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ENVIRONMENTAL PERFORMANCE AS A DRIVE TO GENERATE DESIGN OPTIONS… IN EARLY URBAN DESIGN STAGE: A PARAMETRIC MODEL DEVELOPMENT FRAMEWORK[1]

Previous studies have demonstrated that it is possible to utilize parametric model for urban design tasks. There were also attempts to include environmental performances in parametric urban design models. However, environmental performances were only treated as outputs of parametric models in these studies. The feasibility of treating the performances as inputs has not been revealed yet. As a result, the primary objective of this study is to develop a model development framework which can aid the development of parametric urban design models embracing environmental performances as inputs. The development of a parametric model for green open space design was utilized as a case study to demonstrate how this framework can be applied.

Keywords: parametric urban design, environmental performance, parametric design model

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ДЖЕРРИ ЛЕУНГ

ЭКОЛОГИЧЕСКАЯ ЭФФЕКТИВНОСТЬ КАК ОТПРАВНАЯ ТОЧКА ДЛЯ ПОИСКА ПРОЕКТНЫХ РЕШЕНИЙ НА РАННЕЙ СТАДИИ ГРАДОСТРОИТЕЛЬНОГО ПРОЕКТИРОВАНИЯ. ПОДХОД К ПОСТРОЕНИЮ ПАРАМЕТРИЧЕСКОЙ МОДЕЛИ

Предыдущие исследования показали, что для решения задач в области градостроительного проектирования возможно применение параметрического моделирования. Были также предприняты попытки включить в градостроительные параметрические модели экологическую эффективность. Однако в этих исследованиях экологическая эффективность присутствовала только в качестве результата параметрического моделирования. Возможность использования экологической эффективности в качестве вводных данных до сих пор не рассматривалась. Таким образом, главная цель настоящего исследования заключается в том, чтобы найти подход к построению модели, который позволил бы использовать экологическую эффективность в качестве вводных данных в градостроительном параметрическом моделировании. Для демонстрации возможностей практического применения такого подхода предлагается построение параметрической модели озелененного общественного пространства.

Ключевые слова: параметрическое моделирование в градостроительстве, экологическая эффективность, параметрическая модель.

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INTRODUCTION

There is a recent trend in exploring the possibility and feasibility of using parametric modelling techniques in the fields of architecture[2] and urban design. In particular, parametric urban design has been experimented by both practitioners and researchers. There are researchers who focused on exploring parameters[3] and algorithm[4] for urban design parametric models. On the other hand, it has also been demonstrated that it is feasible to utilize parametric models to generate urban design solutions for various urban scales. Parametric modelling was applied to generate the master plan for an industrial site of size 235 hectare in Moscow[5]. In smaller scales, parametric tools were tested to support urban design in pedestrian scale[6].

In parallel, tremendous efforts have been put to explore how to generate designs which are ecological friendly and sustainable[7]. In the field of urban design, studies have been devoted to various issues of sustainability especially environmental performances of urban design solutions[8] in order to create better environment in cities. Specifically, there is a stream of studies which focused on how urban designs would affect environmental performances in terms of human comfort such as thermal comfort in urban space. For instance, it has been suggested that urban designs with deep canyons were preferred in order to improve thermal comfort in hot dry climates[9]. It was found that trees in green open spaces could help to regulate urban micro-climate and mitigate urban heat island effects and air pollution[10]. Shading by trees would also greatly influence human thermal comfort in open spaces[11]. Meanwhile, there were researchers and designers who have been actively exploring how the notion of environmental performances could be incorporated into parametric design. There were a number of studies focusing on optimizing the environmental performances of urban design solutions with the aid of parametric modelling. A parametric approach was developed to search for optimal design in

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order to maximize green areas in the masterplan of a site of approximately 7km^2.[12] A parametric optimization system was developed to optimize solar irradiation and wind speed of urban development in UAE[13]. Solar energy potential from photovoltaic systems in cities could be quantified and compared by using a parametric approach[14]. All these examples show that the use of parametric models could help to maximize the environmental performances of urban spaces.

Although it has been demonstrated that the notion of parametric modelling could be applied to improve the environmental performances of urban design solutions, environmental performances were usually outputs of the parametric models. In previous studies, environmental performances were usually estimated after the design was generated by the parametric models. It would be of interest to explore if it is possible to treat environmental performances as input. Besides, most of the studies focused on later stages of design. It will be beneficial to explore how parametric design can help in early stage of urban design by incorporating environmental performance. Usually, designers start the design process by considering the site forces and contexts. They tend to develop the initial sketches based purely on sense of beauty and vision and as a result they will temporarily neglect the actual performances of the designs[15]. In fact, quantifying environmental performances of urban spaces required extensive calculations. Computer simulation tools will be needed in order to perform such performance estimations. It will be impossible for designers to evaluate and compare the performances of different options especially in the initial design stage without the aid of computational tools. To this end, it will be natural to ask the question how computational tools, together with parametric modelling, can possibly include different types of environmental performances in initial design stages of urban design. According to the notion of performance-based digital design, the designer should be able to explicitly interact with the performances of the design during the design process[16]. Previous studies on generative design framework also suggested that the evaluation process of digital design could become part of the brainstorming process for designers[17]. It will be of paramount importance to develop a model development framework which can guide the development of parametric urban design models which incorporate environmental performances and aid brain storming and design exploration in early design stage.

Consequently, it is of the main objective in this study to develop a model development framework for parametric urban design which includes environmental performances as input in early design stage. Parametric models developed under this framework should help generate design options according to the performance levels required so that further design exploration could be performed. The development of a parametric model for the design of green open spaces would be used as a case study to demonstrate how this framework could be applied.

METHOD

A parametric urban design model can be categorized into three different types. Figure 1 shows these three types of models. Usually, only the parameters will be the inputs in a parametric model. The performance estimation will be performed after the design solution is obtained (Figure 1a). On the contrary, the aim of this study was to embrace performances as inputs. The ideal case will be that all inputs to the models are performances (Figure 1b). However, it may not be practical as there may be performances that cannot be quantified or included into the model. As a result, a hybrid model would be suggested (Figure 1c) under the model development framework in this study. This means that both performances and parameters are the inputs to the model.

THE MODEL DEVELOPMENT FRAMEWORK

Mathematically, the performances of a design option in a parametric urban design model can be expressed as:

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1. Concept of a Parametric Model with Performances as Inputs

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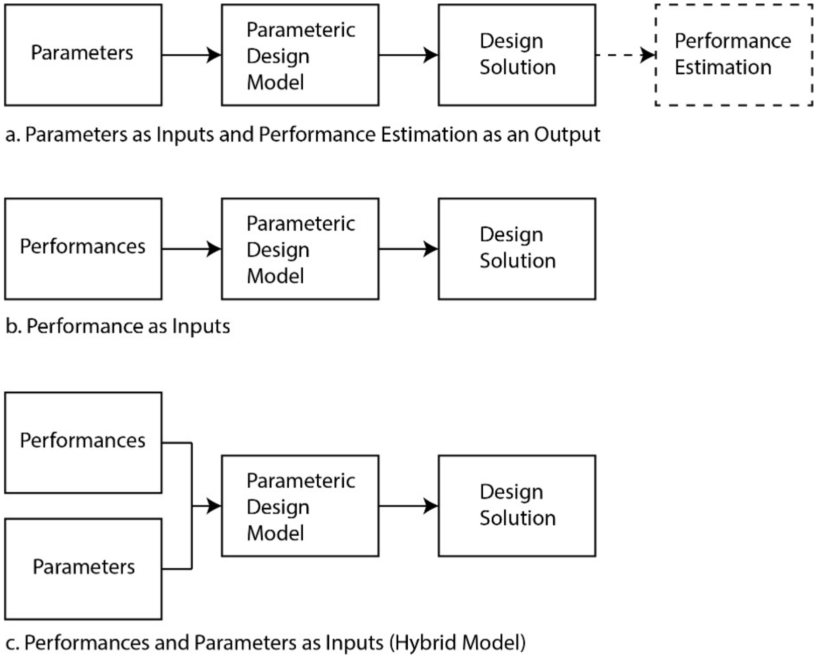

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$$\left.\begin{aligned} p_1 &= g_1(X_1) \\ p_2 &= g_2(X_2) \\ &\vdots \\ p_k &= g_k(X_k) \end{aligned}\right\} \qquad (1)$$

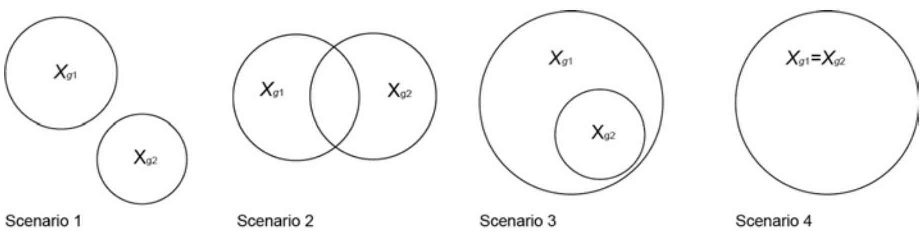
where p's are various performances of the design option; g's are functions connecting different design parameters of the parametric model and the performances; X's are sets of parameters (x's; both controllable and uncontrollable parameters, which will be discussed in a later section of this paper) influencing the corresponding performances; k is the total number of types of performances considered in the design.

Suppose the total number of parameters being considered in a parametric model is n, it is worth noting that any given set of parameters X in equations (1) will not include all these n parameters. This is because there might be parameters which are not related to any of the performances being considered. A given set of parameters X_g will always be a subset of X_{all}, which is the set containing all parameters being considered. On the other hand, there are four different possible types of relationships between any two given sets of X's (assuming they are X_{g1} and X_{g2}) — (1) there is no intersection between X_{g1} and X_{g2}; (2) there is an intersection between X_{g1} and X_{g2}; (3) X_{g2} is a subset of X_{g1}; (4) X_{g1} is equivalent to X_{g2}. Figure 2 shows these four possible relationships. The same parameters can affect different performances if the two sets of parameters are not disjoint. It can be seen that the same parameters can influence different performance goals (scenarios 2 to 4 in Figure 2). As different performance goals may yield different values of the same parameter, conflicting values of parameters may be obtained. The parametric model should be able to inform the designer when such conflicting values were obtained.

Besides, there will be a number of constraints (e.g. design brief and practical issues) when generating a design solution. These constraints do not only affect the design solution, but also some of the parameters in the parametric models. For example, the range of values of a parameter can be restricted due to the constraints. Specifically, parameters influenced by the constraints can also be parameters affecting the performance goals. Suppose X_g is a set of parameters which will affect the performance goals and X_c is the set of parameters influenced by the constraints, there are five different scenarios for the relationship between X_g and X_c — (1) there is no intersection between X_c and X_g; (2) there is an intersection between X_c and X_g; (3) X_g is a subset of X_c; (4) X_c is a subset of X_g; (5) X_c is equivalent to X_g. Figure 3 shows the possible relationship of these parameters. It can be seen that the constraints can influence the parameters affecting performance goals in four out of the five scenarios (scenarios 2 to 5 in Figure 3). As the constraints may restrict the values of these parameters, the ranges of values of these parameters, as well as the performances influenced by them, should be set according to the constraints in the parametric model.

Generally, a design option *DO* can be expressed as:

$$DO = F(x_1, x_2, \ldots, x_n, C) \tag{2}$$



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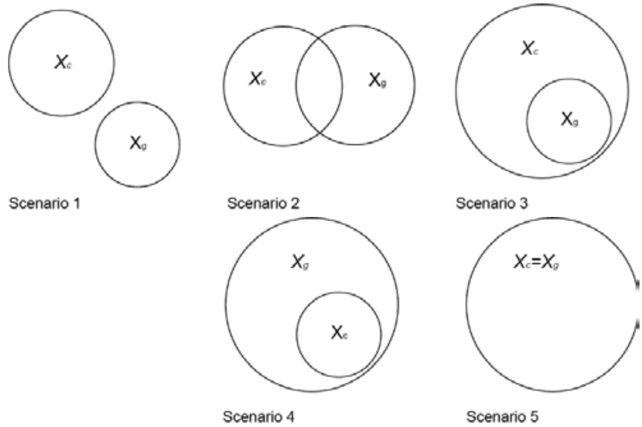
2. Possible relationships between two given sets of parameters X_{g1} and X_{g2} in equations (1)
**Scenarios — (1) there is no intersection between X_{g1} and X_{g2}; (2) there is an intersection between X_{g1} and X_{g2}; (3) X_{g1} is a subset of X_{g2}; (4) X_{g1} is equivalent to X_{g2}*

3. Possible relationships between the set of parameters influenced by the constraints and the set of parameters affecting performance goals
**Scenarios — (1) there is no intersection between X_c and X_g; (2) there is an intersection between X_c and X_g; (3) X_g is a subset of X_c; (4) X_c is a subset of X_g; (5) X_c is equivalent to X_g*



where *F* is a function leading to the design option; *C* is the set containing the constraints of the design; *n* is the total number of parameters being considered in the parametric model.

Usually, there would only be equation (2) when a parametric model is concerned. Designers would play with different values of the *x*'s and get to the final solution of a design problem. However, the situation would be different for a model which embraces the performances as input. In this case, equations (1) would be included. Instead of defining the values of all x_1 to x_n in equation (2), designers would define the values of *p*'s as the goals (performance levels) and some of the values of *x*'s of the design solution. Assuming that x_1 *to* x_m ($m<n$) are the parameters affecting the performance goals, equation (2) can be redefined as:

$$DO = F(x_1, x_2, \ldots, x_m, x_{m+1}, x_{m+2}, \ldots, x_n, C) \tag{3}$$

Since designers will define the values of *p*'s, values of x_1 to x_m will not be defined by the designers. Instead, different combinations of values of x_1 to x_m will be obtained with respect to the values of *p*'s. As mentioned above, conflicting values of *x*'s (x_1 to x_m) could be obtained due to the different performance goals. A weighing or optimization mechanism will be needed in order to generate sets of values of x_1 to x_m. However, this is out of the scope of this study. It will not be discussed here. On the other hand, it is further assumed that the influences of constraints on the parameters have been considered when the ranges of possible values of *x*'s are defined.

COMPONENTS OF THE FRAMEWORK

The design framework consists of three components. They are namely, input, design generator and output. Meanwhile, there are also sub-components under the input components. Figure 4 shows the logic and flow of these components and subcomponents.

Input

The input component includes all the factors that will affect the design solution. Constraints, performance goals, controllable parameters and uncontrollable parameters are the sub-components under input.

Constraints

There are a lot of factors which are pre-defined and cannot be changed (C in equation (3)). However, they will affect the whole design process, as well as the performance of the design. In the field of urban design, site conditions such as zoning, programs, neighborhood geometry, building height and location of the site are some of the factors that should be considered as constraints of the parametric design model.

Performance goals

The performance goals refer to the required performance levels (values of p's in equation (1)) of the design option set by the designers. These performance goals have to be quantifiable otherwise it will be impossible to include them into the parametric model.

Parameters

The parameters (x's) are the variables that are actually adapted to generate design options. Depending on the scale of the design, there can be different parameters. In a bigger scale such as designing master plan of a community, the main axials can be one

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4. Flow and logic of the framework

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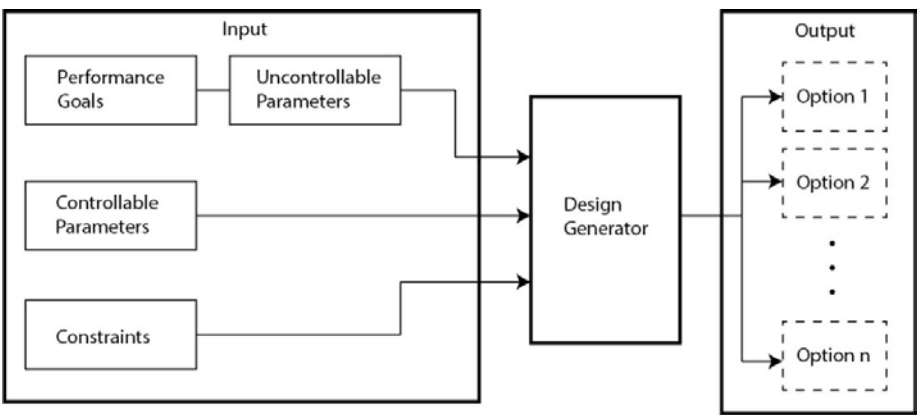


of the parameters. In a smaller scale such as small open space design, the dimensions of seating spaces can be a parameter. Basically, parameters can be categorized into controllable and uncontrollable parameters under the model development framework.

Controllable Parameters

Controllable parameters (x_{m+1} to x_n in equation (3)) are parameters that the designer will define and control the values of them. This is similar to the parameters in any parametric model. By changing these values, different design options will be obtained.

Uncontrollable parameters

Uncontrollable parameters (x_1 to x_m in equation (3)) are the parameters that will affect the performances. The designer will define these parameters and probably the ranges of values of them. However, the designer will not define the exact values of them. Instead, the values of performance goals will be defined. The model will search for the values of these parameters (by using equations (1)) in order to achieve the performance goals. It is important to note that it is not a must to include all parameters which affect the performances as uncontrollable parameters. Designers can choose the parameters they would like to control the values and decide on which parameters they would like the model to search for the values.

Design Generator

This is the actual driver for the design solutions. According to the requirements of the designer, relationship and rules between parameters and constraints, as well as among the parameters, i.e. F in equation (3), will be defined. These relationships and rules are usually defined by mathematical formula. They can be overlapped or co-dependent[18].

Output

The output of the model are the design options for the designer to have further design exploration. There can be two different scenarios when design options are generated. The designer can choose to have design options embracing similar performances for further exploration. On the other hand, the designer can also choose to explore options with different performance levels.

STEPS OF MODEL DEVELOPMENT

When developing the actual model, five main steps would be involved. Figure 5 shows the main procedure of developing such a model.

Step 1: Identify Constraints

Constraints have to be identified as they will be the base of setting up the model.

Step 2: Define Performance Goals

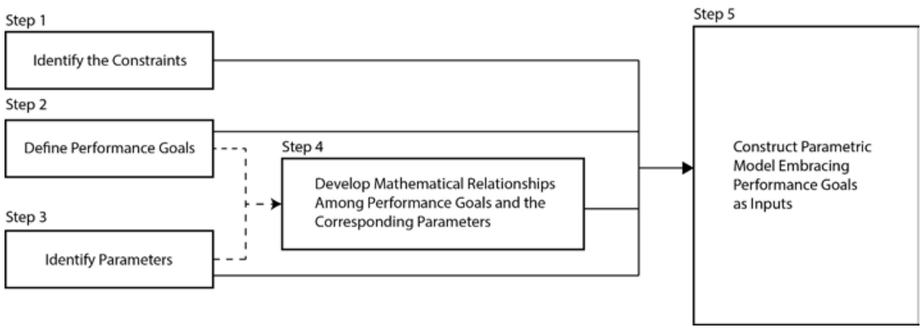
As the primary aim is to develop a model which embraces performance goals as input. It is essential to define the performance goals to be considered. It is important to define both the type of performances and quantify the performance goals.

Step 3: Identify Parameters

The parameters related to the design task have to be identified. The designer needs to quantify and define the ranges of values of these parameters otherwise it will be impossible to use them as input to the model. In this step, both controllable and uncontrollable parameters will be defined. Here, designers may not want all parameters to be uncontrollable parameters. The designer will choose the parameters which will be uncontrollable. Even if a particular parameter will affect a performance goal, the designer can still make it controllable. Parameters not affecting the performance goals will all be controllable parameters.

Step 4: Develop Mathematical Relationship between Performance and Parameters Affecting the Goals

In this step, relationships between performances and parameters affecting them have to be identified. With reference to equations (1), different possible values of x_1 to x_m will be obtained by defining



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5. Procedure of developing a parametric model embracing performance goals as inputs

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the values of p's. Ideally, it would be preferable if there are simple developed mathematical relationships between the performances goals and parameters. However, if there are no developed relationships for certain performance goals and parameters, it will be essential to develop them specifically for the model. In this case, different tools for performance simulations may be needed in order to develop the relationships.

Step 5: Construct the Model

With controllable and uncontrollable parameters, relationship between performances and parameters, and constrains, the model which can generate design options according to the performance goals will be formed.

CASE STUDY

Public open spaces are considered one of the basic elements of cities[19]. They are important parts of the urban landscape and should be conceived as "outdoor rooms" within neighborhood[20]. Due to the increase in awareness of urban sustainability, it is not unusual to have various greenery and trees inside public open spaces. These spaces, commonly known as green open spaces (GOS), can provide social[21], ecological[22] and economic[23] benefits to both individuals and the public.

Thermal and acoustic comfort should be the main concerns when designing GOS. The thermal comfort inside GOS could affect the usage patterns of these spaces[24]. Of all the factors which affect thermal comfort in GOS, sun access / shading was found to be an important factor affecting the quality of open spaces[25]. To this end, shading by trees would greatly influence human thermal comfort[26] in these spaces. On the other hand, various studies have confirmed that water sound could provide masking effect on environmental noise[27], which could help to improve the overall acoustical quality of the environment. In this case study, thermal comfort constituted by tree shading and acoustic

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comfort due to the masking effect of water sound from a fountain would be considered the performances of GOS in order to show how the model development framework could be applied.

Grasshopper, which is a parametric plugin for Rhino 3D, was adapted as the tool to develop the model in the case study. Grasshopper has been adapted in a number of studies concerning models for parametric urban design[28]. As thermal comfort would be considered, ladybug[29], a Grasshopper add-on for thermal analysis, would also be used in this study.

A virtual site located in Hong Kong was defined when formulating the parametric design model. It was a square of dimension 50 m x 50 m. Three sides of it were enclosed by buildings while one side of it was facing a street. The buildings were all of height 15 m. Meanwhile, trees and fountain could only be put at least 3 m from the site edges. It was further assumed that there was a traffic road located 2 m from the entrance point from street to the virtual site. The traffic noise level at the entrance point was assumed to be 70 dBA, Figure 6 shows the configuration of the virtual site.

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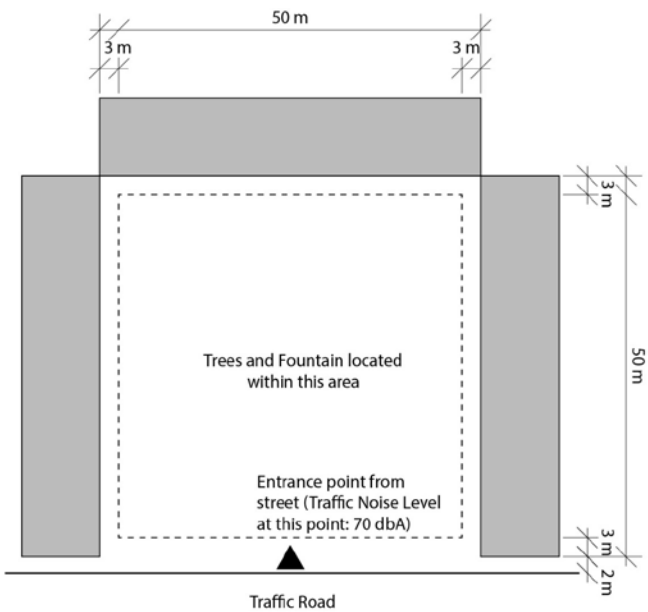

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6. Virtual site defined in the parametric urban design model

ПРИМЕЧАНИЯ

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Step 1

There are various site constraints in the virtual site. First of all, it was located in Hong Kong. The weather, which is directly related to the thermal comfort in the open space, would be affected by this geographic location. Second, heights and positions of buildings were fixed. This would affect the shadow casted and hence thermal comfort in the site. Third, the traffic noise level should also be considered a constraint. All these constraints would be programmed into the parametric model.

Step 2

In this study, the performances considered were thermal and acoustic comfort in GOS. There are various ways to quantify outdoor thermal comfort. In this case study, Universal Thermal Climate Index (UTCI) developed by the European Cooperation in Science and Technology[30] was adapted to quantify thermal comfort in GOS. UTCI has been widely used in outdoor thermal comfort studies[31]. The index is expressed in terms of degree Celsius. In this study, the reduction in average UTCI in the site due to tree shading was adapted as a performance goal. When estimating average UTCI, the time period considered was the hottest week of the year in Hong Kong (22 July to 28 July). Average wind speed and humidity within the hottest week of the year were adapted when estimating the average UTCI.

For the acoustic comfort, previous studies suggested that the masking effect of water sound would be the most effective when the water sound level was 0 to 3 dB lower than traffic noise level[32]. The existence of a region with this sound level difference was used to quantify acoustic comfort in the open space.

Step 3

There are a lot of design attributes that will affect the design of GOS. As the main aim of the study is to develop a parametric model for early design stage, it was expected that further design exploration would be performed after design options were generated by the model. It would not be a sensible decision to include all these attributes as parameters in the model. This is especially true for parameters such as number of seating, which are mainly related to detailed design of GOS. As a result, only parameters related to tree shading and water sound masking were considered. Of all the parameters considered, "Density of Trees", "Tree Crown Diameters", "Tree Height" and "Fountain Position" were defined as uncontrollable parameters. The values of these parameters would be determined by the model after the values of UTCI reduction and the region with sound level difference 0 to 3 dB were defined. Meanwhile, trees were distributed within the site by using a random function. Table 1 summaries the parameters considered in the case study.

Table 1 Parameters included in the model formulation

Parameters	Description
*Density of Trees (Tree Number / m^2)	0.02 to 0.2
*Tree Crown Diameters	3.0, 3.5, 4.0, 4.5 and 5.0 m
*Tree Height	2.5 m + Tree crown diameters (Bottom of tree crown was always 2.5 m from ground)
Tree Shape	Round
Fountain Diameter	3 m to 10 m (The fountain was assumed to be of a circular shape)
*Fountain Position	Along the central line of the site
Water Sound Level	55 to 70 dbA at the edge of the fountain

**Uncontrollable parameters*

Step 4

As there is no developed mathematical relationship to obtain the number of trees needed when the value of UTCI reduction is defined, it was necessary to develop the relationship in this study. Ladybug was utilized to estimate the average UTCI in the site. The densities of trees considered were from 0 (base case: no tree in the site) to 0.2, while the size and shape of trees were the same as the values shown in Table 1. The reductions in average UTCI in the site with respect to different densities of trees when comparing to the base case were estimated. As trees were assumed to be distributed randomly in the site, UTCI reductions were estimated five times with different tree distribution patterns for the same tree density. This was done because average UTCI would vary by a small amount due to different tree distribution patterns, even when the tree density was the same. The following mathematical relationships were obtained by using regression analysis:

$$\textit{UTCI Reduction} = 0.370 \times \ln(\textit{Densiti of Trees}) + 1.741 \quad (4)$$

$$\textit{UTCI Reduction} = 0.364 \times \ln(\textit{Densiti of Trees}) + 1.879 \quad (5)$$

$$\textit{UTCI Reduction} = 0.328 \times \ln(\textit{Densiti of Trees}) + 1.864 \quad (6)$$

$$\textit{UTCI Reduction} = 0.291 \times \ln(\textit{Densiti of Trees}) + 1.823 \quad (7)$$

$$\textit{UTCI Reduction} = 0.254 \times \ln(\textit{Densiti of Trees}) + 1.775 \quad (8)$$

Here, equations (4) to (8) were the relationships between UTCI reduction and tree density when tree crown diameters were 3.0, 3.5, 4.0, 4.5 and 5.0 m respectively. The adjusted R^2 of the equations were found to be 0.984, 0.977, 0.958, 0.935 and 0.907, which means that they fit the data very well and it can be used to obtain the number of trees needed when the value of UTCI reduction was defined. However, it should be noted that the reduction in average UTCI was found to be 1.3 degrees Celsius when the density of trees and tree crown diameter were 0.2 and 5 m respectively. This was the maximum value of reduction in average UTCI in the case study. The input value of UTCI reduction should be confined between 0 and 1.3 degrees Celsius when equations (4) to (8) were used.

Meanwhile, the water sound levels of the fountain and traffic noise levels at different points along the central line of the site were calculated by using inverse square law. The differences between sound levels of the two sound sources at different points along the central lines of the site would be found. The length *l* of the region with sound level differences between 0 to 3 dB (See Figure 7) would be defined by the designer and the model would be able to find out possible positions of the fountain and acoustically the most comfortable zone.

Step 5

With all the parameters and mathematical relationships, the model could be developed using Grasshopper. Figure 8 shows the design options generated by the model by inputting different values of controllable parameters and performance levels. By using the parametric model, the density of trees, tree size, position of fountain, as well as acoustically the most comfortable zone would be obtained for further design exploration.

CONCLUSION AND DISCUSSION

Unlike previous studies which treated environmental performances as an output of parametric models[33], a model development framework to develop urban design parametric models incorporating environmental performances

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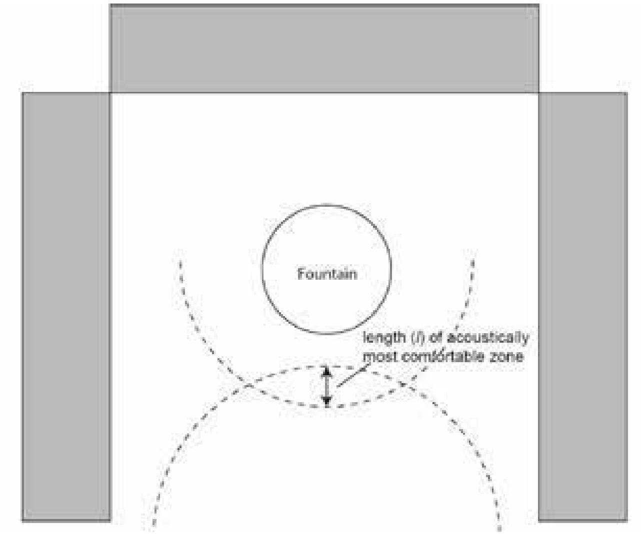
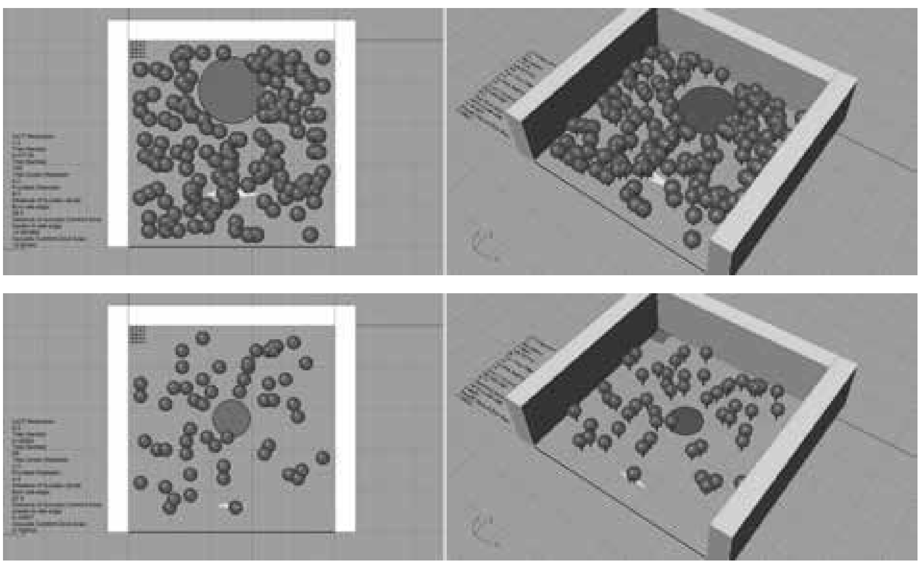


as input in the initial design stage was developed in this study. Usually, designers will not explicitly consider performances of urban spaces in the brainstorming or initial sketch stages. Performances will only be quantified when the design is nearly completed. However, some early design decisions may greatly affect the performances. It may not be possible to make changes to these early decisions at later stage of the design process. With this framework, designers would

8



ИЛЛЮСТРАЦИИ

7. Length of region with sound level differences between 0 to 3 dB (acoustically the most comfortable zone)

8. Design options generated by inputting different parameter and performance values
Input — UTCI Reduction: 1.0 °C; Length of Acoustic Comfort Zone: 3 m; Fountain Radius: 8 m; Water Sound Level at the edge of fountain: 60 dBA
Output — Tree Density: 0.072 (165 Trees); Tree Crown Diameter: 4.0 m; Fountain Center Location: 38 m from street entrance; Center of Acoustic Comfort Zone Location: 13.0 m from street entrance
Input — UTCI Reduction: 0.5 °C; Length of Acoustic Comfort Zone: 2 m; Fountain Radius: 4.5 m; Water Sound Level at the edge of fountain: 70 dBA
Output — Tree Density: 0.023 (55 Trees); Tree Crown Diameter: 3.5 m; Fountain Center Location: 27.5 m from street entrance; Center of Acoustic Comfort Zone Location: 6.5 m from street entrance
**The yellow region is the area of acoustically the most comfortable zone*

be able to explicitly consider different environmental performances of the design and compare the quantified performances of various design options at the initial design stages. As the framework mainly serve the initial sketch design stage, it can help to introduce the performances of urban spaces as part of the brain storming process as proposed in previous studies[34].

In our case study, only parameters related to the environmental performances (i.e. thermal and acoustic comfort) were considered. This is because we would like to keep the case study simple so that it would be easier to understand the process of developing the model. However, it should be feasible to include parameters which were not related to the environmental performances under the developed design framework. For example, parameters such as paths inside the open space could be added to the model developed in the case study. According to different requirements or needs, it will be the designer who decides on what parameters to be included when developing the model.

It is also worth mentioning that it is not necessary to define all parameters related to the performances as uncontrollable parameters. As demonstrated in the case study, the location of fountain, the size of it and water sound level at the edge of it could affect the location and length of the acoustically most comfortable zone. However, only the location of fountain was chosen as an uncontrollable parameter. It was because the size of fountain might affect aspects such as aesthetics, which was not considered in the model. Moreover, water sound level at the edge of the fountain would be affected by the design of the fountain itself, which may also affect the aesthetics of the fountain. On the other hand, there can be more than one uncontrollable parameter related to a performance goal. In our case study, both the size of trees and density of trees, which were related to thermal comfort in the open space, were defined as uncontrollable parameters. Again, the decision on whether a parameter is controllable or not depends on other concerns of the design task which may not be included in the

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model. As a result, it will be the decision of the designer to choose what parameters should be controllable or uncontrollable.

In this study, only thermal comfort and acoustic comfort were included as environmental performances. This was done in order to simplify the problem for the sake of demonstration. According to the developed framework, it would be totally feasible to incorporate more environmental performances in the parametric model to be developed. However, there are also practical issues to be considered when developing a parametric model incorporating multi environmental performances for the initial sketch design stage. Taking thermal performance as an example in the case study, it could take days if not weeks in order to complete the estimation of UTCI if factors such as wind speed at different time of the day inside the open space were considered. It was because the geometry of the site, as well as surrounding buildings in the neighborhood would have to be considered. It would be an extremely lengthy process to develop the relationship between UTCI reduction and number of trees if the change in wind speeds at different time of the day was one of the factors to be included in UTCI estimation. In a practical aspect, designers may not have the time to develop the relationships between the performances and parameters. Adapting the average wind speed in the hottest week of the year may render a lower accuracy in terms of UTCI estimation. However, this should be considered acceptable as the aim of the case study is to consider merely how shading from trees could affect thermal comfort. There has to be a balance between the accuracy of performance estimations and time required to complete the estimations, when developing a parametric model with environmental performances as inputs.

All in all, the success in inclusion of a particular environmental performance will depend on whether there are simplified mathematical model to estimate the environmental performances, or whether it would be possible to estimate the environmental performance in a relatively short period of time given the computational power nowadays. Besides, parameters related

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to thermal comfort and that related to acoustic comforts were independent in the case study. As discussed, conflicting values of the same parameters may occur in the model if the parameters related to different performance goals are not independent. Multi-objective optimization functions might have to be incorporated in the model in this case. In fact, there are a few common algorithms for multi-objective optimization. Some examples of such algorithms include applying a weighted factor for each environmental performance and Pareto approach[35]. Since the main objective of the study is to develop an overall framework to develop parametric model generating design options for further design exploration, optimization functions were not considered in this study. However, it is always possible to include these optimization functions when developing a parametric model under the model development framework.

Although the framework was developed with the notion of urban design, it should be possible to apply the framework to architecture. The framework could also guide the development of urban design parametric models incorporating performances other than environmental performances in urban spaces. However, the success in developing a model according to the framework would lie on the feasibility of modelling or quantifying the performances in concern mathematically. Usually, it would be relatively easier to quantify environmental performances such as thermal and acoustic performances. On the contrary, it may not be feasible to develop a solid mathematical relationship between design parameters and performances such as aesthetic performance of an urban space. As a result, it may not be able to include these types of performance in the model.

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