Evaluating Street Quality for Walkability from 3D Models

W Zhu¹, Y Hua¹ and T Dogan²
¹ Department of Design & Environmental Analysis, College of Human Ecology, Cornell University, Ithaca, NY 14853, USA
² Department of Architecture, College of Architecture, Art and Planning, Cornell University, Ithaca, NY 14853, USA
Email: wz334@cornell.edu

Abstract. Street quality is critical to urban sustainability. Well-designed streets encourage walking behaviour and attract public activities, thus advancing the sustainability of a city as a whole. Currently, most quantificational analyses of street quality are based on two dimensional maps, using network algorithms and economic theories to calculate accessibility and land value or to account for a series of elements such as number of trees and number of courtyards in order to audit quality scores. The analysis from three dimensional models and human-centred views is rarely utilized but could offer new possibilities to provide urban planners and designers with analytical feedback on the built environment and design process. This research explores ways to relate physical features with walking behaviour using Reid Ewing’s Urban Design Tool to measure the street quality for walkability. It applies physical metrics from measuring parameters in 3D models based on the human’s perspective and other building metrics from GIS data online to systematically audit street walkability. To validate this method, we take two separate studies. One is a case study to evaluate the street walkability of two districts in NYC from their 3D models and GIS data and to visualize the scores. The result from digital models and real environment are similar which indicates the feasibility of applying this method in urban scale. The other is a pilot study asking a group of students (N = 8) to evaluate street walkability of 3D models, telling them the scores calculated by this method, to explore how the scores influence their evaluations. This study illustrates the possibility to quantify the evaluation of street quality for walkability using Urban Design Tool in 3D models to inform urban designer’s evaluation in street scale during the design process.

1. Introduction
Street quality includes network characteristics of a district and micro features of the street environment that affect the pedestrian experience [5]. There are many studies by urban theorists addressing pedestrian experience that build a solid foundation for micro features evaluation [7] [8] [10] [11]. According to hundreds of studies on quantitative evaluation of street quality, most of them, however, focus on analyzing networks in 2D maps such as calculating the score for accessibility to amenities. One probable reason is that it is hard to quantify human’s perception of street environments. Therefore, it is necessary to conduct quantitative research on micro features of streets and renew the legacy of those urban theorists.

There are still some tools and methods on quantitatively evaluating the street quality for walkability from micro features, such as pedestrian infrastructure like sidewalks, bicycle lanes and street lighting [15] and Walk score [1] which mainly calculate accessibility. However, none of the audit tools covers all potential micro scale physical features [5]. Urban Design Tool [4] made by Reid Ewing is the
measurement tool that builds direct connection between physical features and design qualities. Using this audit tool can significantly contribute to the understanding on how physical metrics influence design qualities and walkability directly.

Ewing’s approach is to link specific physical features to urban design quality ratings audited by a panel of experts for a sample of commercial streets. By watching videos of pedestrian views of streets, experts rated 130 physical metrics. Then they sorted 20 most related metrics and their coefficients according to statistical methods. These metrics belonged to 5 different urban design qualities: Imageability, Enclosure, Human Scale, Transparency and Complexity [6]. These metrics can give people systematic evaluation on street walking experience. Furthermore, they defined the meaning of each metric and how to measure them when researchers walking in streets. They also calculated the value of each metric in linear models. This tool is called Urban Design Tool [4].

This tool tends to measure objective and explicit physical features to represent street qualities which are more subjective and implicit. In this paper, we used Grasshopper, an algorithmic 3D modeling tool widely used in architecture and urban design [16], to mimic the measuring process from a human’s perspective from 3D models as is guided by the operation methods in Urban Design Tool. Then we used this metrics combined with other data from open GIS data to calculate the walkability scores of the 3D street models.

To validate the application of this tool in 3D models, we did two studies. In the first study, we selected two districts in the most urban environment in the world, NYC, and calculated the scores from the GIS data and 3D models. Then we compared the results with the real environment to see if it is helpful to evaluate the district walkability using this method.

In the second study, we explored if this tool is helpful for designers to evaluate design quality of a specific street design model in the design process. We conducted a pilot study to let people evaluate the walkability of three different street models. Then we calculated the walkability scores of these three models, told the participants the result, and observed if their evaluations were changed.

By conducting this research, we could not only validate the feasibility of application of Reid Ewing’s tool on 3D models in urban scale and street scale, but also explore the possibility of transferring the tool to computer aided design to inform and help designers make better decisions by offering them the quantitative information calculated by this method.

2. Application of Urban Design Tool in 3D models

We apply Urban Design Tool in 3D models. In the Urban Design Tool, there are 20 physical metrics belonging to 5 different design qualities. Each metric is also given a specific method for a researcher to measure when he walking on the street. Then the researcher calculates 5 scores for the 5 different design qualities by using linear models provided as a systematic evaluation of the street walkability.

In this research, we tried to measure these metrics from 3D models together with GIS data. We summed up how to measure each metric in Table 1. Four metrics would be measured in the case study and five would be measured in the pilot study directly from 3D models. Other metrics including number of courtyards etc., proportion of historic building frontage, average building heights, and number of buildings could be extracted and calculated directly from GIS. Metrics like proportion of active uses, however, are hard to measure currently.

| Metrics                      | Urban design quality | Measuring Methods   |
|------------------------------|----------------------|---------------------|
| Measured in the case study   |                      |                     |
| Proportion sky (ahead)*      | Enclosure            | Digital models      |
| Proportion sky (across) *    | Enclosure            | Digital models      |
| Proportion street wall (same side) *| Enclosure/Transparency | Digital models |
| Proportion street wall (other side) *| Enclosure      | Digital models      |
| Proportion of historic buildings | Imageability         | GIS data            |
| Number of buildings          | Imageability/Complexity | GIS data            |
### Average building heights

**Can be measured later**

| Metric                                      | Measurement           | Data Source |
|---------------------------------------------|-----------------------|-------------|
| People                                      | Imageability          | GIS data    |
| Major landscape features                    | Imageability          | GIS data    |
| Courtyards/plazas/parks                     | Imageability          | GIS data    |
| Buildings with nonrectangular plan          | Imageability          | GIS data    |
| Noise level                                 | Imageability          | GIS data    |
| Long sight lines                            | Enclosure             | Digital models |

**Difficult to be measured**

| Metric                                      | Measurement           | Data Source |
|---------------------------------------------|-----------------------|-------------|
| Outdoor dinning                             | Imageability/Complexity | Street views with CV |
| Buildings with identifiers                  | Imageability          | Street views with CV |
| Street furniture and other items            | Human Scale           | Street views with CV |
| Proportion first floor with windows*        | Human Scale           | Street views with CV |
| Small planters                              | Human Scale           | Street views with CV |
| Proportion active uses                      | Transparency          | Street views with CV |
| Accent colors                               | Complexity            | Street views with CV |
| Dominant building colors                     | Complexity            | Street views with CV |
| Public art                                  | Complexity            | Street views with CV |

* indicates the metrics used in the second pilot study

#### 2.1. Metrics

Metrics in Reid Ewing’s research are all physical metrics of streets. Some are numeric such as number of people, number of courtyards etc. Some are binomial such as outdoor dining. Some are proportional such as proportion of historic buildings etc. Each metric is given its value of coefficient in the linear model in the function to calculate the score of design quality.

For instance, to calculate the score of Transparency which is one of the five design qualities, the linear model is: Score of Transparency = \( c_1x_1 + c_2x_2 + c_3x_3 \), \( c_1 = 1.219, c_2 = 0.533, c_3 = 0.666 \), \( x_1 = \text{proportion of first floor with windows}, x_2 = \text{proportion of active uses}, x_3 = \text{proportion of street wall} \) [5].

#### 2.2. Measurements from 3D models

For metrics like proportion street wall, number of long sight lines and proportion of sky could be measured from 3d model in a human’s perspective. To mimic this process, we create a view frame to simulate view sight of human perspective. In this way, what people could see in any position any perspective could be turned to grid of points. (Figure 1)

Every point is a mapping of the information of the building the sight line hits. So we can accordingly calculate how far people could see from this position. We get 50 points in 200 feet street and make an average of each metrics we trying to calculate to make it accurate.

#### 2.2.1. Visual Range Frame Simulation

In the research of Ewing, he used video record of 200 streets at the first status and let experts to evaluate them item by item to get the coefficient of each metric. He used Canon ZR70 MC Mini DC Camcorder (Min Focal Length. 2.8 mm. Max Focal Length. 61.6 mm) to simulate pedestrian’s visual range frame.

After having the coefficient of each metrics in the Urban Design Tool, he established a set of practical definitions and methods for pedestrians to measure and record street metrics. For instance “Frame of vision: your frame of vision is the “box” that is visible when you look ahead with your line of sight parallel to the ground. To better define the area, make a box with your fingers (thumbs and pointer fingers) and hold it up to your face. Slowly move it away until you can see all four sides—this is your box.” [6]

In 3D models, we want to mimic the measuring process described above. We used a way conducted by many painters to simulate visual range frame by establishing visual cone. “We choose the 90°
circle of view as the framework for perspective operations because this circle has a radius of $45^\circ$ visual angle around the principal point, so it contains all possible diagonal vanishing points. In addition, $90^\circ$ is the visual angle accepted since the Renaissance as the outer limit of images projected onto a plane, so we have no use for a larger visual span.” [17]

2.2.2. Measuring proportion of sky. In Urban Design Tool, there are two different metrics of sky proportion. One is called sky ahead the other is called sky across. The difference is in the measurement of sky head, the visual frame is vertical to the street line, while in the measurement of sky across, the visual frame is 45 degree to the street line. Here, we take the measurement of sky ahead for example.

In any point of the street line, we could calculate the number of view lines without intersecting with the buildings and grounds. The result of this number to the total number of view lines would be the sky ahead proportion at this position. When the visual division is more than 20 x 20, the proportion doesn’t change much. So we set the visual division to 20 x 20.

We equally select 20 points in one street line and calculate the average number of the result in each point as the final result of the sky ahead proportion of this street.

2.2.3. Measuring proportion of street wall. “The effect achieved when structures on a block continuously front the sidewalk/path providing a defined street-edge and feeling like a wall. A facade or wall over 5 feet contributes to the street wall if it is set back no more than 10 feet from the sidewalk/path edge.” [6] To mimic this process, we extract the points from sight lines hitting buildings in the simulated visual frame. The proportion of the wall would be the number of amount of the points.

2.2.4. Calculate The Index of Enclosure. Now, we have the values of number of long sight lines, proportion street wall, proportion of opposite street wall, proportion of sky ahead, and proportion of sky across. We don’t have the value of the number of long sight lines so we take it as constant currently, and then calculate the score in the linear model accordingly. Thus, the score of Enclosure is $1.78 + c$ ($c$ is a constant).

2.3. Measurements from GIS data

Metrics like streets average building height, number of buildings, proportion of historic buildings and proportion of green space would be easier to measure from GIS data directly.

The first step is to select neighbouring buildings of a specific street. According to Ewing’s definition of a street, it should be more than 200 feet long; the buildings should be “no more than 200 feet far from the central line of the street” [6].

2.3.1. Importing data from open resource online. We use Meerkat which is a Grasshopper 3D Plug-in to get the GIS data from open resource in the internet. Every building includes its field values such as
constructed years, number of stories and roof height. We select buildings which have smallest distance to the street centre line as its neighbouring buildings and then calculate field values accordingly to get results of metrics we need.

Here, the main problem is to choose the neighbouring buildings of one specific street. We find the nearest point of every building to one chose street and calculate the distance. If the distance is less than 50 feet, then it would be its neighbouring building. This method would roughly choose neighbouring buildings of every street. And then we could calculate the metrics of every street. Here, we have to iterate every building in the map to get neighbouring buildings of every street which could be optimized in the future.

2.3.2. Measuring proportion of historic buildings. “Estimate the proportion of historic buildings visible at street level (out of total block length excluding cross streets). Historic: clearly determined to be pre–World War II: high detailing, dumbbell shape, iron fire escape, and so forth; post–World War II buildings are usually geometrically and architecturally simple (though they may be impressive), have lots of glass surface area, and little detailing.” [6] Therefore, we could say: Proportion of historic buildings = number of buildings constructed before 1945 / number of buildings.

2.3.3. Other Metrics. Average building height, number of buildings, proportion of green space and other metrics are easy to be calculated directly from GIS data.

3. Case study to validate the tool used in urban evaluation
This case study focuses on calculating metrics including sky proportion, historic proportion, average building heights and building amounts in two districts in NYC. The goal is to apply Urban Design Tool to GIS data and 3D models and validate the feasibility and reliability of the calculation. We compare the calculation result with the real situation to check the reliability of this method.

3.1. Case choosing
We chose Manhattan which is highly urbanized and has a large amount of urban data as our case. We chose two different neighbourhoods Financial District and West Village in Manhattan which are in similar size but have very different urban physical metrics.

The data was downloaded from Open NY, and extracted by Meerkat of Grasshopper. We used the data to generate the mass model to measure related metrics and calculate other metrics from the GIS directly.

![3D models of two districts: Financial District and West Village](image)

*Figure 2. 3D models of two districts: Financial District and West Village*

3.2. Mappings
We demonstrate four metrics calculated: sky proportion, historic proportion, average building height and amount of buildings.
We apply different colours based on the result of each street. For sky proportion, red represents low proportion while blue does the opposite. For other three metrics, red represents small number while blue does the opposite.

In these maps, we could clearly see the distribution pattern of each metric of each street. If it follows the real situation, then this method would be feasible. Then we could evaluate street and district qualities according to the mappings.

![Mappings of visualization of different metrics in two districts](image)

* Blue colour indicates small values, red colour indicates large values

**Figure 3.** Mappings of visualization of different metrics in two districts

### 3.3. Results and discussions

Financial District is considered as the centre of finance in the world and home of skyscrapers. From the visualization of proportion of sky ahead, we could found that most area had sky below 10 per cent of the area of the view frame. In the streets around Wall Street, it is almost 0. The average building height shows Wall Street area has taller buildings. For building amount, Financial District has few buildings as buildings there are large and take up much space. Historic buildings concentrate on the south of the area which is also the start point of the development in this area.

West Village is mainly a residential area in Manhattan. Most its buildings are 5 or 6 floors high and districts are regular shaped. We could find the sky proportion of this area is much larger than Financial District. In area next to Washington Park, it is almost 60 per cent. Historic buildings are highly concentrated near Christopher Park. Building height and building amount is even in this area.

We could make a comparison between these two districts and conclude that West Village has better appearance in Imageability, Human Scale, Complexity and Transparency while Financial District has better feeling of Enclosure.

West Village was intended to be rebuilt with more high-rise buildings and getting rid of these high-density low-rise residential blocks. Between February 1961, when the designation was announced, and the following January, Jacobs and her neighbours fought the city’s plans for the West Village.

“As the streets of successful city neighbourhoods always do, must have three main qualities: First, there must be a clear demarcation between what is public space and what is private space. ……Second, there must be eyes upon the street, eyes belonging to those we might call the natural proprietors of the street. ……And third, the sidewalk must have users on it fairly continuously.” [10]
The street ballet is proved by this case study. It also proves that the feasibility of application of Urban Design Tool to 3D models.

4. Pilot study to validate the tool used in street design

There are two types of quantitative information calculated by Urban Design Tool: physical metrics like average building heights and design qualities like enclosure. The physical metrics are more direct to measure from the built environment while the design qualities are much meaningful to the evaluation result. The design qualities can be calculated from physical metrics in linear functions. In order to explore the impact of different types of quantitative information on people’s evaluation on street walkability, we did a pilot study to let people evaluate three different street models under the treatment of giving different types of information. Also, we want to know how this information will influence designers’ evaluation in design process. This study is directly relevant to validate the reliability of the application of Urban Design Tool in a specific 3D street model in design process.

4.1. Hypotheses

The first question is “Can people with different background share the common evaluation on street walkability quality with designers?” As the Urban Design Tool is created according to the evaluation by urban design experts, we would assume that people with design backgrounds may evaluate the street quality more similar to the result by Urban Design Tool comparing with people without design backgrounds. Another question is “How people will be influenced when they get different quantitative information of street quality metrics of Urban Design Tool?” Urban Design Tool proposes that physical metrics will directly influence the design scores and people’s behaviour. We assume the quantitative metrics will influence people’s evaluation. In summary, the hypotheses in this research are:

1. Designers would evaluate the street quality more similar to the result of Urban Design Tool.
2. People knowing quantitative information of street quality would evaluate the street quality more similar to the result from Urban Design Tool.

4.2. Methods and experiment

The independent variables are people’s backgrounds (design or not design); street model images (with perceptual level or physical level of quantitative information or not). People’s background is an attribute independent variable; street model image is an active independent variable. The dependent variables are peoples’ evaluations on images of different streets. We conduct people’s backgrounds as between group variable and street model images as within group variable.

Eight graduate students (4 with design background, 4 without design background; mean age = 24 years old) are selected from Cornell campus. They are recruited by the experiment poster. People with design background are from Department of Design and Environmental Analysis and Architecture. People without design background are from School of Engineering. We conduct the experiment in engineering school library. Subjects have independent desks and quiet environment without much distraction. If they have anything unclear, they can ask us for explanation.

There are three different groups of images belongs to three different street models. The three models have many common elements but different levels for some element. For instance, the low quality street and high quality street have the same footprint but different height for each street building. In each group of images, the four images are in pedestrian’s perspective from the start to the end of the street. The metrics of each physical characteristic is measured in the model and calculated by the linear model to get the final score. (Figure 4)

Subjects will rate the quality of three images in each group as high, medium and low as their evaluation on the street walkability. This result will be compared with the evaluation result calculated by the method developed above.
4.3. Results and discussions

The metrics and score calculated by the method for three streets A, B and C are shown in Table 2. We compare this result with evaluations by people in the experiment if a person has one answer the same as the tool’s result then he gets 1. As there is not possible to have two right answers, the possible scores on people’s evaluation can be 0, 1, or 3.

|                      | A     | B     | C     |
|----------------------|-------|-------|-------|
| Enclosure            |       |       |       |
| proportion street wall| .90   | .95   | .80   |
| proportion of sky    | .21   | .12   | .26   |
| Score                | .76   | 1.27  | .75   |
| Human Scale          |       |       |       |
| proportion windows   | .70   | .90   | .45   |
| Score                | .71   | .91   | .46   |
| Transparency         |       |       |       |
| proportion windows   | .70   | .90   | .45   |
| proportion street wall| .90   | .95   | .80   |
| Score                | 1.20  | 1.20  | .96   |

We get the result that people’s average evaluation score 0.71. The standard deviation is 0.27. We have result for each cell as below. (Table 3)

|                      | No extra information | Physical metrics | Design quality score |
|----------------------|----------------------|------------------|----------------------|
| Design               | M = .75, SD = .43    | M = .75, SD = .43| M = 1.25, SD = 1.09  |
| Non-design           | M = .50, SD = .50    | M = .50, SD = .50| M = .50, SD = .50   |

According to the result, there is a main effect of types of street quantitative information on street walkability evaluation. People’s evaluation gets higher scores (0.87) when they have seen the quantitative information on design quality comparing with other two situations (0.62). There is a main effect of people’s design background on street walkability evaluation. People with design background get higher scores on walkability evaluation (0.92) than people without design background (0.5).

The data support the hypotheses we came up with before. It shows that quantitative information influences people’s evaluation if they have design background. But it does not influence people’s evaluation if they don’t have the design background. Also, people’s evaluations are influenced by design quality score not physical metrics. These findings extend the application of Urban Design Tool.
from built environment evaluation to design model evaluation. The result of the research will provide suggestions for how to apply the evaluation method to design phrase to inform designers at the very beginning of design process. For example, it is better to provide designers with perceptual information which is calculated from the physical information rather than only provide them with physical information. It will be a step to help create Computer Aided Design tool in the future.

There are some limitations for this experiment such as the sample size is very small so the research has a threat of statistical validity. Also, showing the screenshots might not be very easy for people to get the full understanding of the space in the design process. In the experiment, many people got confused when they first saw the images of three streets as they thought they are almost the same. A way to solve this problem might be to let people explore the digital design model in different perspectives. There are also some threats to internal validity, external validity and construct validity in this research that may weaken the conclusion.

In sum, although our results do not enable firm conclusions about quantitative information having a main effect on street evaluation, they do encourage continued investigation of the possibility. The study provides a point of departure for further research on how Urban Design Tool would be applied to influence designer’s evaluation on different design phases.

5. Conclusions and future studies
The research starts from application of Urban Design Tool to 3D models by developing a package in grasshopper (Figure 5) to mimic the system of measuring operation and calculation process suggested in the tool. Our grasshopper-based tool can measure physical metrics from a human’s perspective in 3D models and it simulates researchers’ measuring process in the real environment.

In order to validate the feasibility and reliability of this method, we conducted two studies. The first study is on built environment evaluation in urban scale. By measuring and visualizing metrics from GIS data and 3D models, we can have an evaluation on streets’ walkability of the two districts. The result accords with the real environment. This study shows the application of Urban Design Tool in 3D models can be useful in streets walkability evaluation in urban scale. It makes it possible to analyze and evaluate large amount of streets by using computational methods. In Reid Ewing’s research, he proposed pedestrians measure and record physical metrics by walking along streets which would be impossible for large scale district. In this research however, we could calculate any amount of streets we want if we have their GIS data. And the result would be more accurate.

The second study is on design models evaluation in street scale. In the experiment, people provided their self-report evaluation of three different street models under treatment of different types of information calculated by this method. The result supports the hypothesis that people’s evaluation would be influenced by scores of design qualities. This study shows the application of Urban Design Tool in 3D models can support designer’s evaluation in design process. It helps urban designers to design streets with better walkability according to Reid Ewing’s standard.

One limitation of this research would be the limitation of the model built by Reid Ewing. “The scope of this study was limited to commercial streets, from small town main streets to big city downtown streets.” [6] Also, it is studied in the laboratory environment and may have much difference in real environment. Another limitation of this research is it currently uses grasshopper as a tool to
extract and process data. However, grasshopper is not good to process a large amount of data in a very short time. So it would be better to use another tool in further study. We expect further studies on more general platforms to improve its ability.

References

[1] Carr LJ et al 2010 Walk score™ as a global estimate of neighborhood walkability American Journal of Preventive Medicine 39(5) pp 460–463
[2] Clark MI et al 2010 Key stakeholder perspectives on the development of walkable neighbourhoods Health & Place 16(1) pp 43–50
[3] Duncan D and Aldstadt J 2013 Validation of Walk Scores and Transit Scores for estimating neighborhood walkability and transit availability: a small-area analysis, GeoJournal (78) pp 407-416
[4] Ewing R and Handy S 2009 Measuring the unmeasurable: urban design qualities related to walkability Journal of Urban Design 14(1) pp 65-84
[5] Ewing R et al 2016 Streetscape features related to pedestrian activities Journal of Planning Education and Research 36(1) pp 5-15
[6] Ewing R. and Clemente O 2013 Measuring Urban Design Utah: Island Press
[7] Gehl J 1987 Life between buildings: using public space New York: Van Nostrand Reinhold
[8] Gehl J 2010 Cities for people Washington DC: Island Press
[9] Guo Z 2009 Does the pedestrian environment affect the utility of walking? A case of path choice in downtown Boston Transportation Research Part D 14 pp 343-52
[10] Jacobs J 1961 The Death and Life of Great American Cities New York: Random House
[11] Lynch K 1960 The Image of the City Cambridge MA: Joint Center for Urban Studies
[12] Lynch K 1984 Good city form Cambridge MA: MIT Press
[13] Sevtusk A et al 2016 Pedestrian accessibility in grid layouts: the role of block, plot and street dimensions Urban Morphology 20(2) pp 89-106
[14] Stamps AE 2001 Evaluating enclosure in urban sites Landscape and Urban Planning 57 pp 25-42
[15] Saelens BE et al 2003 Environmental correlates of walking and cycling: findings from the transportation, urban design, and planning literatures Annals of Behavioral Medicine 25(2) pp 80–91
[16] McNeel R et al 2010 Grasshopper generative modeling for Rhino. Computer Software 2011b Http://Www. Grasshopper3d. com
[17] MacEvoy B 2005 Modern Color Models Watercolors (Http://www.Handprint. Com/HP/WCL/Color7. Html) [URL Verified 18/12/2007]