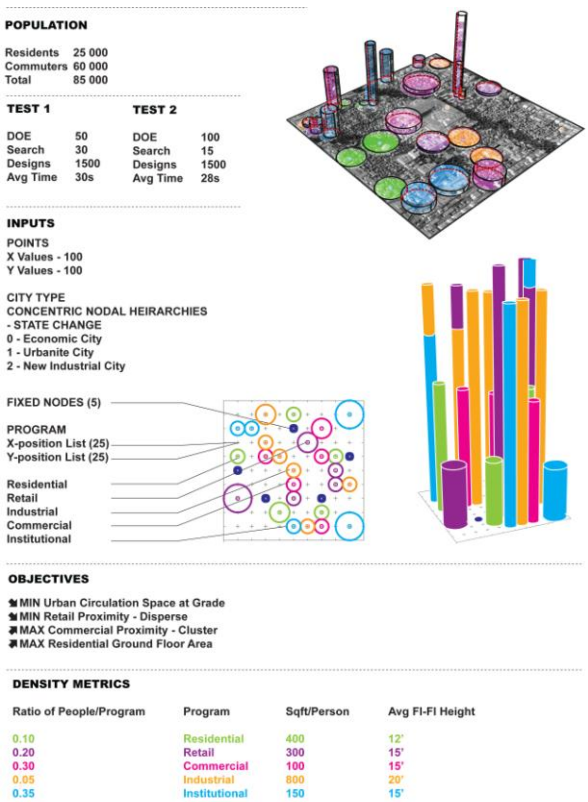

Figure 2. General setup of the experiment.

In *Mode Frontier*, State Change was employed to determine the nodal hierarchy of the given fixed point. This allowed the genetic algorithm to create a variety of urban spaces, widening the design space and enabling potentially unforeseen *optimization*s for our given inputs. Ratios of total program area of urban space to inhabitants were established. A set of rules was established for proximities between programs.

Figure 3. Nodal hierarchies determine the programmatic ordering sequence of geometry created during the experiment.

The proportion of programs within the same urban type is defined by stacking the new programs onto the previously extruded iteration. The hierarchy of programs is consistently valued according to the vertical distance from the transportation hubs (fixed nodes). This looping of programmatic distribution affects the degree of mixed-use program within a building and its neighborhood.

Open space is defined in the experiment as the space at grade that is not assigned to a building program. Open space includes public space, green space, right of way and all circulation space for vehicles and pedestrians.

Program and circulation space are simultaneously and jointly optimized. The custom procedural algorithm also aims to embrace a planning model that overcomes traditional 20th-century zoning. Taking the perspective of developers, neighborhoods are classified according to adaptability of program combinations to height and potential for economic development.

Following the algorithmic computation, *Mode Frontier* returns data on each permutation's inputs, outputs and objectives. This data can be used in *Mode Frontier* to generate 4D bubble graphs and data charts. Using both visual (4D bubble graphs) and numerical (data charts) data, the designer can look for trends and high-performance results within an iterative process. An Utopia Point is the point on the graph where all objectives would be idealized. A Pareto curve is the set of all best designs. The experiment plays competing objectives against one another. It may not be possible to idealize every objective, but rather to establish a range of designs that achieve high threshold of performance for multiple objectives. Here, the designer re-enters the design process to evaluate influence of the urban design factors and weigh the best designs. Unlike multi-objective *optimization* in engineering fields, we aim to produce a range of high-performance designs that may be further evaluated post-computation by designers. This strives to champion the best possible design for the specific situation.

Our experiment returned a set of 62 best designs (Pareto designs). Each one achieved high performance for one or more objectives. Our initial objectives were to cluster commercial properties, disperse retail, maximize the ground floor area of residential properties and minimize the overall circulation space of Masdar at grade (Figure 4).

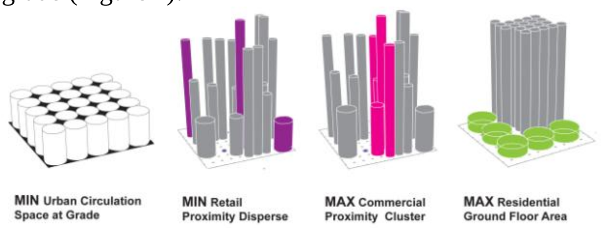

Figure 4. Predictions for each objective individually considered.

Upon examining the Pareto designs we found that three best-fit categories emerged: Best Clustering, Best Area Coverage and Best Overall. For Best Clustering, Design 1493 exhibited the closest proximity values of commercial properties and the best dispersement of retail properties specified in our objectives. The clumping of commercial and dispersement of retail created two identifiable business districts, though it performed less well in overall site coverage. For the Best Coverage category, Design 1244 covered more total area than any other design and showed the maximum ground coverage of residential program. Best

Clustering and Best Coverage are competing objectives; it would be impossible to optimize 100 percent for both. Our ambition was to explore designs that performed as best as possible for these categories.

The Best Overall permutation, Design 1177, performed well in clustering. In this case, two dense commercial areas are apparent, retail is reasonably dispersed, and there is a high presence of residential program at grade, and a high total coverage of land area, as prescribed by our initial input of factors. Design 1177 was chosen as the best-fit design of the experiment (Figures 5, 6 and 7).

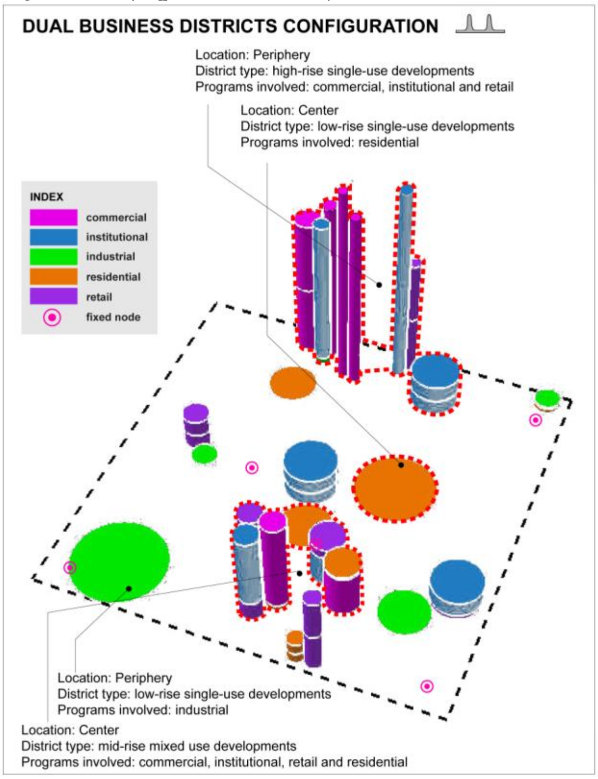

Figure 5. Design 1493: closer analysis.

4. NEXT STEPS

Masdar 2.0 (beta) illustrates our initial set of experiments with programmatic *optimization* in urban design. We would like to extend this experiment to include different inputs within an *optimization* workflow. As part of our future work, we can consider additional types of inputs such as building, block and city morphology, circulation systems, city services, land value and potential economic *optimization*s as they relate to urban form and social inputs. Each type of input will require the definition of a metric by which they will be evaluated. Each type of input can be tested to compare how the input will perform in an environment of multi-objective *optimization*. This process is ideal if automated-testing returns results that are otherwise unattainable by traditional processes. It is possible that certain types of inputs are more suited to this process than others. We would like to test not only how different types of inputs can be optimized, but also how each type could perform in a multi-type, multi-objective experiment.

In our research, we discovered two potential limitations to *optimization*. The first is that the design of a good experiment is crucial. The design inputs must be valid. The parametric model and custom procedural script must be designed to enable the genetic algorithm to explore a wide design space. The experiment must also be designed to methodically and realistically return convincing results.

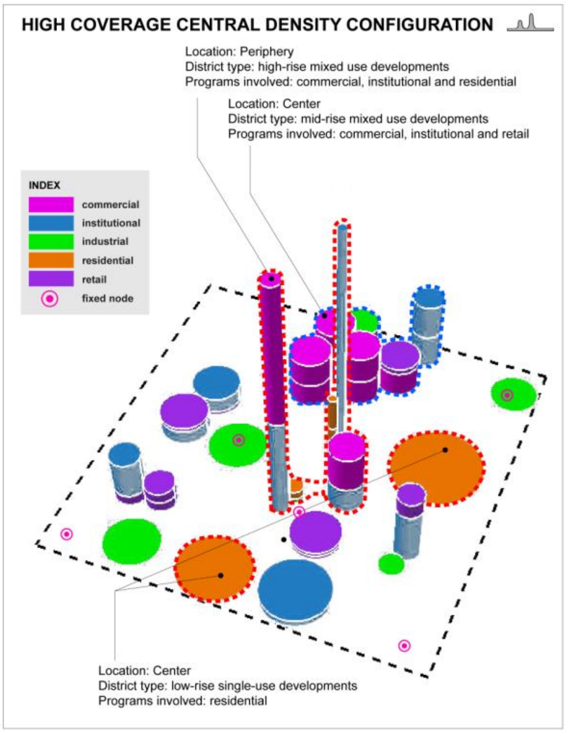

Figure 6. Design 1244: closer analysis.

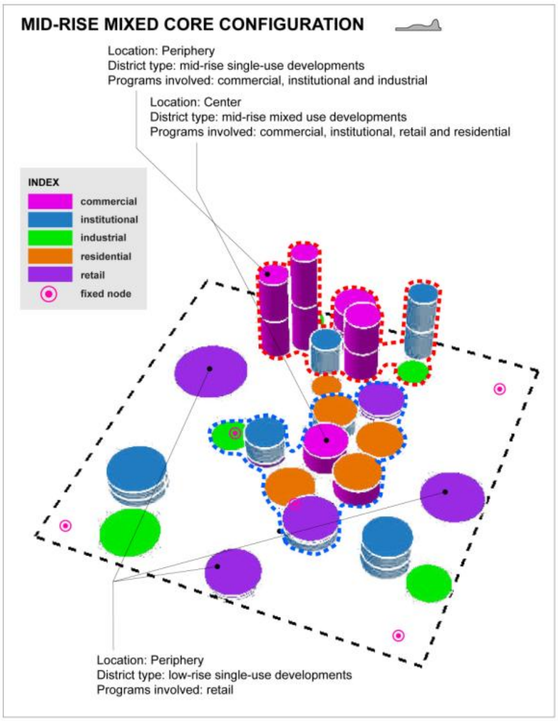

Figure 7. Design 1177: closer analysis.

The second concerns computational power. Succinctness in modeling and in defining parametric relationships can help control the computational needs of the experiment. Exponentially more computational power is needed as accuracy increases, approaching reality.

We recognize that urban design is viewed through many different lenses and must perform according to various criteria. The type of input or comparison of types of inputs can frame the scope of the experiment. It is important to be able to create the ability to test for as many different factors as are involved in urban design so that the conversation surrounding the potential design can be inclusive.

5. CONCLUSION

Building on previous research, we have adapted, applied and automated an existing workflow for *optimization* in architecture to urban design. Using the experiment's unique given constraints, we designed a specific parametric model, custom procedural algorithm and *optimization* objectives to create a new type of design experiment and broaden the potential influence a multi-objective workflow to other fields. Our workflow was executed on typical hardware (PC computers) using existing software without any previous advance knowledge of scripting, Engineering Knowledge Language or the function of genetic algorithms. The workflow requires the experiment itself to be well designed in order to be an advantageous tool. Depending on the number of inputs, input ranges and influences, complexity of the model, possible States, and overall scope, the experiment will require a specific design. The authorship of the design workflow is of great importance; it frames not only the parameters of the experiment but also the design project itself. The goal is to design a design space large enough to compute and return design possibilities that would otherwise be impossible to come to independently and to control the scope of the experiment so that it is possible to compute with typical hardware. The design of multiple experiments that build on one another is possible and interesting. The author must understand how factors relate to one another within a given experiment and throughout possibly multiple experiments. The experiment is only as good as the data and the design of the experiment itself.

The use of a functionalist algorithm may contribute to the development of a 21st century aesthetic. This new methodology does not rest uniquely on morphological output of data. The designer can define the metrics by which the data is evaluated, how that data is expressed and the possible ranges and potential interactions across the design space. The choice is to control more rigorously the factors that contribute to design practice and imagine new possibilities in design and workflow.

Automated *optimization* processes do not produce a single best design but a range of high-performance designs. The output data of the experiment must be evaluated and judged by the parties involved. High-performance results that are surprising tend to expose latent assumptions embedded in design culture. In this exploration we seek to open a conversation about what makes a great urban design within the context of measurable factors. A more collaborative, accountable and quantifiable methodology in urban design will change the way developments, neighborhoods and cities are built. We believe that by bringing explicit factors of urban design to the table we can rigorously discuss why a particular design or approach may be favored over another. By openly discussing design priorities we can learn how to create more ideal places to live, work and play.

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