COMPARATIVE URBAN PERFORMANCE SIMULATIONS

by

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Bachelors of Design
Boston Architectural College, 2014

Submitted to the Department of Architecture
in Partial Fulfillment of the Requirements for the Degree of

Masters of Science in Architecture Studies
at the
Massachusetts Institute of Technology
June 2017

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ABSTRACT

This research is concerned with applying environmental urban performance analysis methods to comparative urban master planning. Using bottom-up physics-based urban simulation algorithms, the author established a repeatable methodology for computationally analyzing and comparing urban environments. Conditions simulated included, individual building operational energy use, floor-by-floor spatial daylight autonomy, and site wide occupant mobility. The study area is the Interstate 195 redevelopment site in Providence, Rhode Island. Four historic master planning documents were sampled from 1992 to 2012. The predominate instrument for geometric modeling and simulation was the MIT Urban Modeling Interface (UMI). The methodology proposed in this study provides both, a specific framework of values for performance optimization in Providence as well as a more general framework for the automation of urban simulations in disparate regions. Results from this experiment were processed using custom instrumentation, built using web-based network architecture, to provide rapid result visualization and interactive urban data display. The research concludes by proposing a new architecture of urban system modeling.

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ACKNOWLEDGEMENTS

I would like to thank Professor Christoph Reinhart and Professor Miho Mazereeuw for their extraordinary support and wisdom during this thesis process.

I would also like to thank my classmates, lab colleagues, and the BT softball team. It has been a pleasure to learn and grow with you.

I would like to thank Professor Michael Dennis, for his continued contribution to my education.

To my family and partner Beth Savrann, I could not have done this without you. You are my trim tab - always helping me find center.

For Tina.
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After the rapid decline of the textile and jewelry industry, the city of Providence, Rhode Island, commissioned several major planning documents. During the period of 1990 to 2012 and following the interstate 195-highway relocation, considerable planning resources were directed towards the redevelopment of the reclamation land and the Providence Jewelry District. Following the proposal of a local architect, William Warner, the Rhode Island Department of Transportation demolished an ageing elevated highway and redirected traffic around the core of the city. "The highway engineers who chose the original alignment for I-195 could not have done a better job in dividing downtown Providence." said Gene Bunnell, author of Transforming Providence: Rebirth of a Post-Industrial City.

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3 Obara, Culture, Community Development, and Sustainability in a Post-Freeway City. (2012)
4 The 1992 Old Harbor Plan, see Bunnell, Transforming Providence. (2016,Troy, New York)
In the years following the highway relocation, many major master plans have been commissioned with similar and competing visions. To understand the many proposed future urban environments of the Providence Jewelry District this thesis analyzes four sampled master plans using contemporary computational valuation methods\textsuperscript{5}.

Each of the proposed planning documents were reviewed in detail and simulated for comparison. The predominate focus of the simulations were on energy use, access to daylight, and connectivity of the site. The term simulation was used here to describe an artificial and active model used to produce and record measurable data on the design and performance of an urban environment.

\textsuperscript{5} Reinhart, Davila, \textit{Urban building energy modeling—A review of a nascent field}. (Building and Environment 2016)
BACKGROUND

The Massachusetts Institute of Technology School of Architecture and Planning has a long tradition of urban simulation and modeling. The peak of inflated expectations was fueled by the advent of time-sharing computers at academic and research institutions. The advantage computation gave to urban simulations was the same advantage computation gave to many domains, the ability to do precise measurement quickly.

The scale of the city, difficult to model by hand - building by building - could be modeled systematically using a set of rules or procedures. In the 1970s project titled, URBAN 5, a machine that discusses urban design by Negroponte and Groisser⁶, digital blocks with assigned attributes were used to represent microworlds, or simplified areas of inquiry that allowed researchers to focus on specific problems while abstracting out other details⁷.

⁶ See Moore, Emerging methods in environmental design and planning: based on the proceedings of The Design Methods Group First International Conference. (Cambridge: MIT Press, 1973)
⁷ Steenson, Microworld and Mesoscale. (July–August 2015), 58–60
The ubiquity of urban computer modeling increased rapidly in this period. Initially these advances came from top-down statistical techniques, used to quantify and assess urban performance. Massachusetts Institute of Technology Professor of Management, and pioneering American computer engineer and systems scientist, Jay W. Forrester, presented research that would be published in 1969 as Urban Dynamics. Forrester built a large-scale, interactive, computational model of a hypothetical urban environment. Forrester used his model of a city like a laboratory for the study of urban social structures, processes, and systems.

Urban Dynamics used system dynamics, common in industrial design, to address population, housing, and industry within an urban area. Forrester’s work, complex and highly dependent on computation, Using IBM Systems/360 Model 67 hardware installed at MIT in 1968, opened a new branch of system dynamics studies and birthed the program language called DYNAMO.

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8 Forester, Urban Dynamics. (Pegasus Communications, 1969)
DYNAMO - DYNAamic MOdeling - was a language formed at MIT that took the general and popular programming language FORTRAN and provided a library for system modeling.\(^{10}\) These dynamic system models, because of vast complexities, were highly interdisciplinary, often straddling the traditional academic fields of mathematics, psychology, engineering, and business. With each discipline doing its part in a larger system dynamic, many innovations were to follow. Around this time, urban affairs became a target issue and grant funding followed.\(^{11}\) American cities were deemed damaged and close to failure. Governments nationwide were reassessing the design and role of cities post-suburbanization.

At MIT this lead to a formal decree from President, Howard W. Johnson,\(^ {12}\) and the appointment of ex-Boston mayor, John F. Collins, to the faculty, and the formation of the Urban Systems Laboratory.

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\(^{11}\) Ibid., 9

The Urban Systems Laboratory (USL) was a group of researchers focused on studying the city using system dynamics and urban simulations. This group was seminal to the MIT School Of Architecture and Planning, as it marked its entry into the grantsmanship and big science endeavors of the time.  

Correspondence from USL Executive Director and Professor C. L. Miller to MIT President Dr. Jerome Wisner

Subject: Architecture Computer Lab

Date: July 22, 1969

"The three tube ARDS graphic unit, purchased by the USL through two Sloan Grants, will not be moved to the Webster Buildings but will be turned over to the Department of Architecture for use in their departmental computer lab..."

13 Ibid., 11
As computation progressed so did simulation technologies and the ubiquity of computing within the School of Architecture and Planning\textsuperscript{14}, record keeping of shared computer time at MIT shows architectures introduction to the computer as an instrument of design and the Urban Systems Laboratory stands out as its own entity amongst electrical and civil engineering.\textsuperscript{15}

The Urban Systems Lab sponsored a range of projects; in addition to research in system modeling the USL sponsored research in computer-assisted design. In addition, to challenges of system modeling, there were axillary challenges of representation and user experience. Records from the Urban Systems Lab research agenda shows three main challenges, (1) data gathering and entry, (2) computational efficiency and accuracy, (3) result viewing and understanding.

\textsuperscript{14} Turkle, Nielsen, Orsini, \textit{Project Athena at MIT: Computing in the School of Architecture and Planning}. (May 1988)

\textsuperscript{15} MIT Urban Systems Laboratory Records, 1968-1974, AC-366, Institute Archives and Special Collections, MIT Libraries, Cambridge, Massachusetts
Figure 5: Forrester, World Dynamics (1973)
Many of the systems for data entry and display were foundational to contemporary design applications. For example, the program, DISCOURSE, developed by William Porter, in 1969 was a program for the computer-aided design of cities and included a street network, parcels, and building footprints.\textsuperscript{16} and COGO or Coordinate Geometries by Betsy Schumacher and Charles Miller, was a system for describing geometry in Euclidean space.\textsuperscript{17} Both of these technologies provided clear classification of the primitive data points for urban simulation and modeling. Schumacher declared a number of primitives still common in urban computing today. These primitives included points, curves, courses, chains (or parcels), profiles, networks, blocks and regions.\textsuperscript{18}

\textsuperscript{17} Schumacker, URBAN COGO: A Geographic-Based Land Information System (1971)
\textsuperscript{18} Ibid., 17
Figure 6: Bottom-up modeling process.

Much of the Urban Systems Laboratory research used an approach to urban modeling that can be classified as bottom-up modeling, where Individual base elements are modeled in detail and connected to create a complex system\textsuperscript{19}. These bottom-up models held an inherent understanding of geometric space because of the spatial referencing and shared coordinate systems deployed. Bottom-up urban models differ from the top-down models where holistic systems are subdivided from the top down.

\textsuperscript{19} Mario Bunge, A World of Systems (Dordrecht; Boston, Reidel, 1979)
On May 6th 2013, almost forty years after the USL closed for lack of funding, during a public symposium on Sustainable Urban Design, the MIT Sustainable Design Lab released UMI, the Urban Modeling Interface, an open platform for architects, urban planners, and real estate developers interested in modeling the environmental performance of new and existing settlements. "The objective of umi is to give users access to meaningful information that facilitates design interventions at the neighborhood, street and building scale."\textsuperscript{20}

Much of the Urban Modeling Interface’s base functionality was designed to reduce carbon emissions in urban environments; however, as of 2017, UMI was showing the beginnings of a collective ecosystem for developers around the world to introduce new simulation functionality. Evidence of this propagation was found in recent literature, for example outdoor thermal comfort, urban building-Integrated agriculture\textsuperscript{21}, and developer financial return.

\textsuperscript{20} Reinhart et al, UMI - An Urban Simulation Environment for Building Energy Use, Daylighting and Walkability (Proceedings of BS2013, Chambéry, France, 2013)

\textsuperscript{21} Khadija Benisa, Development of a simulation-based decision support workflow for the implementation of Building-Integrated Agriculture (BIA) in urban contexts (Journal of Cleaner Production 2017)
Fundamentally, there are two major avenues of development both in 1960 and today; (1) The development of the simulation engines and (2) the development of the graphics and result display and result processing. This remains similar to the research agenda of the Urban Systems Laboratory. It was also evident that in the last half-century, urban design has witnessed the rise of computational urban modeling, at first in the form of top down system models and more recently in the form of bottom-up geometric urban modeling such as the Urban Modeling Interface. By following repeatable steps, each urban structure can be represented and modeled with its surrounding context as a specific coefficient within a simulated environment. Whole neighborhoods or districts can be modeled and simulated to provide building-by-building performance data. Street networks, parks, and shading devices are included in the model and influence building performance.
This experiment used lessons learned researching the history of urban modeling and innovative environmental urban performance analysis methods to compare urban masterplans. This was done to test if comparing urban simulation results can help reduce carbon, increase livability, and influence the development of our built environments. There were three major research goals; (1) Compare masterplans of new settlements; (2) Create the necessary tools for repeatable simulation analysis; (3) Survey areas where urban performance simulation can enter existing modes of practice. This experiment is performed using four historical master plans of Providence, Rhode Island. Each master plan was analyzed using a set of urban performance simulation techniques. The results of each experiment were then combined for project-to-project comparison. Results were then used to analyze the existing urban planning and policymaking process. In addition to exploring a new paradigm of comparative, multi-design evaluation, this model also aimed to assist in future computational urban design – including, but not limited to the coevolution and subsequent convergence of future generative urban planning.
METRICS OF URBAN PERFORMANCE

This research simulated three major metrics of urban performance: (1) Building operational energy use; (2) floor-by-floor spatial daylight autonomy; (3) site wide occupant mobility. These metrics were chosen because of their simulation accuracy and their influence on the master planning process. The simulations produced monthly results for a full calendar year using local weather and urban attributes.

Operational Energy

Building operational energy use was defined as energy use intensity, as a representation of energy use per unit area \([\text{kWh/m2}]\) this included heating, cooling, lighting, and equipment loads. Demand was calculated by aggregating the monthly simulation results of heating, cooling, lighting, and hot water energy usage for each building. The unit used, Energy Use Intensity (EUI), is an established metric in mayoral offices around the world, projects like Boston’s BERDO\(^{22}\) attempt to quantify and analyze a cities energy demand profiles to reduce carbon costs and increase grid resiliency. The common axiom is that, “you cannot manage what you do not measure.”

\(^{22}\) Thomas Menino, May 08 2013, An Ordinance Amending the Air Pollution Control Commission Ordinance in Relation to Reporting and Disclosing the Energy and Water Efficiency of Buildings.
Spatial Daylight Autonomy

Floor-by-floor spatial daylight autonomy is a recently new urban performance metric, as it is a computationally expensive simulation to run. Whereas, Spatial daylight autonomy is measured by calculating the daylight that enters a building through windows and openings. Known as sDA, Spatial daylight autonomy describes how much of a space receives sufficient daylight. [Unit: sDA300/50% (area that receives at least 300 lux for at least 50% of occupied hours)] sDA is an important urban performance metric because the metric quantifies a human perception of daylight and performance is highly dependent on the shape and form of the building and when the building is occupied.

Figure 8: [left] Frame from a solar path animation. [right] Saratsis, *Daylight Density* (SMARCH Thesis 2014)
The last analyzed performance metric was site wide occupant mobility. Occupant mobility is an indication of site wide connectivity and centrality to amenities. The metric used here was the Walk Score percentage, a percentage of connectivity each building has with surrounding amenities.

This metric was chosen because of the metrics dependency on the urban street grid, public parks, and open areas traversable by site occupants. This metric considers the form and fabric of the masterplan and distances between points of interest and individual buildings.

Each of these metrics were deemed important to the study area because of deep and extensive research on the forces shaping Providence. Energy, Daylight, and Walkability are all metrics that, if improved, could attract an innovative workforce, shape Providence, and inspire confidence in redevelopment.
Providence, Rhode Island, is more than an intermediate city that falls between New York and Boston. Many view Providence as the birthplace of American Industrialization. In 2011, U.S. Secretary of the Interior, Ken Salazar, proclaimed, “The seeds of the Industrial Revolution were planted here in the fields of the Blackstone River Valley.” Yet the city’s industrial reputation has faded dramatically over the last half century.

There have been many historical forces that have shaped Providence in the settlement’s short lifespan. Founded on religious freedom in 1636, Roger Williams stated “A place where you are free to worship or not worship.”

Providence slowly attracted colonists, it was bestowed with clean water and safe access to the Atlantic but little suitable farmland. Functioning as a subsistence economy, only having enough food to support itself, Providence was forced to take on more complex manufacturing to crystalize knowledge into tradable goods.

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23 Dickie, Margaret, Becoming a city; from fishing village to manufacturing center. (New York: Harcourt, Brace & World, 1968)

Down city, Providence committed local efforts on manufacturing. The soft running water was ideal for early water mills and textile washing. The British immigrant Samuel Slater, a machinist and forefather of American industrialization, brought new technologies for advanced textile production. Moses Brown, a local businessperson and leader in Providence, hired Slater to run a textile mill. Slater's ingenuity and commitment to his craft fueled a manufacturing revolution in the region. Quickly the settlement became the center of a regional manufacturing network and it was reshaping their territory. The East bank and Great Salt Lake was slowly filled in and accommodated much of Providence's commercial and industrial growth as business attracted to manufacturing expanded. This demand for manufacturing also increased demand for energy sources, initially relying on the waterpower of local rivers and the burning of whale oil candles, Providence quickly adopted electricity and hydrocarbon consumption. In 1827, Samuel Slater opened one of the first American cotton mills to run on steam.

26 Ibid., 23 p119
Providence’s complex manufacturing economy was an advantage during the war of 1812 when America was forced to turn its trade inwards. Originally, Providence’s built environment was shaped by a network of sea wharfs and their relationship with local manufacturing, in the 1800s Providence began to shape itself to support a network of rail and road. Train tracks and steam trains branched out from the center of Providence. In 1848 the Union Passenger Train Depot was built and the settlement rapidly turned its direction inwards and sea trade was momentarily less important to Providence. New roads connected Providence to the constellation of early American villages and a larger land network. Immigrants flocked to Providence - as opportunities were abundant - laying strong cultural roots in the fresh land and forming new neighborhoods. Between 1880 and 1910 population doubled and jumped to 224,000 residents.

Figure 10: [top] Chester Smolski, Providence aerial image. (RIC Special Collections)
As the American civilization rapidly expanded and as technology rapidly increased, Providence, under the forces of competition, watched its hold on manufacturing decline. Cotton mills began to open in the American South, in proximity to raw cotton and farmers willing to take low wages. At first only producing coarse cotton goods, but quickly improving to the quality of Providence’s finer fabrics. At this point Providence’s economy was extremely volatile, slumping under the pressures of competition but boosted by the First World War. This trend continued until 1948 - when the depression hit. At this point, it was finally clear that the 1900’s marked the end of Providence’s growth.

This development is not so surprising. Southern wages, at the time, were so low even New England investors were moving their money South. Banks and investment left Providence and the mills and factories were stuck with outdated equipment and outdated practices. New England lost its importance as the nation and population moved westward; Providence’s position between New York and Boston mattered less as materials, goods, and customers were located farther and farther west, it was then that Providence turned 180 degrees back to its waterways and began to reinvent itself.

27 Ibid., 23 p147
Figure 11: Map of Providence from the *New Encyclopedic Atlas and Gazetteer of the World.* (1917)
“...Providence, Rhode Island, was a gritty wasteland of neglected waterways, derelict railroad yards, and vast parking lots, derided as a smudge on the road from New York to Cape Cod” says Leazes and Motte in Providence; The Renaissance City. During the period of 1960-1980, from the Interface Providence Plan, prepared by faculty members at the Rhode Island School of Design28 to the Capital Center Plan by Skidmore, Owings & Merrill LLP, Providence begin to redesign interstate highways and rail lines and reconnect it’s urban fabric.

As of 2014, Providence had a population of 179,154 residents. Approximately 40,000 residents left the city after peak population in the early twentieth century. William Warner, a Connecticut born, MIT educated, and already established architect and urban planner29 was partly responsible for what is called the “Providence Renaissance”.

28 Bunnell, Gene. Transforming Providence: rebirth of a post-industrial city. (Troy, NY 2016)
Warner's first major contribution to the city came in 1983 when Warner began promoting the idea of uncovering – covered by land bridges and transportation infrastructure – the Providence river, a confluence of the Woonasquatucket and Moshassuck rivers, soon after Providence began to reclaim its connection to water. Warner in 1992 proposed the Old Harbor plan a proposal to redirect traffic around the core of the city and continue the waterfront reclamation towards the head of the rivers and the beginning of the Narragansett Bay. The 1992 Old harbor plan and plans following were gathered for this experiment.
Figure 12: The four selected planning documents. Old Harbor Plan (1992); the Jewelry District Concept Plan (1999); Providence 2020 (2006); and the Knowledge District Plan (2012).
The study methodology consisted of the following Inputs. Data regarding master plans issued by Providence from 1992 to 2012 were reviewed. Four documents in this time period included the required information to build a simulation model. The requirement of a simulation model are as follows: (1) The existing conditions data, vector geographic information or raster satellite imagery, at the time of document publication. (2) The published and public Design Document, including plans, elevation, rendering, prescriptive or performative urban code, and implicit declared design intentions. (3) Local construction practices and materiality data. For the later, local construction practices, this study assumes all new construction is built using the same modern construction practices for all models, regardless of year the design was authored.
DATA COLLECTION

The data required to build an urban performance model is disparate and decentralized and varies from city to city. In the case of the city of Providence, the major repository of urban planning data is owned by the City’s department of Planning and Development. Here the public can access recent archived urban masterplans and GIS, Geographical Information System, data.

Existing conditions data, documents and files regarding the site conditions such as existing street grid, existing building footprints, existing zoning, and existing infrastructure was public - but not easily assessable. The full datasets and files were requested from the sub department of GIS and Mapping, which along with federally owned satellite imagery in this study are classified as Semi-Public Existing Conditions Data. Urban planning data, provided as a Portable Document Format (PDF) file, was either city approved urban code, ie setbacks and zoning, or a planning document authored by a commissioned third party such as an architecture firm. These documents for the purpose of this study are classified as existing urban design documents.
EXISTING CONDITIONS

The existing conditions data, building and infrastructure, was crucial to the construction of an urban performance model as it functioned as the adjacent boundary of the site model. By combining satellite imagery, land zoning, GIS building and parcel footprints, and an additional building information sourced from the Providence jurisdiction’s tax assessor online database, a three dimensional model was constructed to serve as a base case that received the proposed master planning design document data from each of the samples.

Satellite imagery was important for the classification of building typology in addition to zoning and assessor data. Satellite imagery spanning the same study period of 1992 to 2012 was gathered through a federal repository of public raster images geolocated and projected to the geographical location on earth. These images are included in the appendix and show the stages to the 195 highway relocation.
Figure 13: GIS Existing Building Footprint Map, False Colored by Use Type. Data provided by Providence Planning and Development office.
GIS data provided by the city, included multiple years of vector building footprints, parcel outlines, and street networks. Each vector building footprint object included a unique Identifier that was retained to assist in the merging of external data. The parcel outlines included an attribute describing the zoning of each parcel. This attribute was propagated and assigned to the building footprint by using a geographic join function to associated each building footprint with it’s associated parcel. The parcel data also served as land boundaries within the model, this land boundary defined elements such as sidewalks, parks, parking lots, and the water edge.

The street network provided by the city was discarded because of overlapping, inconsistent polyline data – meaning the street data provided was of low value and redrawing the street network manually was faster than cleaning the street data. Therefore, it was deemed best to rebuild the street network data needed for this site and this site only.
GEOMETRY AND USETYPE

The key to both existing conditions models and new design urban performance models are the general geometry of a building and that building’s declared use type. Each of these attributes opens many other avenues of data gathering and analysis. In the case of the existing conditions model use type is less valuable because in this study existing buildings only influenced the simulation by shading adjacent new construction. Potential future urban performance models could consider the use of adjacent building to provide design insight; however, for this study existing buildings functioned only as shading devices to surrounding new construction.
The geometry LOD, or level of detail was classified as a 2.5D extrusion, the geometry was an extrusion of the footprint to the assessed building height and did not include architectural elements such as pitched roofs, dormers, sectional changes in shape, etc. Once a base case existing model was built it was then modified and adjusted according to the intentions decoded from the design data. This process required two major inputs, one input for the intentions of an intervention and two the site specific data regarding the construction of new buildings. The process of extracting intentions from planning documents to design data was highly dependent on expert interpretation. To ensure consistency across samples, selected documents were reviewed in detail following an established methodology to model precisely what each planning document proposed. The planning documents, provided as a Portable Document Format (PDF) files, followed a general structure: A message from the mayor, and executive summary, a set of guiding principles, existing conditions analysis, concepts, and plans. Each document had commonalities of graphical urban data communication elements; these elements included plans, renderings, elevation, sections, and diagrams. Each design document had differing scale and scope yet all documents addressed the 195 Redevelopment Site and Providence Jewelry District.
Only planning document data within the defined boundary of this experiment was extracted, additional master planning efforts outside of the experiment boundary were disregarded. This was necessary to provide a direct plan-to-plan comparison; however, future experiments could include a larger experiment boundary to recreate a more holistic and accurate interpretation of the planning documents.

In addition to the planning document, design data required local and specific methods of construction not defined in the planning documents but assumed by extracting information on contemporary and vernacular building construction in Providence, Rhode Island. Because each planning document did not explicitly declare construction methods, the experiment assumed the same construction methodologies for each plan. Because of the increase in building information modeling, future planning documents could, one day, include granular building data specific to construction methods and materiality. In this experiment, generalizations were made, for example in all four samples commercial buildings had identical construction and material profiles.

**Figure 14:** Aerial Imagery of the study area. (Apple Maps 2016)

**Figure 15-18:** Programmatic Distribution Axonometric Studies.
The four selected planning documents were the following: the *Old Harbor Plan* (1992); the *Jewelry District Concept Plan* (1999); *Providence 2020* (2006); and the *Knowledge District Plan* (2012). A short summary of each plan was prepared below.

**Old Harbor Plan (1992)**

Sponsored by the Providence Foundation, the *Old Harbor Plan*, proposed the removal of the aging 195 highway infrastructure and proposed the redirection of traffic around the core of the city. Designed by local architect, William Warner, the *Old Harbor Plan* proposed a new street grid connecting downtown Providence with the industrial Jewelry District. The street grid was infilled with residential and commercial program of similar density to the surrounding existing fabric. The plan also called for a waterfront park and small gardens throughout the intervention. Although the plan was never implemented, the proposal served as the beginning of a longer incremental planning process of the reclaimed land.\(^{30}\)

\(^{30}\) For more information about the 1992 and 1999 plans see Ryan *Ibid.*, 2
Jewelry District Concept Plan (1999)

In 1997 the Jewelry District Association was formed and in 1999 the association hired Thompson Design Group to author the Jewelry District Concept plan. The plan was modest and retained much of the existing street network, knitting downtown and the Jewelry District with a contextually scaled mixed-use neighborhood. The plan focused on infilling existing parcels and introduced programing for a large waterfront hotel and a cultural museum. Both the 1992 and 1999 plans were referenced in a later 2008 Jewelry District/Old Harbor Planning Framework study a document sponsored by both the Providence Foundation and the Jewelry District Association.

In 2006 the design firm Sasaki and Associates authored a comprehensive plan of Providence, titled Providence 2020. In this document a grand vision of the future of Providence is proposed. The document leads with the following vision of Providence: “In the future, Providence will be a waterfront city, where the water, continuous parks, and transit link the Valley to the Bay. Along this spine, downtown will be a premier environment for a great variety of economic activities, with innovative industries, commerce, higher education and medical services, research, retail, culture, and housing for a diverse population.” The plan called for high density infill and focused its resources on the 195 redevelopment site, the jewelry district and a string of program outside the city core. The plan also came with a series of massing studies and proposed new building height restrictions, some as high as 300 feet, across the skyline of Providence.
2012 Knowledge District Plan  

The most recent plan examined was the 2012 Knowledge District Plan authored by design firm Perkins + Will. In the Knowledge District Plan, mixed-use program was distributed along a linear path of Laboratory space. The Knowledge District Plan attempted to connect academic and private partnership to urban space for collaboration and commerce, as the Providence Planning and Development office describes it “The plan strives to establish an inspirational vision that will spur investment and facilitate new growth and prosperity in Providence.”
MODEL BUILDING

The sampled planning documents above were then interpreted and modeled within the previously mentioned existing conditions model. Building, streets, and parks planned in each sample that were located outside of the study area were disregarded. In this process there were three major inputs required for the modeling process: (1) The proposed street network; (2) The proposed building footprints; (3) the proposed building heights. After the proposed geometry was modeled using all available resources, data was associated to each building by its defined use type. In the case where a use type was not defined for a building an assumption of use type was made based on the following criteria, similar shaped geometry, renderings of the unclassified building, and the master plans' vision and goals. Few building were unclassified across the four sampled masterplans. Public parks are included as a method of travel and connect adjacent pathways. Areas that are not considered pathways of mobility are private parcels, building footprints, and unplanned interstitial places not explicitly denoted for travel or parkland.

Figure 19: [top] Dogan, Reinhart, Shoeboxer: An algorithm for abstracted rapid multi-zone urban building energy model generation and simulation. (2017)
The simulation process required climate data in addition to the previously mentioned, building geometry, construction standards and usage schedules associated to the proposed master plan sampled. Climate data sets for building performance simulation have been available for a number of years following the initial establishment of a viable data format, the typical meteorological year (TMY)\textsuperscript{33, 34}, and the subsequent provision of data for the Energy Plus thermal modeling engine in the form of an Energy Plus Weather (EPW) file.\textsuperscript{35} An EPW file from T.F. Green Airport outside of Providence was used to generate the necessary weather inputs for the simulation. Table 1, Lists the algorithms used for each performance metric studied. After simulation was complete, results were extracted for four different aspects of analysis: (1) General Observation; (2) Operational Energy Use; (3) Spatial Daylight Autonomy; (4) and Occupant Mobility. The results are listed in Table 2 and findings from each aspect of analysis are listed below.

Figure 20: [top] Floor-by-floor Spatial Daylight Autonomy Wireframe.

\textsuperscript{33} Hall, Prairie, Anderson, Boes. \textit{Generation de typical meteorological years for 26 SOLMET stations}.
\textsuperscript{34} Crawley, Hand, Lawry, \textit{Improving the weather information available to simulation programs} (Building Simulation 1999).
\textsuperscript{35} Reinhart, Davila \textit{Urban building energy modeling – A review of a nascent field} (Building and Environment 2016)
### Spatial Daylight Autonomy

Received Daylight: sDA 300 lux

<table>
<thead>
<tr>
<th>Function</th>
<th>Algorithm</th>
<th>Publication</th>
</tr>
</thead>
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Figure 21: Matrix of simulated samples.
General Observations

Before parsing the results of the simulation, there were a series of observations that could be made in comparison of the geometric mass and programmatic distribution of the four samples. Over the period of 1992 to 2012 the masterplans of this area increased in density and building count. The Providence 2020 plan, proposed in 2006, introduced of over 800,000 square meters of new floor area, this was nearly four times the floor area proposed in the 1992 Old Harbor Plan. This increase of density however did not lead to an increase in energy use intensity – energy use intensity is normalized for area. A general observation was also made about programmatic use type and the distribution of use types across the site. The 2012 Knowledge District plan included a strip of designated laboratory space across the site. The 1992 Old Harbor plan was modest in size and building height compared to later samples and was modeled with only one parking structure. This observation was interesting in comparison to the 1999 Jewelry District Plan which declared nine parking structures across the site. Observations of programmatic distribution suggested that operational energy - as overall site wide energy use intensity -would be difficult to quantify or predict without programmatic use type specific modeling and simulation.
Operational Energy

The four samples had a combined average energy use intensity of 116 kWh/m²/y. This was within the expected range of energy use intensity in this region and this climate zone. All samples - except the 1999 Jewelry District plan - had a range of energy use intensity, EUI, from 50 kWh/m²/y to approximately 200 kWh/m²/y. The 1999 Jewelry District plan lacked this upper bound of energy intensity as it also lacked industrial programmatic use. This observation - of identical energy use intensity minimums and maximums – was caused by energy demand of two different building types (1) the low energy intensive parking structure and (2) the high energy intensive industrial structure. This observation, in addition to general observations of differing programmatic allocation and distribution, proves that direct project-to-project comparison of site wide energy use intensity lacks direct comparison, as energy use intensity was highly dependent on the unique recipe of program distributed across the site.

A direct comparison was found by filtering programmatic use types and by isolating energy use intensity by programmatic use type, for example the 2012 Knowledge District residential building stock had the lowest average energy use intensity at 101 kWh/m²/y.
This is an interesting observation considering all construction of residential building across the four samples are identical and that all window to wall ratios are controlled for. The 1999 Jewelry District plan had an average energy use intensity of 7 kWh/m²/y higher than that of the 2012 Knowledge District. This proved that building footprint, building height, and building site location influenced energy use intensity in addition to overall energy consumption.

An additional observation was the 2006 Providence 2020 plan, the densest plan of the four, had the highest annual energy demand, 98776 MW, and a midrange site wide energy use intensity, 18 kWh/m²/y lower than that of the 2012 Knowledge District. This observation illuminates the benefit of gaging both the total energy demand and a normalized metric of energy intensity, as again the programmatic distribution is the main driver of variances within comparative operational energy use.

**Figure 22:** [previous] Operation Energy Use Over Time.

**Figure 23:** [top] Operational Energy and Energy Use Intensity Frequency Distributions.
Spatial Daylight Autonomy

The four samples had a combined average spatial daylight autonomy of 42% sDA 300lux. The sensitive inputs for this metric were the combined average window-to-wall ratio, controlled for at 40%, the density of adjacent buildings, and building form. Considering all windows opening equal, it was interesting that the 1992 Old Harbor Plan outperformed the spatial daylight autonomy of all samples with an average residential spatial daylight autonomy of 52% sDA 300lux, an order of magnitude higher than the site wide spatial daylight autonomy. Prompting the question, what was special about the design of residential building stock in the 1992 Old Harbor Plan? On closer visual inspection of the form and shape of all building across all samples it was clear that the 1992 Old Harbor plan had highly resolved building footprints, this meant that building footprints articulated geometric conditions to increase the performance of both individual buildings and the neighborhood as a whole.
Further evidence of the importance of highly resolved building footprints can be found in low performing buildings such as the buildings shown in figure 24. Wide and deep floor plates struggled to receive daylight across the bulk of the floor area. This finding suggested that spatial daylight autonomy, in addition to functioning as a metric of received daylight, could also function as a metric of resolution. This also means that spatial daylight autonomy could function as an indication of a masterplan’s magnitude of building location and shape prescription, as highly resolved plans may be viewed as highly prescriptive plans.
Occupant Mobility

The four samples had a combined average occupant mobility of 61% Walk Score and showed correlation to site density. A frequency distribution of occupant mobility of all four samples was off-center to the right and the curve showed a long tail and a large range of underperforming mobility in buildings across all samples. This suggested that occupant mobility had many occurrences far from the head of distribution and by isolating occurrences – few additional pathways – could push the occurrences past a tipping point therefore improving performance. To test this observation four additional pathways were added to the 2012 Knowledge District plan at a location of low performance. The additional pathways bisected the original street network and increased site wide occupant mobility by a considerable 8% Walk Score. This finding suggested that unplanned interstitial places not explicitly denoted for travel or parkland could be used to optimize the results of an occupant mobility simulation.

Figure 25: [top] Frequency Distribution of Occupant Mobility.
Table 2: Simulation Results for the four selected samples.

<table>
<thead>
<tr>
<th>Sample</th>
<th>FAR</th>
<th>New Buildings</th>
<th>Total Floor Area</th>
<th>Mean Building Area</th>
<th>Residential Occupants</th>
<th>Site Total Population</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>count</td>
<td>Floor m$^2$</td>
<td>Floor m$^2$</td>
<td>people</td>
<td>people</td>
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<tr>
<td>1992 Old Harbor</td>
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<td>47</td>
<td>224153</td>
<td>4769</td>
<td>2584</td>
<td>7911</td>
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<tr>
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<td>0.95</td>
<td>46</td>
<td>240136</td>
<td>5220</td>
<td>1986</td>
<td>6975</td>
</tr>
<tr>
<td>2006 Providence 2020</td>
<td>1.92</td>
<td>77</td>
<td>844556</td>
<td>10968</td>
<td>9211</td>
<td>30147</td>
</tr>
<tr>
<td>2012 Knowledge District</td>
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<td>61</td>
<td>624798</td>
<td>10243</td>
<td>1732</td>
<td>24305</td>
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</table>

<table>
<thead>
<tr>
<th>Use Types</th>
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<th>Residential SDA</th>
<th>Commercial SDA</th>
<th>Industrial SDA</th>
<th>Site Total Demand</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%sDA 300lux</td>
<td>%sDA 300lux</td>
<td>%sDA 300lux</td>
<td>%sDA 300lux</td>
<td>Yearly MW</td>
</tr>
<tr>
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<td>49</td>
<td>52</td>
<td>44</td>
<td>45</td>
<td>27594</td>
</tr>
<tr>
<td>1999 Jewelry District</td>
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<td>44</td>
<td>36</td>
<td>0</td>
<td>24905</td>
</tr>
<tr>
<td>2006 Providence 2020</td>
<td>40</td>
<td>44</td>
<td>34</td>
<td>23</td>
<td>98776</td>
</tr>
<tr>
<td>2012 Knowledge District</td>
<td>40</td>
<td>50</td>
<td>46</td>
<td>24</td>
<td>84475</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Site WA</th>
<th>Residential WA</th>
<th>Commercial WA</th>
<th>Industrial WA</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>% Walk Score</td>
<td>% Walk Score</td>
<td>% Walk Score</td>
</tr>
<tr>
<td>1992 Old Harbor</td>
<td>49</td>
<td>62</td>
<td>53</td>
</tr>
<tr>
<td>1999 Jewelry District</td>
<td>37</td>
<td>73</td>
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<tr>
<td>2006 Providence 2020</td>
<td>40</td>
<td>68</td>
<td>53</td>
</tr>
<tr>
<td>2012 Knowledge District</td>
<td>40</td>
<td>73</td>
<td>60</td>
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</table>
Two proof-of-concept data-viewers were used in this study: (1) the UMI Dashboard, a client-side single-project dashboard used for quick simulation result analysis. The dashboard allowed the ability to drill-down to calibrate and communicate results. The dashboard provided a scorecard view with high-level site wide averages and an orthographic plan false colored by selected performance metric or programmatic distribution. The “Data View” feature provided stacked bar charts and scatterplots for drilling down and investigating the high-level site wide averages.

(2) CUPS: Comparative Urban Performance Simulations web viewer was a server-side multi-project data store that used a micro services architecture and allowed drag-and-drop file upload of n amount of simulation files. This tool served as a comparison engine and included combined frequency distribution charts, combined bar charts, and a module for 3D geometry display integrated from a third party.
Both dashboards were enabled by the Urban Modeling Interface’s unique data model, which packaged all results and dependencies into one singular result file. Each of the sampled master plans were stored and parsed using this innovative method. Previous experiments would have required bespoke and complicated result analysis workflows. The Providence experiment could be reproduced or shared easily because of portability and standardization of the file’s initial dependencies and outputs. Data regarding model geometry, dependent files, and simulation results were parsed using JavaScript Object Notation – see figure xx.
The dashboard also provided a collection of automatic visualizations – interactive and ready for external presentation. This reduced the time of production of charts and figures while maintaining a continuous graphical standard, and also illuminated unexpected observation by providing a large range of initial visualizations. The tool shown in figures XX and XX were fundamental to the comparative analysis performed on each sample and the experiment as a whole. It was clear during the experiments that the public, specifically urban simulation stakeholders, would benefit from these tools.

Figure 26: [Top] A user interacts with the UMI Dashboard.
Figure 27: Elevation of the UMI Dashboard displayed on a touchscreen.
In conclusion, historical masterplans were compared using computational analysis methods. The findings were as follows: There exists a series of worthwhile observations that could be made when comparing the geometric mass and programmatic distribution of proposed masterplans. Both the total energy demand and a normalized metric of energy intensity are required to reasonably understand site wide operation energy use.

The energy profile of a masterplan is highly dependent on the programmatic distribution. Comparison of operational energy use is best when isolated by programmatic use. When site wide window-to-wall ratio is controlled for and a spatial daylight autonomy simulation is executed, the outputs are indications of received internal daylight and additional measures - such as an indication of building footprint resolution and a magnitude of building location and shape prescription by the master plan.
Wide and deep floor plates performed poorly when simulated for spatial daylight autonomy. Occupant mobility simulations can be used as an indication of site wide connectivity and centrality to amenities with potential areas of optimization, depending on street network topology. Expertise in each masterplan was tested by all metrics and weak points or hot spots were only identifiable when a masterplan sample was compared to a field of samples.

A repeatable method for physics-based bottom up modeling was achieved and supplemented by two analysis tools. The major difference of the two tools was that one was a single sample analysis tool and one was a multi-sample analysis tool. Different data visualization strategies were required for each.

Figure 27: [top] Providence 2020 with infill.
Many potential applications for this methodology emerged during this experiment. There were applications that fit into existing modes of practice and applications that suggested new modes of practice.

Entry to existing modes of practice included: (1) site analysis and site selection due diligence (2) multi-asset portfolio simulation and property management analysis. (3) Centralized management of proposed masterplans for comparative design competition or commissioning. (4) Masterplan document quality assurance and control during the design phase.

The application of centralized management of proposed masterplans for comparative design competition or commissioning could function as a design proposal requirement and by deploying, a similar repeatable methodology as described above would provide deep and fair quantitative analysis to the already qualitative masterplan competition phase.
In closing, the data required to build urban performance simulations is abundant. Previous work in this field has advanced the technology to maturity, it is now time that these methods enter existing modes of practice. Cities need to quantify their planning efforts beyond the traditional metrics. To reduce carbon, increase livability, and make the most of planning resources, urban stakeholder across the globe need to rethink the way masterplans are procured, delivered, and designed to live on.

Figure 28: [top] Author and sister on site in 1996.