SYMPOSIUM ON SIMULATION IN ARCHITECTURE + URBAN DESIGN
SimAUD 2020

# A Case of High-Performance Building Form Design Workflow Informed by Computational Simulation

**Haobo Liu[1], Adam Rysanek[2], Andrea Frisque[1] and Jeanie Chan[1]**

[1]Stantec Consulting Ltd.
Vancouver, Canada
{Haobo.Liu, Jeanie.Chan, Andrea.Frisque}@ stantec.com

[2]University of British Columbia
Vancouver, Canada
arysanek@sala.ubc.ca

**ABSTRACT**

This paper aims to formulate and test a parametric high-performance building design workflow that allows architects to explore realistic space attributes. It also allows architects to assess their environmental performative outcomes such as daylight simulation, solar radiation and occupant visual link in order to inform decision making during the design process. Using the Rhino and Grasshopper platform, a new workflow is proposed for generating and analyzing building forms generatively and extensively to predict their environmental performance. This approach comes from the improved interoperability between the parametric model tools, simulation engines and statistical analysis tools, enabling significant ability to compare energy performance with other performance metrics. The overall framework is divided into four steps: site setup, massing generation, performance evaluation and visualization, and design development. Through a residential building design case in Vancouver, it is anticipated that, by incorporating knowledge about the environmental performance of a design early in the volume-making process, the proposed framework will help designers better navigate performance objectives in the architectural design environment.

**Author Keywords**

Parametric design; procedural form generation; environmental performance; parallel simulation; building archetype modelling

**ACM Classification Keywords**

Simulation Theory, Model Development

## 1 INTRODUCTION

Architects regard themselves as professionals of building form manipulation. Tracing back to the Roman Republic, Vitruvius stated architectural design as a procedure of making space that fulfills the criteria of commodity, firmness, and delight [1]. Since the birth of modern architecture, the organization of building form has become a core research area of design practice [2], and one of the epistemologies regards space as an enclosed volumetric massing [2]. Meanwhile, in mainstream building performance modelling software, the building form is input into the simulation engine as a volumetric zone including its geometrical attributes, programs, behaviours, schedules as well as loads [3]. This connection gives us the opportunity to design an artful volumetric form with consideration via building performance modelling in the preliminary design phase.

In the contemporary world, our increasing understanding of climate change and its future risk, along with the understanding that buildings contribute significantly to greenhouse gas emissions, forces us to assess or re-assess the relationship between building form design, thermal performance, and overall building environmental quality. More municipalities are adopting performance-based codes which require the building to comply with the specific energy target at the time of permit application. For example, in British Columbia, new construction projects must meet the Energy Step Code [4].

In traditional building energy modelling procedures such as the LEED Standard, which uses ASHRAE 90.1 Appendix G [5], the focus has mostly been placed on verifying the final design performance. This is unlikely to cue architects to perform robust and elegant design actions in the design process. However, as the parametric model tools and simulation engines improve, a significant potential is the ability to compare building performance between different form designs. This asks us to change the attitude of the performance model in architecture design, moving from a performance-analysis to performance-informed workflow. It requires, among other measures, fundamental thinking of design strategy, where architects are not yet proficient with the methodology to make this change happen.

The workflow proposed in this paper is for parametric demonstration of various performative outcomes according to basic form exploration in the preliminary design phase. It contains architecture information and enables various volumetric massing iterations with the facilitation of computer-based parametric programs. Performance can be tracked as design iterations are initially developed, helping to draw out more sustainable buildings designs.

## 2 COMPUTATIONAL BUILDING PERFORMANCE MODELLING

From the scientific viewpoint, it has long been acknowledged that the decision to invest in a particular building design depends on measurable performance

SimAUD 2020 May 25-27, Online

metrics, such as a design's environmental footprint. One of the greatest analysis tools available to professionals is building performance simulation (BPS) tools [3]. These are computer programs that can provide the capacity to simulate building energy physics in detail or estimate the future energy consumption resulting from an installed retrofit. With over three decades of development, BPS tools have become the industry standard for the design, specification, and evaluation of energy supply systems and energy demand reduction measures in new or retrofit building projects. Simulations using tools such as eQUEST, IES Virtual Environement, or EnergyPlus are most widely known in the industry. These tools usually combine digital models of a building with weather data to accurately simulate the thermal behavior of individual zones of a building and interactions between the different building components. In using any of these tools, one may find thousands of different implementable simulation inputs, from building occupant schedules to air-conditioning system configurations. Understanding that optimizing building design using BPS tools is sophisticated and time consuming. Researchers in the BPS industry have pursued a niche computational solution to this problem: the use of integrated workflow execution software, or wrappers, that permit parametric optimization of building design using BPS tools. BEOpt is one of the most well-known wrappers in this domain[6].A typical use of the BEOpt may involve an EnergyPlus model repeatedly evaluating the performance of different glazing systems on a façade until the most cost-optimal glazing system configuration is found, as in the example of façade design in a cold climate [7]. In general, existing optimization wrappers for BPS tools are limited to evaluating parameters that are easily configurable in the BPS tools themselves. As BPS tools were adopted initially by engineering consultants in the buildings industry, it follows that nearly all easily configurable parameters have also been engineering-centric, such as façade material properties, and/or building energy system types. As this encompasses a broad set of variables, it is perhaps simpler to define what parameters have not been easily configurable within the typical BPS-driven optimization process. These are virtually all parameters affecting the preliminary architectural design of buildings: building programming, massing, orientation, and glazing ratio etc. This has been an unfortunate paradigm for the building design process, particularly in light of future building codes. As countries are beginning to adopt increasingly stringent energy performance targets for future buildings [8], it will be contingent on architects, and not necessarily engineers, to identify building forms that can satisfy environmental quality requirements passively [9]. Perhaps in light of this, the typical engineering-centric parametric optimization paradigm is now changing. A new type of parametric modelling software, catering to architectural design, has emerged, and Grasshopper, a visual programming language for the 3D computer-aided design (CAD) software, Rhinoceros, is at the forefront of this new field. Grasshopper is a generic platform, allowing architects to develop algorithmic processes for preliminary building design as well as connect these algorithmic processes to third party BPS software tools [10]. For example, the ARCHSIM plug-in for Grasshopper, produced by MIT spin-off company Solemma, allows co-simulation between a Rhino Grasshopper parametric architectural design model and EnergyPlus to perform energy simulation [11]. These emerging tools act as the connection between the model and the analysis results in a way that allows the designer to keep manipulating model parametersuntil the desired analysis result is achieved.

Furthermore, several computational plug-ins are available for Grasshopper, such as the Colibri developed in Core Studio in Thornton Tomasetti. Colibri[12] is an open-source tool for investing simulation-based, multi-objective design and decision problems. These tools could be used to wrap an ARCHSIM-evaluated parametric design problem with a parallel simulation solver [13].

## 3 COMPUTATIONAL BUILDING FORM DESIGN

In the last decades, in accompaniment with the development of computation, researchers have been exploring form language using computer algorithms [14]. Steadman first suggested that if one would be given appropriate geometric definitions of certain classes of plans, systematic methods could be developed for computing all possible plans of each program type [15]. More recently, Steadman proposed a new approach to building design based on generating possible form iterations of building archetypes [16]. In this new method, Steadman assigns a binary code of 0 and 1 to indicate the absence or presence of dimensionless strips of accommodation or open space across each plot. Homeira Shayesteh continued P. Steadman's work and applied it in an urban form generation method for Tehran[17].H. Shayesteh uses the archetypal representation to explore and better understand the relationships between urban built form characteristics, plot size, housing layout, and ground coverage about density. H. Shayesteh investigates the evolution of the stereotypical house form in Tehran over time. Namely, H. Shayesteh analyzed stereotypical forms for housing and developed a model that brings together parameters of an urban structure (e.g. block and plot size,ground coverage ratio) with parameters of the built form (e.g. access frontage, day-lit depth, plan shape). Several years ago, in an effort to explore frameworks of integrating volumetric zoning and energy modelling, Samir proposed a procedure to link the morphological attributes of a form with its thermal behaviour [1]. His framework aimed to provide a feasible way for designers to examine the relationship between architectural forms and the thermal performance of the forms. It was later studied further by Janssen et al., who explored low energy design strategies with a factor in limitations and constraints of both passive and active systems being discussed [18]. Further investigations which look at niching of the genetic algorithm data are needed to give a more diverse population in the result and thus give the architect more design options [19]. Timur Dogan has recently evaluated new plan typologies concerning exterior morphology and interior organization with their energy performance, but the focus has been on the comparison between real volumetric zoning and the ASHRAE zone method [20].

In the urban scale, Bill Hillier, from University College London in the late 1970s to early 1980s, conceived the term space syntax, which includes a set of theories and techniques for the analysis of spatial configurations [21]. This method later helps urban planners generate designs by breaking down form into components. Most recently, with the development of the Decoding Spaces tool kit [22] and other analytical and generative components in Grasshopper, the computational generation of street network, parcellation and building form based on the urban context and various design goals, become possible. Theresa Fink and Luc Wilson have tried to apply these tools to urban design workflow [23]. For example, the KPF urban interface [24] tests the computational urban design informed by environmental performance metrics. However, in the urban scale, there numerous unknown parameters that could affect the complex design process, such as long-term development, population increase, transportation, and climate change [24].

In this reviewed research, there are readily available algorithms and methods in different areas. But there remains a research gap, in building form scale, of how to integrate computational design platforms into the real design process to generate a more diverse and unique population of building volumetric options and test how this could provide the architect with a greater balance between performative outcomes of a computational model and design independence.

## 4 A NEW WORKFLOW FOR HIGH-PERFORMANCE BUILDING FORM DESIGN

A new workflow is proposed here for a computational approach to generating architectural form and predicting their environmental performance. The aim is to deliver a parametric volumetric model that allows architects to explore and demonstrate realistic building attributes and determinants to assess their performative outcomes. The overall framework is divided into four steps: site setup, building form generation, performance evaluation and visualization, and design development. Through a residential building design test case in Vancouver, Canada, the paper evaluates how architects could adopt this workflow in the design process and maintain the feature throughout the whole preliminary design process (Figure 1).

### 4.1 Step 1: Site setup

In the first step, the existing urban data of the site is imported into Grasshopper in the form of SH files. Other site attributes, including weather, surrounding buildings, site boundary, and set back, are attained and inputted into Grasshopper as site data. This step helps designers collect climatic information and design constraints for later form generation. In this paper, the site is located at Yaletown, Vancouver, a residential community known for its beautiful surrounding landscape, high real estate value, and environmental issues such as summer overheating. The site constraints include 8-meter setbacks from the site boundary, and a maximum gross floor area of 18,000 $m^2$. The site geographical information is downloaded from the Vancouver Open Data Catalogue[25].The model below generally reflects the contextual features of the site (Figure 2).

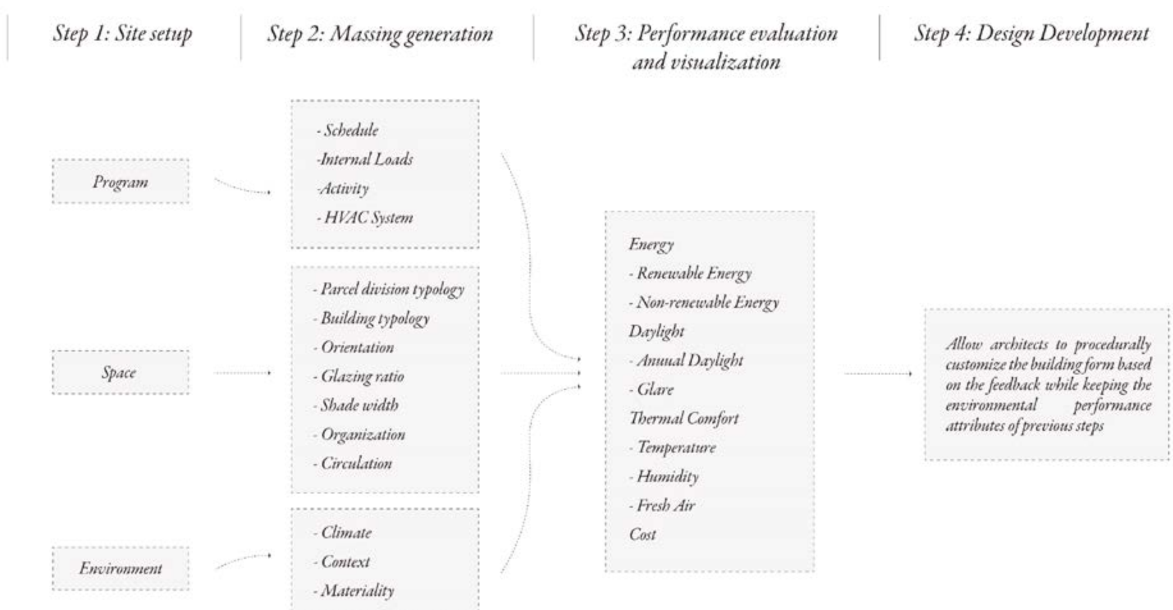


**Figure 1.** New workflow for high-performance building form design

**Figure 2.** Input site information and constraints

### 4.2 Step 2: Massing generation

In the second step, the building form is generated from the algorithm based on different variables, such as parcel division, building typology, orientation, glazing ratio and shade depth. Deploying some readily developed tools in Grasshopper, such as the Ladybug tool [26], Decoding Spaces [24] with customized scripts, this step is able to generate various types of building massing.

Three common residential building typologies are established, which includes block type, row type, and tower type. Block type represents low-rise residential townhouses along the street; row type represents mid-rise residential apartments; tower represents high-rises. Along with four parcel divisions methodologies, we received a total of twelve building typologies (Figures 3 and 4).

Building orientation influences street appeal, interior view, and how much solar radiation is captured by the building. Twelve different orientations are set up for each building typology. The basic building orientation is facing towards the south and is rotated incrementally by 30 degrees. However, since block building typology is not applicable for rotation, it only has one orientation (Figure 5).

Window to wall ratio (WWR) represents the percentage area determined by dividing the building's total glazed area by its exterior envelope wall area, which could influence the daylighting access, radiation impact, and heat loss. A varying WWR is studied at 30%, 40% and 50%. The same WWR is applied to each façade following residential building design convention.

External shades block out the extra sunlight and prevents solar radiation from hitting the window surface during summer. This helps bring down the temperature and reduce cooling loads, but it can also block out needed sunlight and increase the heating and lighting energy consumption. Especially under the context of global warming, the impact of shade needs to be studied. The shade simulated here means horizontal shade or outside balcony. The length of the shade input includes 0 and 1.2 meters (see Figure 6).

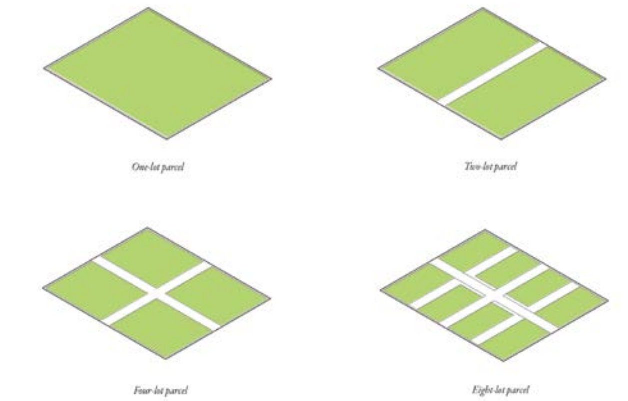


**Figure 3.** Parcel division typology

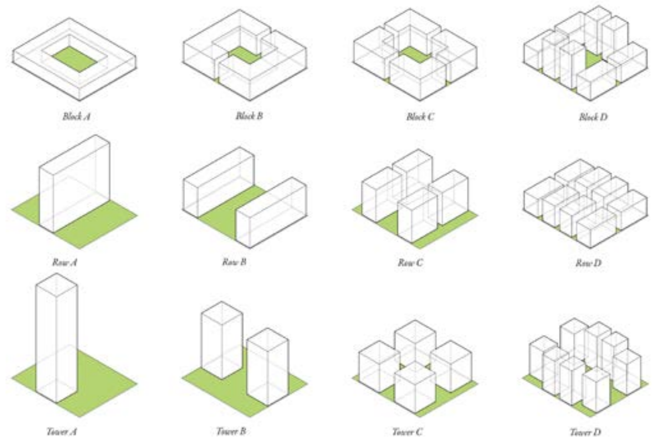


**Figure 4.** Building typology

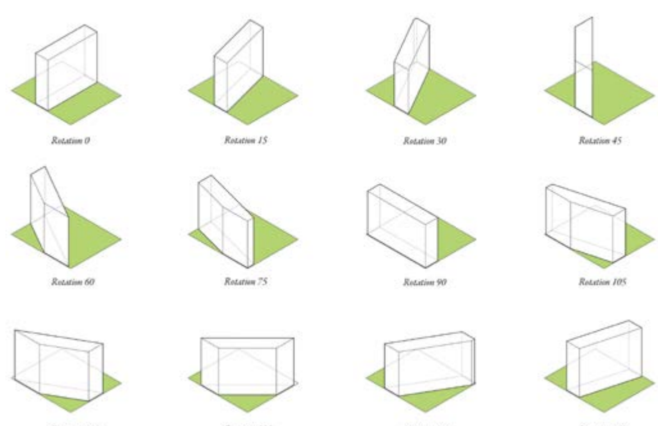


**Figure 5.** Orientation

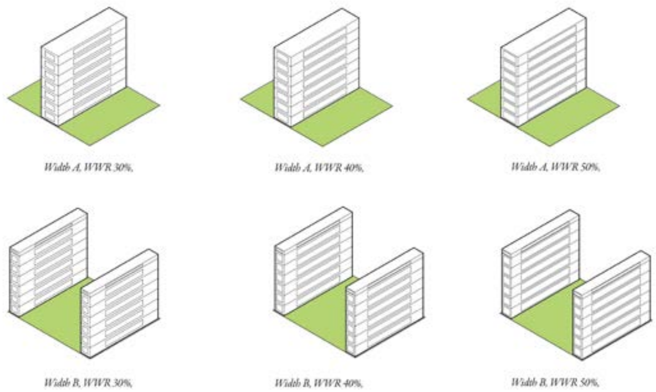


**Figure 6.** Glazing ratio and shade width

### 4.3 Step 3: Performance evaluation and visualization

In the third step, the building forms generated from the last step are transferred into performance simulation engines that undertake predictions of environmental performance. For example, EnergyPluscould be used as an energy simulation engine, whereas Daysimcould perform annual daylight simulation. This project intentionally limits the scope of performance metrics to solar radiation and other non-energy rubrics due to the limitation of time. However, customized performative metrics could be set up based on local codes and project targets. For instance, in British Columbia, Canada, specific Total Energy Use Intensity (TEUI) and Thermal Energy Demand Intensity (TEDI) targets should be included as per the BC Step Code [4].

The metrics set up in this design include three categories. This first one is the site requirement, which includes building footprint, building height, and gross floor area. These prerequisites are based on local building codes and building permit requirements. The second group is solar radiation, which contains useful solar radiation (when outdoor T<10ºC), harmful solar radiation, (when outdoor T>22ºC) and the surface to area ratio. This group is set up to measure solar radiation in both winter and summer. Surface to area ratio is a measure of how compact a building is, and is expressed as the ratio for the external surface area of the building to the treated floor area. The third category is comprised of occupant comfort metrics, such as window area of view quality (targeted area >10%) and public sunlight access. This category evaluates the non-thermal conditions of these design (Figure 7).

After determining the metrics, the algorithm runs the form options with a repeating procedure. All the possible choices are computationally tested under the same gross floor area with different footprint and heights. After running a parametric simulation of 5760 cases within 48 hours through several remote computers, the results are uploaded to a parallel coordinate platform. As shown in Figure 8, each case corresponds to a line on the top and detailed information in the bottom charts. This gives us the opportunity to visually analyses the large data set generated by parametric simulations and interact with the result. Decision makers could eith use the parallel coordinate to filter out desirable choices or use the slider interface to compare different design input and desing outcomes.

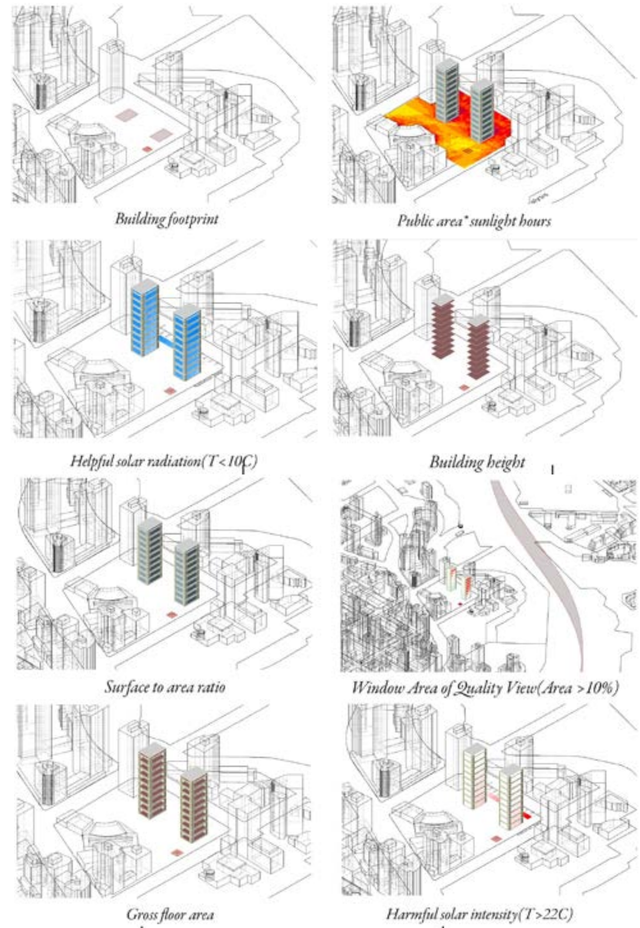


**Figure 7.** Eight **simulation metrics**

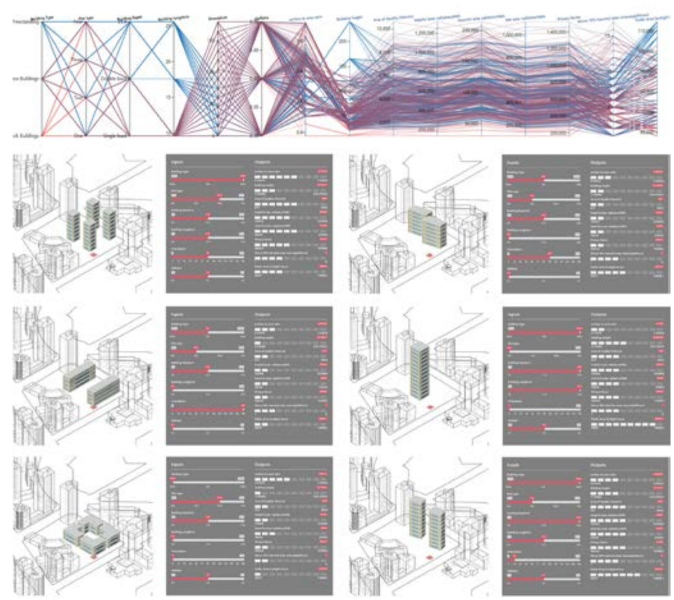

**Figure 8.** Parallel coordinate platform

### 4.4 Step 4: Design Development

In this step, further design operations are performed to develop the design in detail. The objective is to allow architects to procedurally customize the building form based on the feedback while keeping the environmental performance attributes of previous steps.

Based on the simulation results in Step 3, Two design options, which have relatively better performance in each category, are selected. The selection rubric is to improve every target instead of maximizing only one of them. As shown with detailed performance results in Figure 9, Option A is a row building with 0-degree rotation and Option B is a row building with a 30-degree rotation towards east. The view quality results for Option A and B are similar, but the solar radiation result for Option A is better than Option B, which means that Option B receives more solar radiation in cold winter and less radiation in warm summer. However, as the city requires to maintain an orthogonal urban grid between buildings, Option C is proposed to keep the shape of Option A but rotates the façade by 30 degrees to keep the solar benefits of Option B (Figure 10).

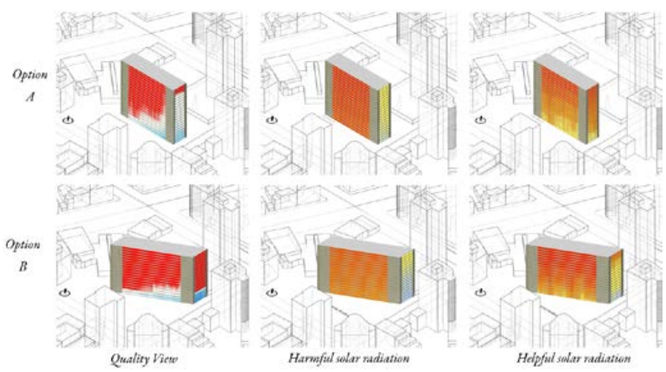


**Figure 9.** Compare Option A and B

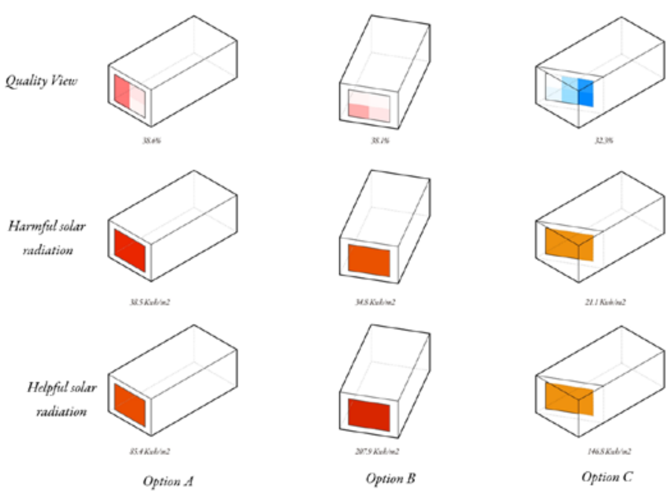


**Figure 10.** Compare Option A, B and C

In the following design process, some significant operations are made procedurally for the building form. Firstly, during the public hearing and meeting, the neighbourhood residents report a concern that the massing will offend the solar rights for a nearby square and block the neighbourhood view to the surrounding landscape. To make sure the existing solar access and visual link will not be blocked by the proposed massing, the solar envelope is generated through a backward solar boundary tracing method to trim the top part of the mass (Figure 11).

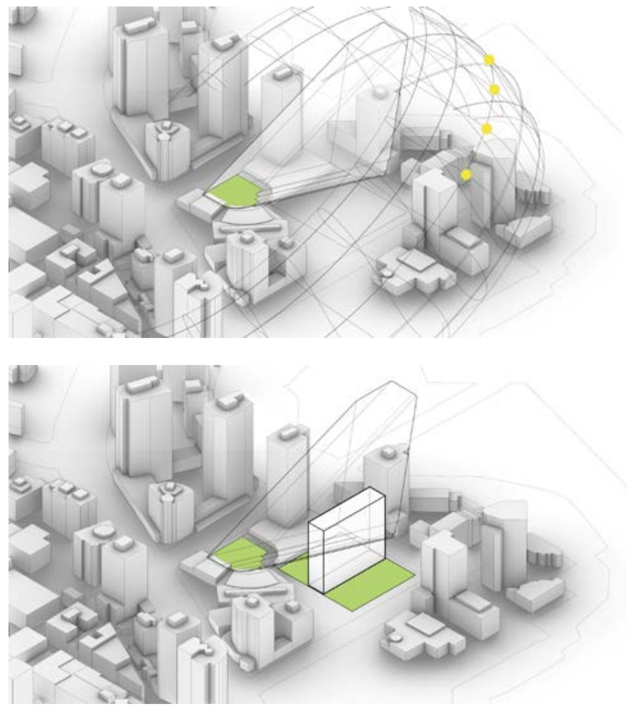

**Figure 11.** Trim the building to ensure solar rights

Secondly, the idea of bringing the vertical landscape to the midlle-part of the massing through including a sky garden is proposed, which significantly increases the visual link to views for the neighbourhood (Figure 12). Thirdly, the podium program is arranged based on the daylight requirement for different programs. For example, daycare and gym rooms are put on the south side of the podium, but storage and service space are arranged on the north (Figure. 13). Finally, the massing façade is modalized and rotated by 30 degrees based on the previous discussion of Option C.

## 5 CONCLUSION

This paper explores a procedural simulation workflow of building environmental performance, to facilitate systematic environmental analysis of architectural designs in a parametric demonstration manner. As presented, a parallel simulation and analysis method has been applied to the design process to help designers quickly explore a vast number of potential choices and perform strategic design solutions. The design investigates how simulation tools

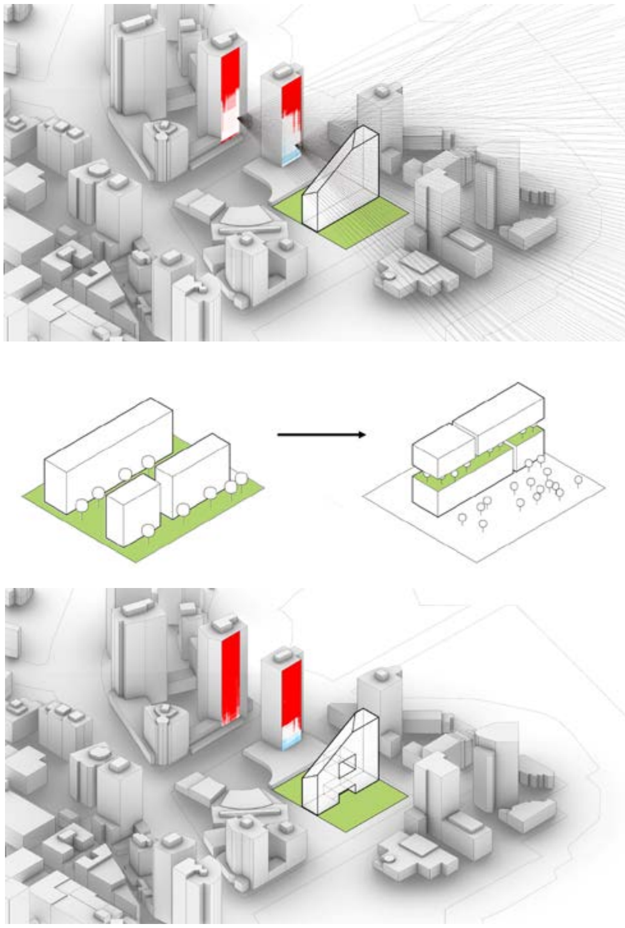

**Figure 12.** Sky garden to ensure the visual link

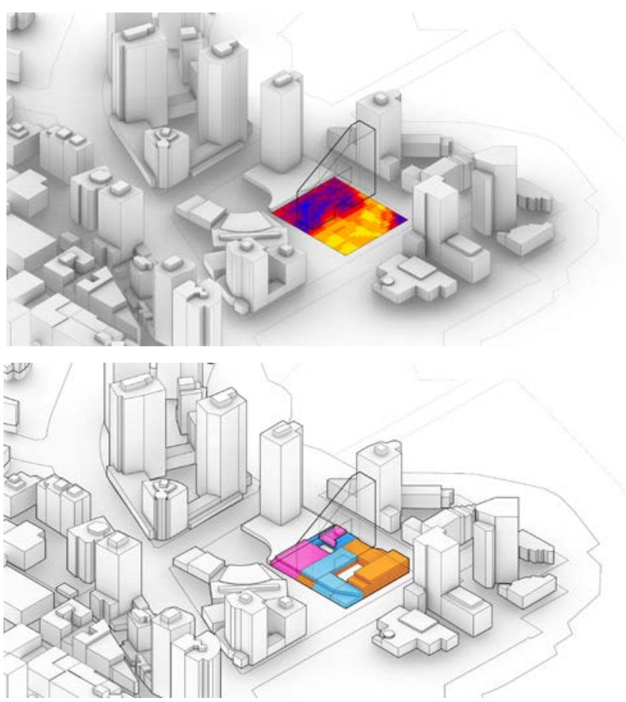

**Figure 13.** Program arrangement based on the solar requirement

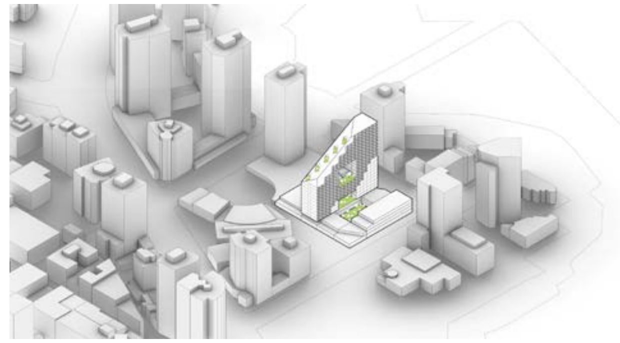

**Figure 14.** Modalize and rotate the facade

**Figure 15.** Street view rendering

**Figure 16.** Neighbourhood view rendering

could inform the designer's judgement and guide every move. Undoubtedly, if early simulation becomes part of the standard design process, architects will begin to understand the underlying interactions and will make active and elegant design actions with the confidence that they will lead to a better building (Figure 14 and 15). This research intentionally limits the scope of the relationship between building form design and non-energy performance in the massing design stage, due to the limitation of time. However, we should be aware that the result is limited to pre-defined parameters (selection criteria; typologies, degree of rotation), which might influence the result. Furthermore, research has shown that, in order to get more accurate result in later design stage, massing method could not represent a high accuracy and resolution for energy simulation[20]. In further research, providing deeper information about the building form could be a focus such as introducing interior floor layout into the parametric simulation process. Also, investigation of the building program, construction material, human activity as well as other important topics is still regarded as necessary.

## REFERENCES


[1] E. V. A. M. M. Samir S. Emdanat, “A Conceptual Framework for Integrating Morphological and Thermal Analyses in the Generation of Orthogonal Architectural Designs,” 1996.

[2] A. Forty, *Words and buildings : a vocabulary of modern architecture*. Thames & Hudson, 2000.

[3] D. B. Crawley, J. W. Hand, M. Kummert, and B. T. Griffith, “Contrasting the capabilities of building energy performance simulation programs,” *Build. Environ.*, vol. 43, no. 4, pp. 661–673, Apr. 2008.

[4] L. Governments, “BC Energy Step Code A Best Practices Guide for,” no. July, 2019.

[5] R. and A.-C. E. American Society of Heating, *90.1 user’s manual : ANSI/ASHRAE/IES standard 90.1-2010*. American Society of Heating, Refrigerating and Air-Conditioning Engineers, 2011.

[6] C. Christensen, R. Anderson, S. Horowitz, A. Courtney, and J. Spencer, “Energy Efficiency and Renewable Energy Building Technologies Program T OF E N BEopt™ Software for Building Energy Optimization: Features and Capabilities,” 2006.

[7] M. Thalfeldt, E. Pikas, J. Kurnitski, and H. Voll, “Facade design principles for nearly zero energy buildings in a cold climate,” *Energy Build.*, vol. 67, pp. 309–321, 2013.

[8] K. Lo, “A critical review of China’s rapidly developing renewable energy and energy efficiency policies,” *Renew. Sustain. Energy Rev.*, vol. 29, pp. 508–516, Jan. 2014.

[9] E. Rey, W. Frei, S. Lufkin, and D. Aiulfi, “An Innovative Architectural Strategy for the Integration of Energy Issues into the Design Process of a Commercial Center in Switzerland,” no. June, pp. 83–95, 2014.

[10] “Robert McNeel & Associates. Rhinoceros 6.0,” 2018.

[11] C. Cerezo, T. Dogan, and C. Reinhart, “Towards standarized building properties template files for early design energy model generation,” *2014 ASHRAE/IBPSA-USA Build. Simul. Conf. Atlanta, GA*, pp. 25–32, 2014.

[12] CORE studio, “Second Colibri Release,” 2017. [Online]. Available: http://core.thorntontomasetti.com/food4rhino-release-second-colibri-. [Accessed: 11-Jan-2020].

[13] S. Stevanović, “Optimization of passive solar design strategies: A review,” *Renew. Sustain. Energy Rev.*, vol. 25, pp. 177–196, Sep. 2013.

[14] P. Philippou, “Building Types and Built Forms,” *J. Archit.*, vol. 20, no. 6, pp. 1127–1138, 2015.

[15] P. Steadman, *Architectural morphology : an introduction to the geometry of building plans*. Pion, 1983.

[16] P. Steadman, *Building types and built forms*. Troubador Publishing, 2014.

[17] H. Shayesteh and P. Steadman, “Coevolution of urban form and built form: a new typomorphological model for Tehran,” *Environ. Plan. B Plan. Des.*, vol. 42, no. 6, pp. 1124–1147, 2015.

[18] P. Janssen, K. W. Chen, and C. Basol, “Design Tool Development-eCAADe 29,” 2011.

[19] K. W. Chen, P. Janssen, and A. Schlueter, “A Design Method for Multicriteria Optimization of Low Exergy Architecture Optimal Retrofit of Preserved Buildings (OReP),” 2013.

[20] T. Dogan, E. Saratsis, and C. Reinhart, “THE OPTIMIZATION POTENTIAL OF FLOOR-PLAN TYPOLOGIES IN EARLY DESIGN ENERGY MODELING Massachusetts Institute of Technology , Cambridge , MA 02139 , USA,” *Build. Simul. Conf.*, 2015.

[21] F. E. Brown, *Space is the machine*, vol. 18, no. 3. 1997.

[22] A. Abdulmawla, S. Schneider, M. Bielik, and R. Koenig, “Integrated Data Analysis for Parametric Design Environment mineR : a Grasshopper plugin based on R Environment Analysis Parametric mineR : a Grasshopper plugin based on R,” no. September, 2018.

[23] T. Fink, R. Koenig, and U. Weimar, “Integrated Parametric Urban Design in Grasshopper / Rhinoceros 3D Demonstrated on a Master Plan in Vienna,” vol. 3, no. Feng 2009, pp. 313–322, 2018.

[24] L. Wilson, J. Danforth, C. C. Davila, and D. Harvey, “How to Generate a Thousand Master Plans : A Framework for Computational Urban Design,” 2019.

[25] City of Vancouver, “Open data.” [Online]. Available: https://vancouver.ca/your-government/open-data-catalogue.aspx. [Accessed: 11-Jan-2020].

[26] S. R. M. Mackey C., “The Tool(s) Versus The Toolkit,” *Humaniz. Digit. Real.*, 2018.