A Parametric Urban Design Model to Optimize Life Cycle Carbon Footprint of Green Open Spaces

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Abstract

More people live in cities nowadays. In fact, urbanization can pose ecological burdens to our planet. Human activities in urban areas constitute 71 to 76% of global carbon emissions, which is one of the causes of climate change. Research results also suggested that land use patterns and urban morphology can affect carbon emission in cities. Consequently, there is an urgent call to designing cities which can reduce carbon emission. To this end, studies have shown that trees in urban green spaces could help offset carbon emission in cities by carbon sequestration. Although there have been studies on the carbon balance of urban green spaces, few attempts have been made to investigate the optimization of green space design to reduce carbon emissions from cities. In parallel, there is a recent trend to utilizing parametric design models for urban design tasks. Efforts have been put on examining the use of parametric urban design models in optimizing urban design options. Moreover, previous studies suggested it is possible to adopt performance values as parameter input to generate design options. Accordingly, the primary aim of the current study is to develop a parametric urban design model which takes life cycle CO_2 sequestration of trees as the parameter input to generate urban green space design options in the early design stage. A case study will be conducted to illustrate how the model can be developed. The Rhino3D plugin Grasshopper will be used to develop the parametric design model. Space Syntax measure intelligibility will also be included in the model. Life cycle CO_2 sequestration of the open space can be optimized against the intelligibility of the space by using the model.

Keyword: *carbon sequestration, parametric design, green open space*

Introduction

According to United Nations, 55% of the world population lives in urban areas (United Nations, 2018). It has also been projected that the percentage will become 68% by 2050 (ibid). However, urbanization can pose challenge to sustainable development. Specifically, it was estimated that about 71 to 76% of global carbon emission is constituted by activities in urban areas (United Nations, 2017). Previous studies also suggested that urban form and morphology can affect the carbon emission from cities (Makido et al., 2012; Wang et al., 2019). Consequently, it should be vital to design cities which can help to reduce carbon emission.

Trees are essential elements in the sense that they can form the spatial structure of open spaces (Mahmoud & Omar, 2015). They can also render multiple benefits, including social, economic and environmental benefits. In particular, tremendous efforts have been put into understanding the environmental benefits of urban trees. It has been confirmed that the plantation of trees can provide shading to open spaces and hence help improve thermal comfort in the spaces (Abdallah et al., 2020). There has also been a body of study concerning the capability of mitigating urban heat island effects by trees (Aboelata & Sodoudi, 2020; Zhou et al., 2017). Apart from these benefits, researchers have even found that trees could store a large amount of carbon in urban areas (Hutyra et al., 2011; Strohbach & Haase, 2012) when considering the life cycle of the trees in open spaces.

Meanwhile, there has also been a current trend to utilize parametric design model for urban design tasks. By defining values of urban design parameters, various urban design options can be generated by using a parametric urban design model. A number of studies have been conducted to examine the parameters (Beirão & Duarte, 2009) and algorithms (Schneider et al., 2011). Previous studies also suggested the possibility of incorporating the notion of environmental performances of urban spaces in parametric design models (Saleh & Al-Hagla, 2012; Taleb & Musleh, 2015). There have been studies on the use of parametric models for green open space design (Leung et al., 2017).

Although there have been efforts to include various environment performances of urban spaces in parametric urban design models, no attempt has been made to include life cycle CO_2 sequestration of trees in a parametric model for green open space design. Accordingly, the primary objective of the current study is to develop a parametric design model which incorporates the life cycle CO_2 sequestration of trees for green open space design in early design stage. As it is obvious that more trees can render a higher value of CO_2 sequestration, the spatial structure formed by the trees, quantified by Space Syntax measures, would also be included in the model. As a result, a parametric urban design model which optimizes CO_2 sequestration of trees against the spatial structure of open spaces would be developed.

Methodology

Virtual Site

A site had to be identified before developing the parametric design model. A virtual site was defined in the current study. It was assumed that the virtual site is an open space with a rectangular shape. Both the length and width of it ranged from 50 m to 200 m. Trees would be placed within the site and the distribution of trees would be random. Furthermore, it was assumed that the site would not be demolished in 50 years.

Parametric Design Model Development

The first step of developing the parametric design model was to reveal the relationship between the parameters and the CO_2 sequestration of the site. The parameters and the ranges of values of them had to be defined. There were two types of parameters in the current study, namely, alterable and fixed parameters. The alterable parameters considered in the current study were the width and length of the site, as well as the density of trees planted in the site. The values of these parameters could be altered by the model according to the CO_2 sequestration input. Meanwhile, there were also parameters that were fixed in the current study. They were the lifespan of the open space (50 years) and the average carbon sequestration per tree after 50 years. Table 1 shows the parameters and ranges of values of them.

Table 1. Parameters and ranges of values of the parameters

Parameters	Ranges of Values
Alterable Parameters	
Length of Site (*L*)	50 to 200 m
Width of Site (*W*)	50 to 200 m
Tree Density (*D*)	0.025 to 0.1 tree/m^2
Fixed Parameters	
Lifespan of the Open Space	50 years
Average Carbon Sequestration per tree after 50 years	0.7380 $MgCO_2$ (to be derived in the next section)

The net life cycle CO_2 sequestration per tree would be needed in order to develop the relationship between the CO_2 sequestration of the site and the parameters. Normally, it is needed to consider the types and characteristics of trees to be planted and the construction and maintenance of trees in the open space in order to estimate the carbon sequestration. As the main objective of the current study was to examine the development of the parametric design model, it was decided that carbon sequestration estimation would not be performed from scratch. Instead, references from previous studies would be taken in order to derive the carbon sequestration per tree. In the study by Strohbach et al. (2012), the carbon sequestration of trees was calculated by considering the construction and maintenance, as well as the growth and mortality rates of the trees. The average carbon sequestration per tree would be derived from the results from this previous study. This value would be used to estimate the total carbon sequestration of the site after 50 years.

As the trade-off between carbon sequestration and the spatial structure due to the placement of trees would be considered in the current study, it was also essential to quantify the spatial arrangement of the site after trees were placed. The notion of intelligibility of Space Syntax (Hillier et al., 1976) was adopted. Intelligibility is the correlation between connectivity and visual integration. In Space Syntax, the connectivity of a node is defined as the number of nodes which are directly connected to this node. Meanwhile, visual integration "measures the visual distance from all spaces to all others" (Hillier, 1996). A higher value of intelligibility usually means that it is easier for an individual to navigate through the space. Intelligibility has also been adopted in a previous study concerning the spatial structure of open space resulting from tree placement (Mahmoud & Omar, 2015).

In order to find the relationship between intelligibility and the parameters, design scenarios embracing various combinations of site dimensions and tree densities had to be generated. The scenarios were generated by altering the parameter values step by step. The site width and length increased from 50 m to 200 m, in a step of 10 m. On the other hand, the tree density changed from 0.025 to 0.1 tree/m^2, in a step of

0.005 tree/m^2. Grasshopper, the parametric design plugin of Rhino3D, was used to generate these design scenarios parametrically. After the design scenarios were generated, they were imported to the software DepthMapX for intelligibility value calculation. The results from DepthMapX would be used to form the mathematical relationship between intelligibility and different design parameters.

With the average carbon sequestration per tree and the above described mathematical relationship, the parametric design model with total carbon sequestration as parameter input will be developed. In the current study, Grasshopper of Rhino3D would be used to develop the parametric design model. Grasshopper was chosen due to the convenience of visual scripting and its capability to incorporate programming codes C#, Python and Visual Basic.

Results

Carbon Sequestration Calculation

From the study by Strohbach et al. (2012), it was found that the net carbon sequestration was 162 $MgCO_2$/ha after 50 years. The size of the study site was 2.1 ha and the number of trees in the site was 461. As a result, the carbon sequestration per tree was approximated to be 0.7380 $MgCO_2$ after 50 years. The total carbon sequestration *CarbonSeq* (in $MgCO_2$) of the site after 50 years was given by:

$$CarbonSeq = L \times W \times D \times 0.7380 \qquad (1)$$

Relationship between Intelligibility and Parameters

By using DepthMapX, intelligibility values of various design scenarios were computed. A series of intelligibility and the corresponding parameter values were obtained. By using the machine learning Python package scikit-learn, the relationship between intelligibility and the parameters was formed. The adjusted R^2 of the model was found to be 0.82, which means that the model should fit the data reasonably well. Consequently, the intelligibility could be expressed as:

$$\text{Intelligibility} = 2.0907 - 0.3934ln(L \times W) + 42.2110D + 0.0261\big(ln(L \times W)\big)^2 - 3.4950 \times ln(L \times W)D - 83.1695D^2 \qquad (2)$$

Developing the Parametric Design Model

There were three main modules in the parametric design model. The first module was the input and parameter calculation module. The second one was the design visualization module, and the third module was the data output module. Figure 1 shows the basic concepts of the parametric model.

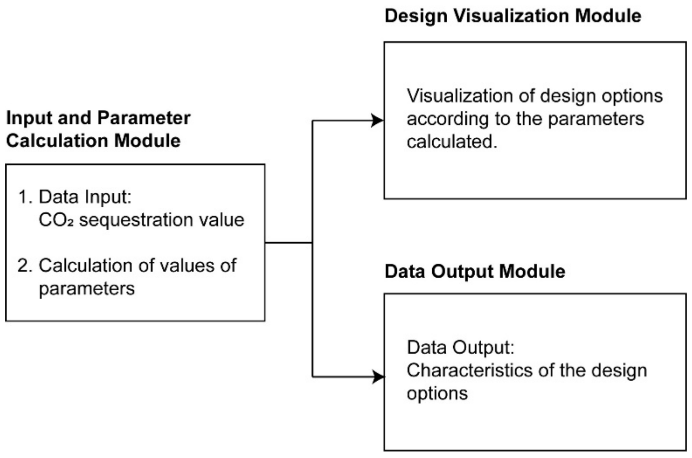

Figure 1. *Basic concept of the parametric design model*

Input and Parameter Calculation Module

The main objective of the study was to create a parametric design with the CO_2 sequestration value as input. It was needed to find out the possible combinations of parameter values after a desired CO_2 sequestration value was given. By adopting equation (1), it was possible to find the combinations of values by brute-force search algorithm. Brute-force, or exhaustive search, is an algorithm which systematically searches through all possible solutions of a problem and checks if some of the solutions will actually solve the problem. In the parametric design model developed in the current study, a brute-force solver was created with Python in Grasshopper to search for the combinations of parameter values which would satisfy the CO_2 sequestration value input. If there was no combination of parameters which could satisfy the input value, the solver would search for combinations rendering the closest CO_2 sequestration values to the input value. As there could be more than one combination of parameters which could render the input CO_2 sequestration value, there was also an input for the user of the parametric design model to choose which solution to inspect or explore. The combination of parameters chosen would be used to calculate the intelligibility of the site after tree placement. Figure 2 shows the flow inside the Input and Parameter Calculation Module.

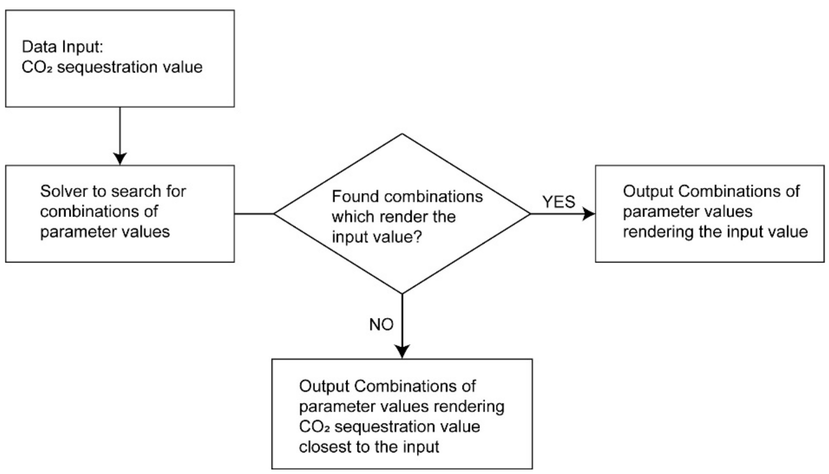

Figure 2. *Flow inside the Input and Parameter Calculation Module*

Design Visualization and Data Output Modules

The parameter values computed from the first modules would be supplied to the design visualization and data output modules. The design visualization module made use of the parameter values to create the visualization of the design. The characteristics of the design, including the dimensions of the site, tree density, total CO_2 sequestration after 50 years, tree cover percentage, and site intelligibility, would be collected in the data output module. These characteristics could be seen in the visual scripting environment in Grasshopper. They will also be printed along with the design visualized. Figures 3 and 4 show the visual script of the parametric design model in Grasshopper and two examples of the visualization designs.

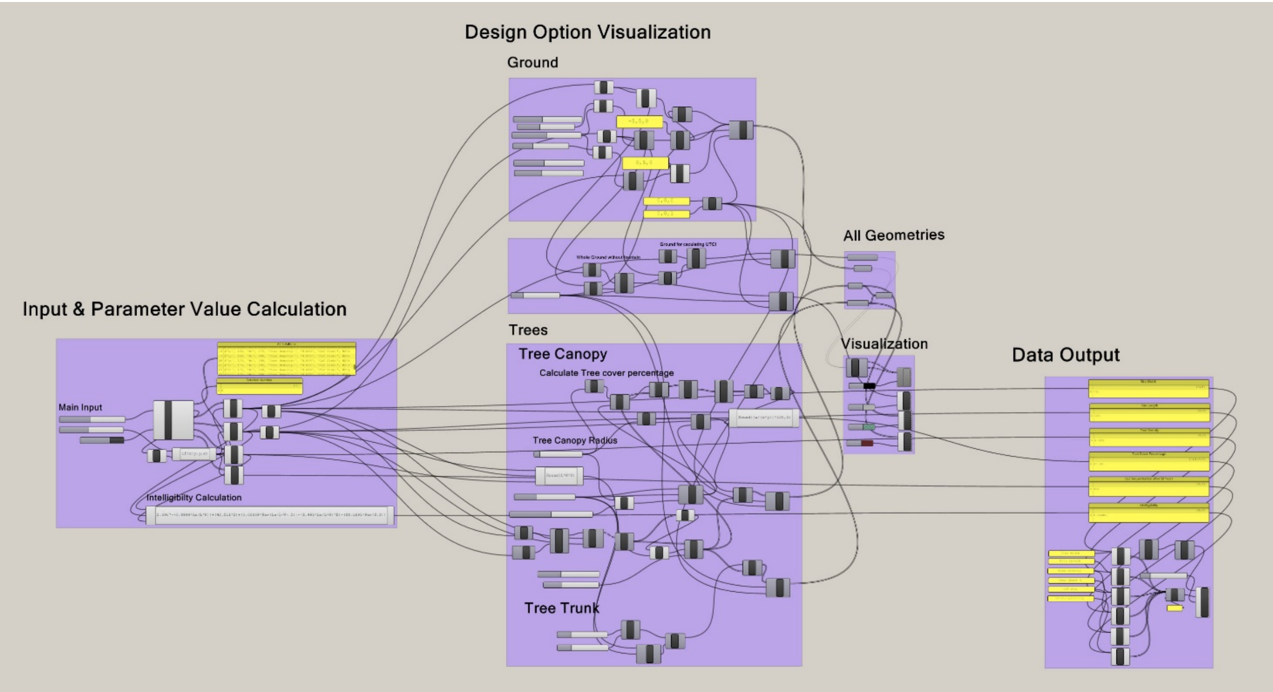

Figure 3. *Visual script of the parametric model in Grasshopper*

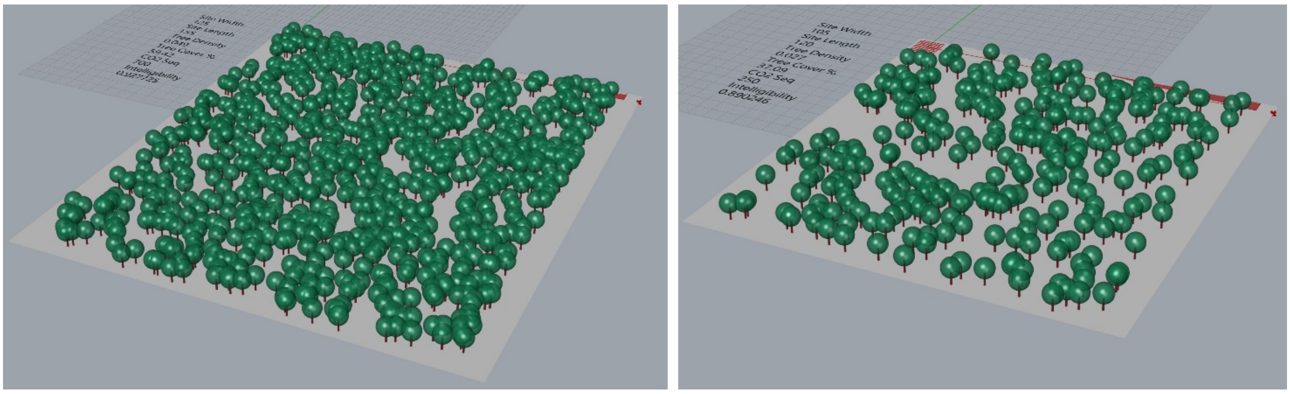

Figure 4. *Examples of design option visualization*

Conclusion and Discussions

In the current study, a parametric urban design model which embraced life cycle CO_2 sequestration of trees in open space as parameter input for the early design stage was developed. With the CO_2 sequestration value input, possible design options with respect to site width, length and tree density would be generated. The intelligibility values of these options would also be found so that designer could play with different combinations of CO_2 sequestration and intelligibility for further design development.

When developing the parametric design model, average CO_2 sequestration per tree was derived from a previous study. It was because the main objective of the current study was to demonstrate the development of the model instead of estimating CO_2 sequestration of a particular open space. When applying the model to a particular site, CO_2 sequestration per tree has to be revealed by considering the types of trees to be planted and the construction and maintenance of the space. The net CO_2 sequestration per tree can be found from the difference between the carbon storage of the trees and the carbon emission due to construction and maintenance. The model will become usable for that particular open space design task once the estimated value of CO_2 sequestration, as well as the shape and size of the site, are supplied to the model. In fact, the model developed in the current study can be considered a general framework for developing a parametric design model which embracing CO_2 sequestration as input for a particular site.

A brute-force solver was incorporated in the input and parameter calculation module of the parametric design model of the current study. How the solver is scripted will affect the speed of generating the design options. As the combinations of parameters will be found by searching through all the possible solutions, the increment step of each parameter will highly affect the number of possible solutions and hence the speed of getting the combinations of parameter values which can render the input value. If the model is to be used in the context of a public design forum, the increment step of each parameter should be determined such that the combinations can be found within a few seconds. It will not be practical to wait for hours to get a design option in a public design forum. However, if the model is meant for the designer to explore various design possibilities, smaller increment steps, which can probably generate more combinations of parameters, will be a more sensible option. The decision on how the brute-force solver should be scripted will mainly depend on how the model will be used.

The intelligibility was one of the outputs of the model. As discussed, intelligibility should be considered a measure to understand the spatial structure of the design option. Intelligibility, as well as CO_2 sequestration, could be considered performances of the design option. As a pilot study for including the carbon footprint of open spaces in a parametric design model, only these two performances were included. It should be possible to include other performances of the open space in the model. In fact, this should be considered the next step of the study. In future studies, various design performances should be incorporated. Besides performances, more parameters can also be included in future studies. By considering more performances and parameters, it will be possible to create a parametric design model which embraces performance as input more comprehensive.

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