GENERATIVE URBAN MODELING:
A DESIGN WORK FLOW FOR WALKABILITY-OPTIMIZED CITIES

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ABSTRACT

This paper presents an urban analysis work flow using a Rhinoceros/Grasshopper massing tool. The tool utilizes terrain elevation models as part of the design process to subdivide sites and generate urban form to be explored parametrically. It can then be linked to various performance assessment methods. As a proof of concept, the study uses a walkability calculator for three urban form alternatives, and applies genetic algorithms to optimize generated designs through allocation of land-use. Results show a great diversity that converges to near optimal solutions. A discussion is drawn about the effort and time spent to model such iterations versus it's automation using this work flow, and conclusions show the potentials, limitations and directions for future research work.

INTRODUCTION

Cities are growing exponentially across the globe. Studies report that the cumulative change in urban expansion for the period of 1970 to 2000 was 58,000 km^2, which is approximately in the order of 2% of the global urban land area in 2000 (Seto et al., 2011). The United Nations' latest figures demonstrate that by the year 2100, the world population is projected to reach 10.1 billion (United Nations, 2011). Accordingly, new neighborhoods are being built every day; pushing the definition and boundaries of cities, which significantly decreases urban densities (Angel et al., 2010) and contributes considerably to carbon emissions (Hutyra et al., 2011). This expansion tends to take place at the outskirts, where the terrain morphology is often less benign to urban developments due to irregularities in the landscape. This expansion process necessarily involves the planning of road networks that will, with certain reasoning, adapt to that terrain. Interestingly, a road network, once in place, tends to be remarkably resistant to change as exemplified by a visual comparison of part of Egypt's capital, Greater Cairo's downtown core (Zamalek, Tahrir and Garden City) in 1933 and today (Figure 1).

Expanding urban grids and massing is a process that is oftentimes unplanned in informal settlements. Local government and planning authorities routinely face this challenge with very limited, if any, budget. Hence, there is a pressing need to develop urban design workflows that support a smarter approach towards street grid subdivision and generation of urban massing that consider environmental performance. The purpose of such workflows is to enable the evaluation of multiple design iterations and optimize for certain performance criteria, such as resource efficiency and resident's health and comfort. In this day and age, design computation has become ubiquitous throughout the design world, from small scale offices to multinational firms. Given the ever growing power of personal computers and the increasing use of cloud computing, workflows based on such technologies can thus help design teams throughout the world to develop low-tech urban solutions using high-tech design tools.

Although generative tools for urban form were previously investigated computationally (Beirão et al., 2011; Luca, 2007) and in terms of certain environmental performance criteria (Oliveira Panão et al., 2008; Keirstead, et al., 2011), site design and its relationship to terrain in the third dimension has thus far been disregarded. Given the likeliness that new developments increasingly take place in non-flat terrains, this paper presents a new urban analysis workflow that develops street and massing layouts for new neighborhoods in such environments. A parametric urban massing tool was developed in the Rhinoceros/Grasshopper environment that allows urban environmental master planning to take place within a three-dimensional terrain elevation model. The tool can be linked to a number of existing environmental performance analysis tools in Rhinoceros/Grasshopper that include operational building energy use, access to solar radiation and daylighting. In this particular study, the urban massing component has been linked with a new walkability calculator. Walkability was consciously chosen as an initial sustainability performance indicator, since planning of urban density is a necessary step to
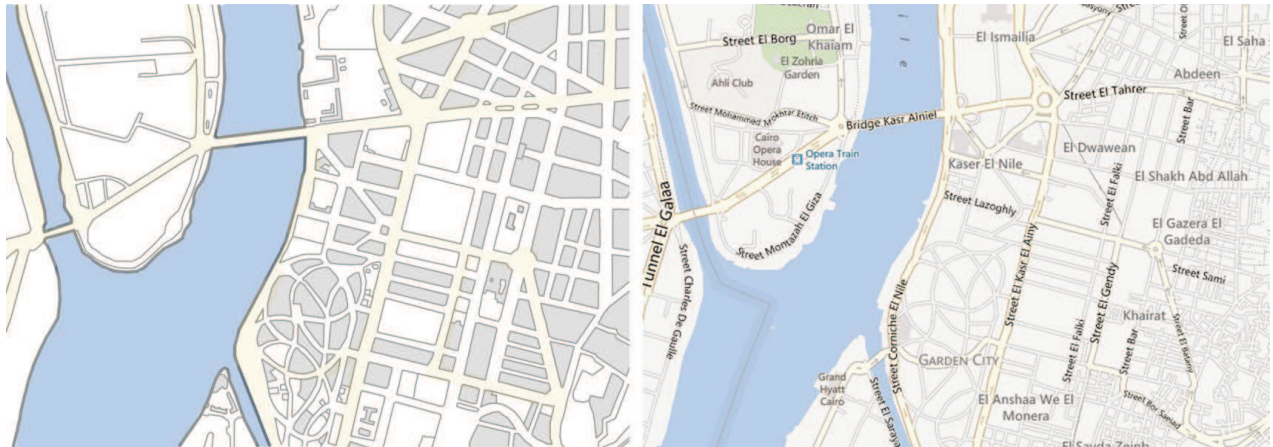
Figure 1 A comparison between minimally changed street structures in downtown Cairo, Egypt.
(Left) Author adapted map of Cairo in 1933 (Nicohosoff, A., 1933).
(Right) An online contemporary map of the same area (Bing Maps, 2011).

contain urban growth. It constitutes a key challenge to sustainable urban developments worldwide as explained above. The paper describes details of the urban massing tool, walkability calculations and optimization procedures along with an example case study.

URBAN FORM GENERATION METHODOLOGY

The proposed workflow for the conception of urban form is twofold: Firstly, an exploration of parametric massing is performed using a generative street division and urban massing tool. In a second step, a walkability calculation is applied to the resulting street grid to evaluate the potential walkability of the design.

Generative Urban Form Workflow

Generation of urban form in its primary stages typically, but not necessarily, involves the subdivision of a development plot area using a certain design rationale. From this subdivision, street networks are planned and land lots are assigned setbacks and massing height limitations. This is coupled with land-use zoning

assignment to accommodate various programmatic needs (housing, commercial, green areas, etc.). The proposed tool utilizes this form generation process computationally through the following steps:

1. Load terrain elevation map (Figure 1).

2. Iteratively subdivide terrain following design logic.

3. Manipulate the terrain for build-ablity (Terraform).

4. Set street widths offsets and building lots.

5. Zone parametrically controlled building forms.

In this paper, terrain subdivision logic is based on utilizing an orthogonal brute-force search for minimum slopes with control on minimum lot size in pixel values (Min_Lot). The code determines whether the given terrain is in the orthogonal horizontal or vertical sense, and slopes are calculated in the opposing sense by subtracting the lowest elevation height from the highest one in each pixel row. This determines build up "blocks" that interface with the design of walkable streets, which is a performance metric to be optimized later in the assessment process. Figure 1 shows
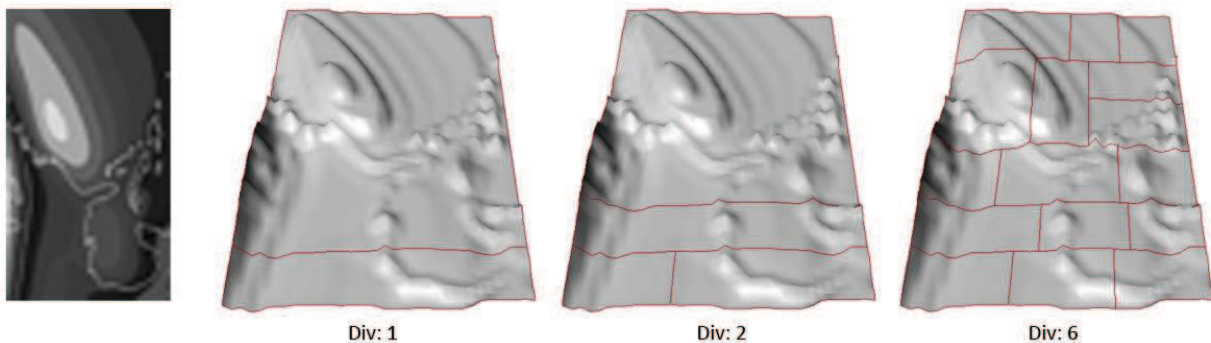

Figure 1 Arbitrary elevation map converted from pixels to a terrain model. Subdivisions (Div) are parametric

subdivision slider-controlled iterations (Div) in the Grasshopper definition, limited by conditional minimum lot sizes and the divided blocks' orientation.
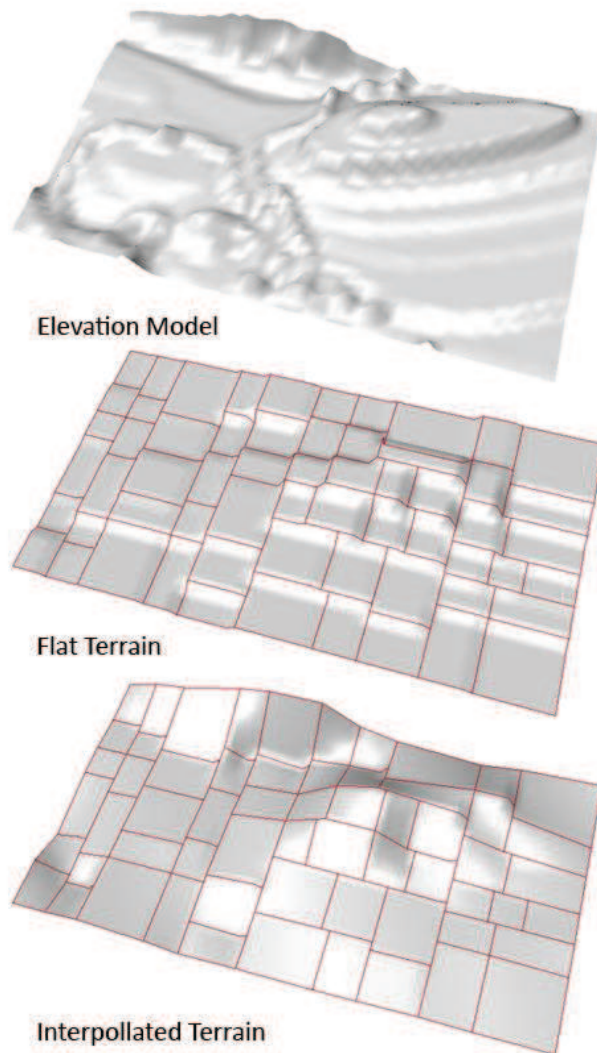

Figure 2 Terraform Processes

Building lots are then terraformed through two options: flat areas that maintain an average elevation between the four corners of each lot in the terrain, or a bilinear interpolation of the elevation of those same corners (Figure 2). Street offsets are directly proportional to lot size, and are slider-controlled as well. Building forms are parametric in depth and height, and follow three massing options that emulate typical urban typologies (Figure 3). By defining 2D geometry in Rhino, the user can link these geometrical "zones" to massing options to act as a land-use allocation tool. The tool is therefore used to explore massing parametrically in the early urban design and planning stages. An example

generated neighborhood is presented in Figure 3. The generated urban form that is adapted for the terrain condition can now be tested and optimized for various performance metrics. In this study, the evaluation of how "walkable" a neighborhood can be is undertaken, and the appraisal methodology is presented next.
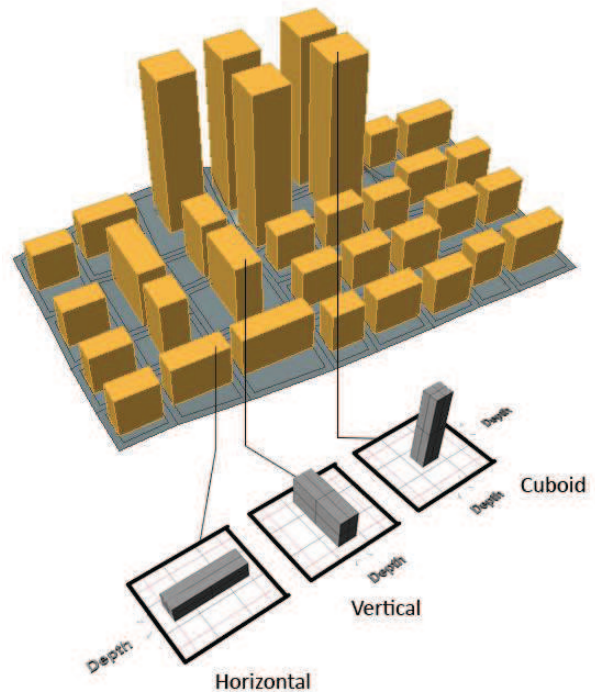

Figure 3 Example neighborhood and massing options

Walkability Assessment

The evaluation of neighborhood walkability and its relationship to human health and carbon emissions has been the subject of numerous publications (Hoehner et al., 2011; Frank et al., 2010). Any chosen scheme to assess the walkability of generated neighborhoods will be supported by the workflow's current design rationale. Since the subdivisions are based on minimum slope, the produced streets will have the lowest slopes that insure less effort in walking activities.

In this paper, the validated (Carr et al. 2011) "Street Smart" walk score algorithm was utilized to assess the walkability of generated urban form. Street grids generated from the tool are linked to a Grasshopper walk score definition. It is assumed that each block will host a multi-functional building with housing. Different amenities are randomly placed on the grid, and the definition utilizes a shortest path script that is based on the A* algorithm to compute distance to surrounding amenities. A score between 0 and 100 is then given to each housing point based on the walking distances to the following land-use categories:

amenity_weights = {

"grocery": [3],

"restaurants": [.75, .45, .25, .25, .225, .225, .225, .225, .2, .2],

"shopping": [.5, .45, .4, .35, .3],

"coffee": [1.25, .75],

"banks": [1],

"parks": [1],

"schools": [1],

"books": [1],

"entertainment": [1],

}

Assigned weights for amenities are the numbers placed after each category. Multiple numbers denote the score other amenities of the same type get after the first count. A polynomial distance decay function is used. It gives a full score for amenities that are within quarter mile of housing egress. Walk scores beyond this decrease with distance. At a distance of one mile, amenities receive about 12% of the score. After one mile, scores slowly decrease with greater distance. Other penalties for low street intersection densities and average block length are also factored into the score (Walk Score, 2011). The total sum of the weights listed above is 15. However, the walk scores are linearly expanded to range from 0 to 100. Table 1 demonstrates the meaning of the computed walk scores.

Table 1 Definition of Walk Scores

WALK SCORE	DESCRIPTION
90–100	**Walker's Paradise** Daily errands do not require a car.
70–89	**Very Walkable** Most errands can be accomplished on foot.
50–69	**Somewhat Walkable** Some amenities within walking distance.
25–49	**Car-Dependent** A few amenities within walking distance.
0–24	**Car-Dependent** Almost all errands require a car.

The walkability of an overall neighborhood and individual locations within it depend on where the above mentioned amenities are located. In order to find the potential for walkability within a neighborhood the amenities should therefore be distributed so that the majority of housing units receive maximized walk score. Given that there are an enormous number of combinations possible, an exhaustive search is not practical. The optimization problem is suited for the utilization of evolutionary algorithms. This step is described next.

Optimization

The method used for land-use allocation optimization in this research was a Genetic Algorithm (GA). It is a scheme that imitates evolutionary processes through simulating procedures of population, crossover and mutation of competing solutions. A GA is commenced with randomly chosen locations for amenities (genes), creating parent solutions of zoning (chromosomes) from a controlled search space to create an initial population. Within each chromosome, housing egress has a walk score (W) generated based on the location of genes. Those walk scores are tested for the following conditions:

- If $W<minW$

    Then $N=0$

- Else if $minW<W<aW$

    Then $N=N+((W-minW))/aW$

- Else if $W>maxW$

    Then $N=N+1$

Where (minW) is the minimum W that would be considered acceptable, (aW) is the threshold of an acceptable walkscore, and (maxW) is the maximum satisfactory walk score. In this study, minW = 50, aW = 69 and maxW = 70 according to corresponding values in table 1. N is a placeholder of performance initiated as a zero value number. The population evolves towards better chromosomes by applying the following fitness function:

- $f(x)=N/n$ $\qquad\qquad\qquad$ (1)

Where (n) is the number of housing egress points tested during the population. The function evaluates the performance of each chromosome, to be chosen as parents later to generate a new population. "Survival of the fittest" is applied through random selection that is weighted towards chromosomes of better performance. As a process of evolutionary search-and-find, two chromosomes are chosen for either operation of crossover or mutation. This populates new generations to be tested and reselected, and through many generations, the chromosomes within the final populations are near optimal.

URBAN PERFORMANCE APPLICATION

As an example application of the method, an arbitrary hilly site with an area about 1.45 km^2 with maximum elevation difference of 360m was chosen as a virtual platform for urban modeling. Three street divisions were generated as shown in figure 4. The aim was to simulate equal population densities (21600 people) in different urban form configurations. The "light" setting refers to minimizing site subdivisions, giving higher emphasis on massing height and grouping functionality (27 buildings, with 800 people / building). The "dense" configuration suggests smaller lots with a compact massing (150 buildings, with 144 people / building). The "moderate" is a contrast between both settings (82 buildings with 144 people / building and 14 buildings with 700 people / building). For the example, amenities were chosen to be of great challenge to the site area, and were as follows: 2 Grocery, 3 Restaurants, 3 Shopping, 1 Bank, 1 School, 1 Books, 2 Entertainment and 2 Coffee. The park areas were pre-selected for each scheme. Figure 5 demonstrates an example walk score analysis for arbitrarily placed amenities in the light configuration. It shows that land-use zoning affects walk scores considerably.
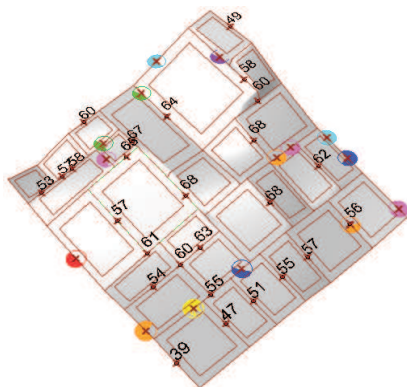

Figure 5 Example generated Walk Scores

Optimization was implemented through a tool in Grasshopper named Galapagos, an evolutionary solver that utilized a GA to optimize the walkability of the three explored urban massing options. The GA evolved zoning for the cases through 50 iterations, controlled by producing 50 populations/iteration. Figure 6 shows the land-use placement results on the generated grids of the near-optimal solutions, and the resultant walk score for pre-generated housing egress.

The results explored by the GA showed a great diversity in the imitation of each run. This eventually converged to reveal near-optimal zoning in the different configurations. Tested fitness reached minimum bounds between 0.1 and 0.4, which shows how a neighborhood could have poor walk scores if not carefully planned. However, the maximum fitness reached in the light setting was 0.842, and in the moderate 0.719 and 0.828 in the dense. This satisfied an overall neighborhood evaluation, but if examined closer, may not be a pleasant setting for all individual lots. The full tabulated optimization results are shown in Figure 7. The optimization process ran approximately for 15, 60, 240 minutes for the light, moderate and dense configurations respectively on a laptop equipped with an Intel® Core™ i7 2.8GHz CPU and 8 GB RAM.

Although optimized solutions varied in the three cases in terms of land-use placement, they all shared a common feature: the calculated centroid of the three solutions was almost central to the arbitrary terrain model. While it may be intuitive to create diversity by spreading functionality across a development site, this consistent result shows that having a neighborhood center that assembles varying zones improves walkability significantly.

Important amenities that give higher scores, such as "Grocery", spread out in all sites to give equality across the housing egress points. In all cases, some points on the outskirts do not receive the minimum acceptable
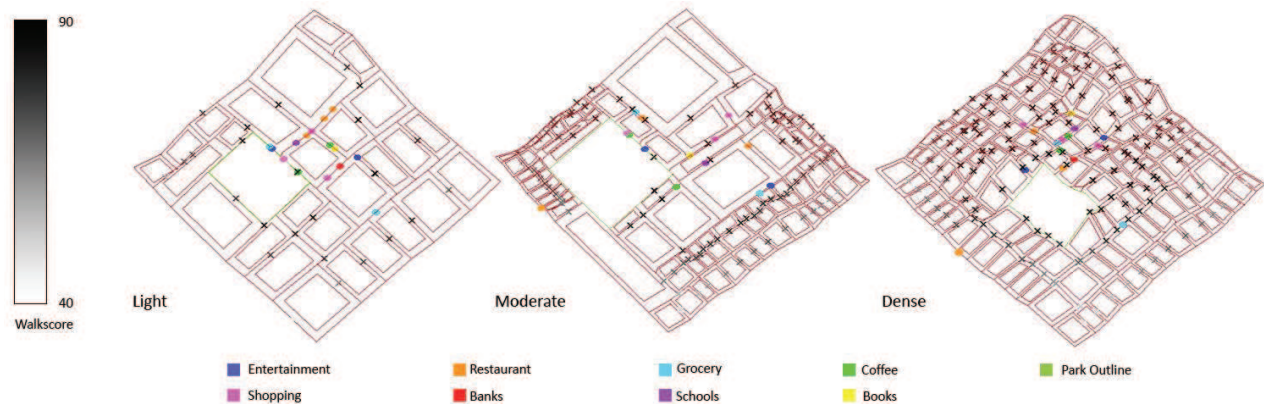

Figure 6 Optimized land-use allocations and consequent walk scores for generated housing egress

walk score. However, in such cases, if entrances to buildings change, it will achieve a better score that may be acceptable. Optimization shows performance directions, yet it should be used with flexibility.
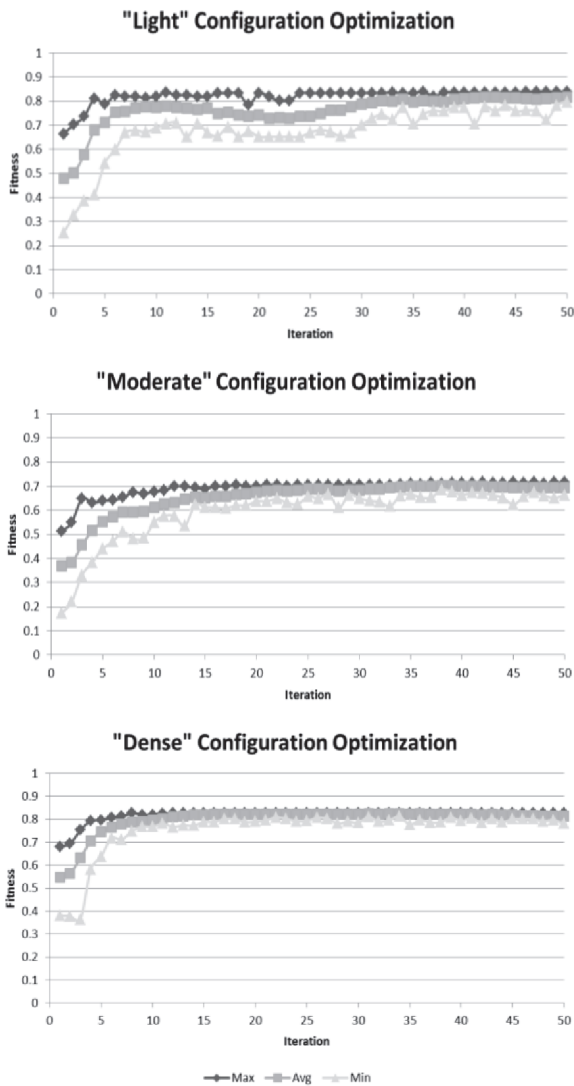

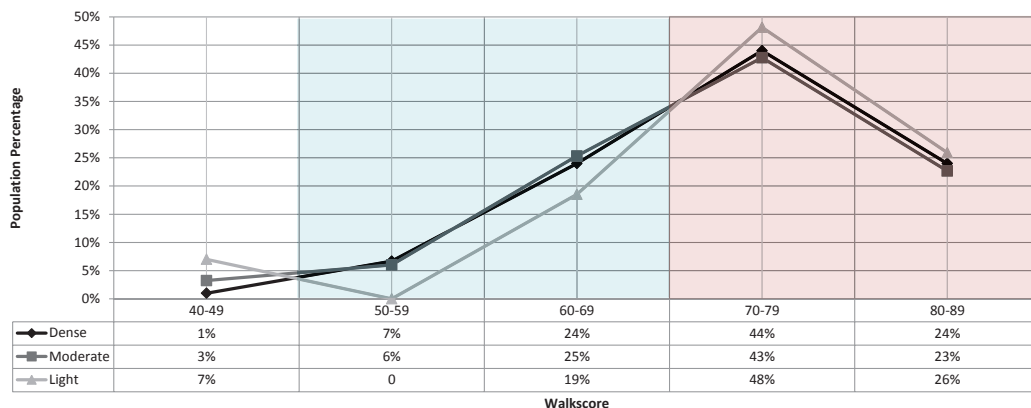Figure 7 Iterations against fitness function in walkability optimization

Figure 8 shows population percentage plotted against walk scores. It demonstrates that 65-70% of the people living in all scenarios receive a walk score higher than 70; making them living in a neighborhood that is "very walkable". The remaining population lives in situations that are mostly "car dependent". The visualization of ensuing massing options is shown in figure 9. Massing models were generated based on the optimized walk scores. The light design scenario adapted Le Corbusier's approach to urbanism: "towers in the park", with the heart as bigger towers to accommodate all amenities. The dense configuration was generated as a compact neighborhood with central "down-town" area that is proportionally larger, and the intermediate was a set as a gradient between both. The variation in performance between the three configurations is slight, but favoring the "light" scenario. Reasons for that are discussed next.

DISCUSSION

The utilization of automation procedures to generate form gives unlimited degrees of freedom to design exploration. When applied to urban design, inquiries into performance become more delicate. The investigation of urban form is taken from a morphological approach to a performative one; a question the designer must ask is: what are the urban qualities we seek through the act of design?

The employment of the current minimum slope design rationale combined with the utilization of a numeric evaluation of walkability, such as walk score, makes the quantitative optimization of the problem successful. However, disregarding terrain when calculating the walk scores is a weakness, and the development of numeric penalties for reaching amenities that are higher in elevation, and where the shortest route may be "hilly" should be taken into consideration. In addition, the scoring system is street dependent, meaning that walking distances from the housing unit to the street are ignored. This makes the "light" configuration perform better, although in reality a distance from the building to

Walkscore	40-49	50-59	60-69	70-79	80-89
Dense	1%	7%	24%	44%	24%
Moderate	3%	6%	25%	43%	23%
Light	7%	0	19%	48%	26%

Figure 8: Population percentages against Walk score

the street should be taken into account and would influence walk score dramatically.
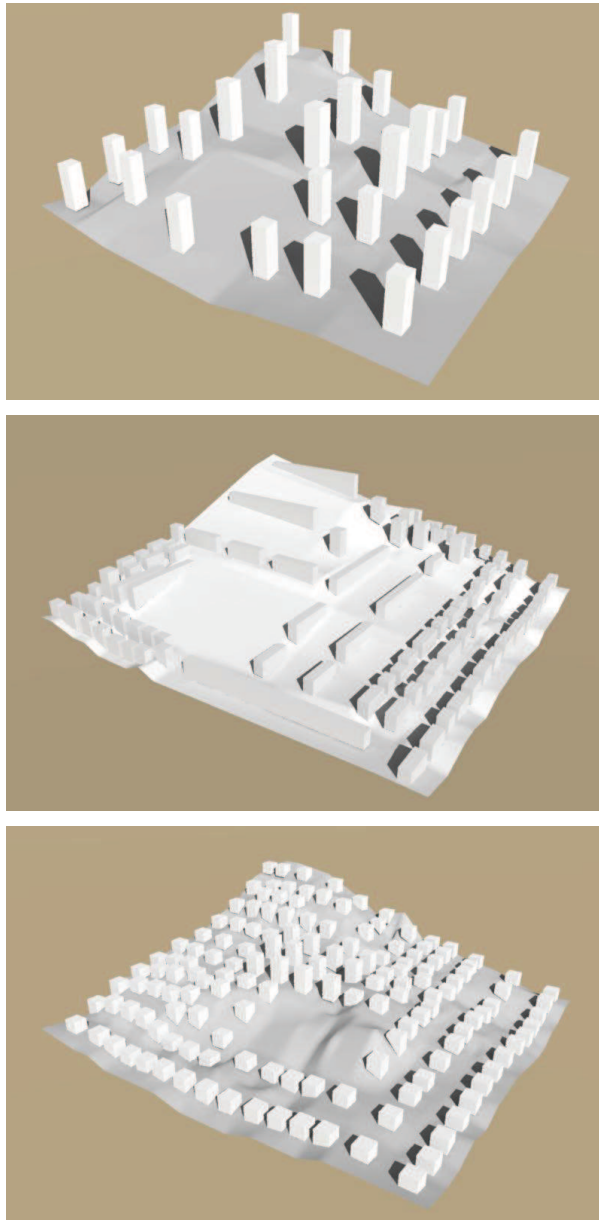

Figure 9 Light, moderate and dense massing options as generated by the work flow

The utilization of this tool diminishes effort and time spent to model hundreds of street divisions that are adapted to complicated terrains. The focus shifts to gaining insight into urban morphology and its effect on performance through iterative explorations and optimization procedures. The learning curve is steep, and the work flow outcomes are of great value to urban designers and planners. However, the tool needs further development to include effective capabilities such as control of massing orientation.

Cultural adaptation of the work flow should be considered. The current choice of amenities reflects average North American interests. However, relatively important destination points, such as location of water, should replace certain amenities when the value of such locations is considered vital.

CONCLUSION

The analysis of the previous research results showed the potential and limitations of this workflow. The tool successfully explored urban form in hilly situations using Grasshopper, which is an accessible, user friendly platform for parametric investigations. This makes investigations into massing particular to non-flat terrain scenarios achievable and flexible.

This work flow highly complements current parallel developments in urban modeling environments. The presented application utilizes performance placeholders for the ability of the tool to question urban metrics. For further development, it is suggested to investigate the utilization of optimization schemes to be urban form finders. A number of competing fitness attributes could be studied, such as neighborhood operational energy use, urban daylight availability, fluid dynamics of wind and consequent ventilation, or walkability and bikeability schemes, to name a few. Therefore, the exploration of virtual, parametric urban space through the design of weighted fitness functions controlled by designers will prove vital. The fact that different performance metrics are competing is a driver for urban form that explores unlimited possibilities only conceivable due to building performance simulation.

In an ever-growing world, and as more populations migrate to cities, the significance of this work flow, which supports the generation of sustainable urban form, is indisputable. It currently subdivides terrain models based on minimum slopes, and parametrically controls the number of divisions, street widths, massing types and its properties. This initiates the means to evade haphazard and unaware urban forms, and paves the way to discovering possibilities of performance that is optimal for the design of sustainable cities.

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