An Integrated Performance Analysis Platform for Sustainable Architecture and Urban Infrastructure Systems

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This applied research brings together the performance analysis of a building's micro-scale and urban-infrastructure's macro-scale. A New York City lot, is serving as the background of experimentation with parametric design, performance simulation, data analysis and visualization. The paper describes the process of integrating design intentions, location parameters, climate data, material properties, and space quality and sustainability metrics into one platform. Although in-depth domain knowledge is irreplaceable, the paper argues that the exploration into contemporary, easily accessible and algorithmic simulation software, provides a unique educational opportunity for architects and students to integrate performance driven design in their every-day practice, and become aware of the consequences of their design on urban infrastructure systems. This allows them to reduce the time frame between design iterations and performance evaluation for the benefit of better informed decisions.

Keywords: Real-time performance evaluation, Infrastructure systems, Sustainability, Parametric design, Performance driven design

INTRODUCTION
The research hypothesis is that contemporary, accessible, and easy to use computational tools, provide an unprecedented opportunity to increase the education and awareness of architects and urban designers on performance driven design. By allowing a real-time -or near real-time- analysis of various performance metrics, users can evaluate the impact of each design decision on both the building and the urban infrastructure. The more architects familiarize themselves with those tools the easier it will be for sustainability to become a critical driving factor of the design process. Rhinoceros’ plug-in Grasshopper (GH), through its visual programming interface and wide adaptation in the academic and professional community, provides a powerful computational environment and a unified communication platform among the various fields. Grasshopper's plug-ins Ladybug (LB) and Honeybee (HB), used for the purposes of this research, allow for the evaluation of building's envi-
Different design options correspond to different performances regarding water, energy and solid waste. Therefore, the research explores the correlation between parametric architectural design and urban infrastructure systems, by juxtaposing spatial and qualitative metrics with energy, water and waste metrics. A unified multi-dimensional platform, allows for a numeric representation of "flows and entities", in order to simulate a valid working model of the city (Weinstock 2013), and assist the potential decision making.

Despite the great progress in sustainability and building performance analysis, it still appears that in everyday architectural practice, those fields are not always integrated in the beginning of the design process. Although general architectural practice has adopted design related performance notions such as shading, orientation, and materials, there is less focus on heating, ventilation, and air conditioning (HVAC) systems (Negendhal 2015) whose setup can drastically alter the energy demand of the buildings, while the environmental impact of the building to the urban infrastructure is rarely considered. Performance metrics can be incorporated early in the design process in order to comply with the requirements of environmental assessment systems like the Leadership in Energy and Environmental Design (LEED), US Green Building Council (USGBS) or the Building Research Establishment Environmental Assessment Methodology (BREEAM).

BACKGROUND - PRECEDENTS
According to the United Nations, buildings use 40% of global energy, 25% of global water and 40% of global resources while they emit approximately 1/3 of Green House Gas (GHG) emissions. Furthermore, 54% of world's population lives in urban areas, a proportion expected to increase to 66% by 2050 [1]. Various private and governmental initiatives on Smart Cities and Zero Energy Buildings, address the issue, proposing contemporary construction technologies, urban infrastructures and regulatory legislations, in order to ensure the future sustainability of the increasingly dense urban systems.

A popular example is the under construction Masdar City in Abu Dhabi. The city futures state of the art technologies in order to become carbon neutral and produce zero waste, with the ultimate target of creating an entirely energy self-sufficient community [2]. A multitude of future sustainable cities have been recently commissioned, including the Nanjing in China by CK Designworks, the Europa City outside of Paris proposed by BIG, and the Dubai Sustainable City to be designed by Baharash Architecture [3]. But existing cities too are implementing infrastructure upgrades and regulations in order to address the environmental challenges. The 2015 ARCADIS Sustainable Cities Index ranked Frankfurt as the most sustainable city by measuring various social, environmental and economic indexes [4].

Relevant studies demonstrate that low energy buildings contribute significantly to the energy efficiency, energy conservation and renewable energy generation aspects of smart cities (Kylli and Fokaides 2015). One characteristic example of existing implementation of green technologies in NYC is the Solaire Building in Manhattan’s Battery Park City. The Solaire combines various technologies in order to reduce its environmental impact, including a black water and wastewater treatment plant, photovoltaics, efficient windows and walls and more. The building has achieved a significant reduction in water usage and energy demand in comparison to buildings of similar size, function and population (Epstein 2008).

In order to increase their awareness in performance driven design and sustainability, various architectural firms are developing their own platforms. RTKL has developed The Dart, an online interactive tool, through which the users can identify the system variables and get a list of possible strategies and their impact value on different social, economic and environmental aspects. The platform allows the user to select from a list of parameters according to the designer's and client's intention. Input parameters include -among others- daylighting, water man-
agement, material sourcing, natural ventilation and building sector. Outputs include design suggestion of how to achieve specific goals [5]. HOK and Callison both utilize similar software, in order to allow more informed decisions from the initial stages of design, based on multiple sustainability best practices [6]. In parallel, leading universities including MIT incorporate in their architectural curriculum programs that aim to "produce high quality fundamental and applied research that facilitates the design of resource-efficient and comfortable environments at the building and neighborhood scale" [7].

**METHODOLOGY - PLATFORM DESCRIPTION**

As a case study, an existing lot located in Downtown Manhattan was selected to develop a parametric model of a typical residential hi-rise building. The methodology, combines the inputs and outputs of parametric design with those of energy simulation, sustainability, and space quality metrics in order to inform design decisions through the data analysis of the results (Figure 1).

**The Architectural Parametric Model**

The first step was to select the lot on the corner of Leonard St. and Church St. in Tribeca (lot 26, Block 176) with area of 12,518SF, located within a C6-4 zoning area. It can accommodate a mixed use commercial building with offices and apartments, or by complying with the equivalent R-10 residential district zoning code, it can accommodate a "Tower" or "Tower-on-a-Base" residential building. In addition, the lot's geometry allows for a "Public Plaza" which was crucial for the definition of the massing options as it provides additional floor area bonus, therefore altering the final total built area, height, and populations.

After selectioning location, topographic data for Block 176 and the adjacent blocks, including the buildings' footprint and height, lot outlines and pavements, have been collected from the NYC OpenData online library. A combination of data from the GIS file and measurements from Google Earth have been used to construct with adequate accuracy the 3D model of the adjacent context, an important element not only for the massing scenarios but also for the daylight, view and energy analysis.

![Figure 1](https://via.placeholder.com/150)

**Figure 1**
Methodology Diagram
Regarding the parametrization of the design, it was essential to define the parameters in order to construct the geometric algorithm in Grasshopper that generates the various massing options, taking into consideration the zoning requirements: plot area and coverage, Floor Area Ratio (FAR), Gross Floor Area (GFA), the setbacks from Leonard St. and Church St., the setbacks from the adjacent buildings, the size of the required "Rear Yard", the number of floors for each use (residential, amenities, lobby and retail), the floor-to-floor heights, the glazing-to-wall ratio for the facade, and the core’s efficiency.

The Zoning restrictions described in Article III: Commercial District Regulations of the NYC Zoning Resolution have been integrated as limits to the variables of the algorithm. The minimum street setbacks were set to 15ft and 10ft, while the "Rear Yard" minimum width was set to 30ft. The lot coverage which resulted from the various setbacks, was monitored not to exceed 47% since our lot was smaller than 20,000 SF. For some options the "Front Wall" provision was taken into consideration in order for the buildings’ podium to reach the same height as the adjacent building in lot 18. Additionally, the GH algorithm calculates the bonus GFA of 6SF per 1SF of "Public Plaza", up to a maximum of 2 additional FAR points. The "Public Plaza" requires to have a minimum area of 2,000SF, minimum depth of 40ft and to be at least 175ft away from an existing publicly accessible open area or public park on the same side of the street.

In order to achieve taller building options, a common-practice assumption was made to purchase additional unused development rights ("Air Rights") of 51,500 SF from adjacent lots in the Block to be transferred to our lot. The available unused areas have been calculated from the publicly available data provided on the NY City Zoning and Land Use (Zola) website. As a result, our building could have windows on the lot boundaries, with no risk of them being blocked in the future.

Ten massing options (S1-10) were then generated. By following the R-10 Zoning regulations, two main residential massing categories have been selected: "Tower" and "Tower-on-a-Base". The design variables selected were the size of the "Public Plaza", two different residential layouts, the inclusion or not of retail at the lowest levels and the glazing-to-wall ratio of the residential facade (Figure 2).

Two setbacks from the Church St. have been used, 17ft and 40ft, for maximum building footprint and maximum "Public Plaza" area respectively. The two apartment layouts used were Mix A with 4 apartments in total: Three 3-bedroom and one 2-bedroom and Mix B with 5 apartments in total: Three 2-bedroom, one 3-bedroom and one studio. In order to simplify the calculations, each massing scenario had one type of apartment mix for the entire residential portion. Retail was included only for the "Tower-on-a-Base" options and the glazing-to-wall ratio of the residential facade varied between a typical 40% and a higher 60%.

The outputs of the geometric algorithm were: The residential, amenities, lobby and retail GFA, the number and program of floors, the population, the plot coverage, the "Public Plaza" and no-bonus green areas, along with their equivalent soft-scape and hard-scape areas. Construction quantities along with costs were also calculated, based on current average prices of typical construction materials and technologies for similar buildings in NYC.

**Integration of the Energy Simulation**

After the completion of the parametric design model described above, the algorithm for the energy simulation was constructed using the two plug-ins Lady-
bug (LB) and Honeybee (HB) that help explore and evaluate environmental performance. Ladybug imports climate data into Grasshopper and provides a variety of graphics to support the decision-making process during the initial stages of design. "Honeybee connects the visual programming environment of Grasshopper to four validated simulation engines - specifically, EnergyPlus, Radiance, Daysim and OpenStudio - which evaluate building energy consumption, comfort, and daylighting." (Roudsari and Park 2013) (Figure 3).

Materials complying with the ASHRAE 90.1-2010 standards have been assigned to the different components of the building: external walls, roofs, ceilings and glazing. In addition, LB and HB provide components to fine tune more specific parameters of the system, including the heating and cooling set points, the occupancy schedules or the natural air flow.

Furthermore, space quality metrics like the average views and the daylight factor (DF) were included to the platform. Specified areas of interest for the views were the skyline of the World Trade Center complex to the south, the skyline around the Empire State Building to the north, and portion of the Hudson River to the west. The daylight factor is a metric used to measure the diffuse daylight in a space, and according to the British Standards Institution, BS 8206 part 2 CIBSE "a space with a mean daylight factor between 2% and 5% is considered well lit and requires little or no additional lighting during daytime." (Reinhart and Otis 2009) [8].

Integration of Urban Infrastructure Systems

The platform is further enhanced by the integration of the urban infrastructure systems dimension in the parametric model. Specifically, the systems of water, energy and solid waste were included. The three systems have been described based on the organizational framework developed by the Zofnass program for Sustainable Infrastructure and the parametric methodologies generated for the course Data from Infrastructure Systems for Urban Algorithmic Modelling.

Identification of the urban infrastructure systems

The summarization of the critical components of the associated urban infrastructure systems is a significant step before their association to the parametric model. Each infrastructure system was decoded through four system levels that include demand, resources, networks, and nodes of the system (Pollalis et al. in press). Following a high-level approach the basic components were identified and accompanied by the respective performance metrics.

The water system includes the management of water supply, wastewater and stormwater. The main water supply source of New York City is the Catskill/Delaware watershed located 100 miles away from the city. The water is distributed across the boroughs of NYC with 23% of unaccounted water for Manhattan while the water consumption per residential unit is 205 GD (NYC DEP 2012) [9]. Approximately 60% of the City sewers are combined, while combined sewage in Manhattan is 100% (NYC DEP 2015) [10]. This fact implies inflowing rainwater and runoff in the wastewater system. In the case of heavy rain the combined sewer overflow (CSO) occurs resulting in
the discharge of untreated wastewater to the water bodies of the city, a phenomenon that carries risks for the environment and public health.

Regarding the energy system, the main energy supplier for Manhattan is Con Edison that provides electric, natural gas and steam service. The primary energy source for electricity is predominantly natural gas and in some cases fuel oil. In-city generation covers 50% of the total energy demand (80% during peak demand) while the rest is covered by electricity imported from Upstate New York and New Jersey. Generation from renewable sources is limited to customer-sited distributed generation and is relatively low. The overall electricity demand in NYC can reach 11,000 MW (City of New York 2013) [11].

Regarding the solid waste system, each year NYC generates approximately 14 million tons of solid waste from residences, institutions, construction and demolition, fill and commercial businesses (plaNYC 2013) [12]. The average municipal solid waste generation per person is 2.4 lbs/day. The generated residential waste is comprised by recyclable, non-recyclable, and compostable waste. Almost half of recyclables will be recycled (Columbia University 2012) [13]. The overall diversion rate of residential waste is 15% so that the remaining 85% becomes trash and gets disposed in landfills outside of the city that can be even 400km away. Part of the diverted waste is transferred to incineration facilities for energy generation (plaNYC 2013) [12].

**Infrastructure systems in the parametric model**

The objective was to quantify the impact of each design option to the urban infrastructure system through metrics. A group of Grasshopper definitions generates real-time estimations for each system across the ten design options (S1-S10). For each design option five extra options of added sustainable infrastructure solutions were examined. The tower with a water reuse system (S-A), with green roof (S-B), with water reuse, green roof and permeable pavement (S-C), with PV panels (S-D), and with water reuse and PV panels (S-E). In total 60 options were decoded through 43 variables and 20 constants that are related to infrastructure performance (Figure 4).

First, it was important to determine the design related variables that are connected to the algorithm that calculates the impact to the infrastructure systems. These variables concern demographic data (estimated population, number of residential units) and spatial data such as the area size of amenities, plaza hardscape, green areas, and rooftop size. Then for each system, an algorithmic definition was generating the estimations related to the building site's annual performance and the respective inputs to the infrastructure systems.

For the water system, the design options influence the projected total water use, sanitary flow, infiltration to green infrastructure, and generated runoff. In water reuse scenarios the recycling capacity and related coefficients were based on the efficiencies of the Solaire building (Krogmann et al. 2007; Epstein

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**Figure 4**

Local and urban infrastructure systems
Metrics on rainfall, runoff, evaporation and the infiltration rates of green roof and permeable pavement were based on the US Environmental Protection Agency’s (EPA) Stormwater Calculator. At the same time, output values included the respective volumes of the required distributed water (including unaccounted water) from the city’s water supply system, the stormwater inflow to combined sewage, and the overall wastewater inflow from the building site to the NYC wastewater collection system.

For the energy system, the total energy demand was imported from the LB and HB calculations. The breakdown of the total energy demand to fuel consumption and electricity was based on the average ratio for residential multi-family buildings in Manhattan (Howard et al. 2012). In the water reuse options the energy demand for recycling water was added. In the case of PV panels on the rooftop, an algorithm was developed based on assumptions from PVWatts Calculator of the US Department of Energy. The energy demand at the source of generation was estimated by the site-to-source electricity conversion rate due to generation and transmission losses (U.S. Department of Energy 2012) [14].

For the solid waste system, the estimation included only the residential waste that was influenced by the demographic data of the design options. Solid waste generation per capita, residential breakdown in recyclables, non-recyclables, and compostables, the recycling and composting rate were consequently estimated. Accordingly, the respective data for the waste disposal was included (Columbia University 2012; plaNYC 2013) [12][13].

Data Analysis Method
The simulation of design and infrastructure solutions options lead to a multidimensional framework of 72 variables (29 design and 43 infrastructure) and 40 constants (20 design and 20 infrastructure). The employment of data analysis tools was critical for harnessing the results and configuring an efficient parametric design process that can be iterated in the future. After trying various ways of exploratory data analysis a method that combines single, two, and multiple variable analysis was designated. A series of single variable charts were studied through dynamic data visualization, while the Hierarchical Clustering Explorer was used for the multidimensional data exploration. The data analysis was executed for two different datasets. First, across the 10 architectural options and second across the 60 options that integrated different infrastructure solutions.

DISCUSSION - RESULTS
Throughout the process, it was critical to understand the fundamental notions and associated data of the energy simulation and HVAC systems in order to correctly set up the algorithms and to meaningfully assess the results. Grasshopper functioned as the common ground for bringing together architectural practice with the various specialty fields.

Furthermore, main objective of this research was to define each apartment as an energy zone, without resulting in the common practice of re-building a separate abstract model for the calculations (Negendhal 2015). The main obstacle was the long processing time required for solving the energy calculations of more than 80 zones, but even within the achieved time frames of approximately one to two hours, it can be reasonably argued that the design process was informed faster than by outsourcing the task.

The view analysis revealed that after a certain building height the average view of each floor begins to deteriorate, because the indoor spaces not adjacent to the windows begin to lose direct view to points of interest located below them. It also became visually apparent which locations throughout the building would have the most advantageous views, which could directly affect the location of specific functions in the floorplan layout (Figure 3).

The daylight factor analysis, provided a visual confirmation that the thinnest massing options had much better light distribution across the floorplates, which begins to reduce after the first 12ft. At the same time, lowering the floor-to-floor height by 3ft
and widening the floorplate for the base portion of "Tower-on-a-Base" options, resulted in a significant reduction of the daylight factor by 65% (Figure 3).

Additionally, a 50% increase in the glazing-to-wall ratio has resulted in approximately 50% increase in average views and has raised the total energy consumption an average of 8% for the lower massing options and 12% for the higher ones. The construction cost of the facade was also significantly increased by 33%, making evident that although an increase in the size of the windows would benefit the views and daylight, it would have a measurable impact on capital and operational costs.

The energy analysis has also identified the zones with the highest energy demand, based on different function and location in the building, a critical factor for the selection of appropriate construction materials and dimensions of openings (Figure 3). More importantly for the intentions of this paper, it provided crucial outputs that fed the performance analysis algorithm of the urban infrastructure.

The impact of architectural design options on the infrastructure systems was examined through specific parameters that can be indicators of the systems' sustainability. The main focus was to observe the range of values in response to different parametric options rather than assessing each single value of each parameter.

In the water system, across the 10 design options, the total water demand could vary from 33,500 to 54,700 GD. Across the dataset of 60 options the amount of distributed water ranges from 16,500GD to 67,300GD (Standard deviation=15,900) mainly due to water reuse options.

The impervious surfaces fraction varies from 0.57 to 1.00 (10 options) and from 0.28 to 1.00 (60 options) since permeable pavement and green roof are included. The implications are evident in both datasets, as runoff varies from 99 to 167 GD and 47 to 167 GD respectively. At the same time, the estimated sanitary flow that inflows in the city's wastewater system is responsive to population, programmatic uses, and water reuse. Conclusively, the total inflow of wastewater varies from 21,670 to 40,000 GD (Stdev= 6,900) in 10 options and from 1,600 to 40,000 GD (Stdev= 12,150) in 60 options. In contrast to low-rise developments, the impact of stormwater management solutions is low due to a very high FAR (mean = 14.45).

In the energy system, the total demand varies from 2.382 to 3.216 MWh/y (Stdev=0.248) in 10 options and from 2.382 to 3.246 MWh/y (Stdev=0.249) in 60 options. Parameters such as facade orientation, percentage of glazing in the facade, and programmatic uses influence the results. When PV panels are added to the rooftop, local electricity output varies from 0.270 to 0.350 MWh/y. The estimated generated energy at source that is needed to cover the grid electricity demand (excluding fuel consumption) has an estimated range of 1.943 MWh/year (1.030 to 2.794, Stdev=0.5).

In the solid waste system, the residential waste generation is affected by the demographics and the distribution of programmatic uses. Thus, waste generation estimations vary from 233,000 to 442,400 pounds/year, while the projected residential trash disposed to the landfill corresponds to a range of 178,000 pounds/year.

All of the 60 options were compared across a set of variables that are related to the sustainable performance of the systems. By observing the color mosaic of normalized data the options with the best and worst performance were identified. Options S1E ("Tower", 40% Glazing, Resi Mix A, Max Footprint, No Retail, with water reuse and PV panels) and S5E ("Tower", 40% Glazing, Resi Mix B, Max Footprint, No Retail, with water reuse and PV panels) scored the best. On the contrary, options S6 ("Tower", 40% Glazing, Resi Mix 5, Max "Public Plaza", No Retail) and S8 ("Tower", 60% Glazing, Resi Mix B, Max "Public Plaza", No Retail) had the lowest values (Figure 5).

For the comparison of the options, different parameters of each analysis can be combined in radar charts. The axes of the diagrams can correspond to values from different kind of metrics, while their selection depends on the objectives of each projects.
and the intended performance goals. Therefore the identification of an optimum or worst scenario, would highly depend on the weight of importance assigned to each axis (Figure 6).

**FUTURE WORK - CONCLUSIONS**

The research could be further developed in order to evaluate more design and infrastructure scenarios. Multiple parameters could be integrated, regarding different massing iterations, apartment layouts and configurations, locations, zoning regulations, building programs, materials, and their respective market value and construction cost.

More space quality metrics could be added, including daylight autonomy, glare analysis, and thermal comfort, a property directly related to productivity in work spaces (Akimoto et al. 2009). Future development of this research could include various scenarios for the design of the facade, a critical component of a building's performance and one that allows relative flexibility in terms of embedded technologies and design. Integrated photovoltaic panels and vertical gardens are few of the technologies currently gaining traction in the attempt to increase building's environmental performance and improve occupants' quality of life. The occupant's behavior could be also added as a factor, since it can significantly alter the results of any predictive performance model (Li et al. 2014). Furthermore, the integration of empirical data from building performance monitoring could enhance the efficiency of performance based design and facilitate a deeper understanding for both architects and sustainability professionals.

As discussed above, results from both the building and urban scale analyses, provided information that could directly influence the decisions of architects and urban designers. The flexibility of the platform to integrate multiple variables and provide real-time feedback makes it evident that it stands as the foundation of a larger platform that could evaluate and inform an infinite amount of scenarios. Ultimately it could evolve to goal-based modeling through real-time optimization, with the use of Galapagos, an evolutionary solver included in Grasshopper, in order to creatively influence architectural design.

The pedagogical impact of integrating performance analysis of building's micro-scale and urban-infrastructure's macro-scale, into a cohesive, easy-to-replicate, and real-time dynamic model, as described in the workflow of the research, could be profound. The overview of the architecture of the infrastructure systems cultivates an infrastructure-focused consciousness that is critical both for developing the parametric model and conducting the data analysis. The integration of such information in the platform foster better and earlier coordination with engineers. Moreover, it can educate architects about the consequences of their design to urban infrastructure systems, an approach that can expand the archi-
tect's awareness and influence beyond the architectural scale.

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