Principles of comprehensive device generating urban spaces (utilizing parametric technologies)

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ABSTRACT

Traditionally, designers utilized computer as a tool for producing representation of designs. CAD software was essentially treated as a drawing tool. However, researchers suggested that computers should become a partner of designers for concept and design generation. The emergence of parametric design nowadays is a response to this idea. In fact, the notion of parametric design in Architecture can date back to the hanging model of Antonio Gaudi. However, due to the advance in computer technology, parametric design with the aid of computer is only a recent phenomenon in the fields of architecture and urban design.

As parametric design in the realms of architecture and urban design is still in its infancy, efforts have been put on formalize the theory of this design method. Various approaches of parametric model development for urban design have suggested. They are namely associative, shape grammar and performative approaches. Specifically, the notion of performative approach is to integrate performances of the design into parametric design models so that quantified performances can become a driving force for the design. It has also been suggested that quantified performances could be included in the initial stage of design process. There have been studies which devoted to exploring performative approach of parametric urban design. While researches showed that performative approach of parametric urban design could help search for the most optimized design solution, most studies only adapted the idea of combining evolutionary approach of digital design and parametric model as a strategy of performative approach. Few attempts have been made to explore different strategies of performative approach.

On the other hand, there have been studies which investigated the notion of inverse simulation. Conventionally, simulation was utilized to evaluate the performance of a design after it has been generated. Inverse simulation is an inversion of this process. Combination of design elements could be found by a given performance level. Recent studies even showed that this method could help to search for combination of building envelop design features by using a given thermal load target. However, no attempt has been made to utilize this method in the field of urban design. Even worse, this method has not been adapted as a strategy of performative parametric design model in previous studies.

Meanwhile, efforts have been made to examine the application of parametric design model for urban design tasks. It was suggested that parametric urban design models could be used to

design cities in both large and small scale. Various studies have also been conducted to explore the algorithm and parameters related to parametric urban design. Regarding performative parametric urban design, there were also studies which attempted to optimize green space distribution or thermal comfort in urban spaces. However, one drawback of these studies was that only one performance was considered. A parametric design model adapting performative approach will never be a comprehensive one if only one performance is included. It would be of interested to explore how multiple performances could be included in a performative parametric urban design model.

Accordingly, the primary objective of the current study was to explore how inverse simulation could be adapted as a strategy of performative parametric urban design models. A model development framework would be formalized and developed. Meanwhile, an experiment for green open space design would be conducted to demonstrate how this framework could guide the development of a performative parametric urban design model which adapted inverse simulation as the strategy of model development. Multiple performances would be considered in the experiment so as to investigate how the parametric model could be formulated when there is more than one performance to be included.

LIST OF ARTICLES PUBLISHED

1. Leung, T.M. (2019). Parametric Design Modelling in Urban Art: Approaches and Future Directions. Proceedings of 2019 International Conference on Architecture: Inheritance, Tradition and Innovation, Moscow.

2. Chau, C.K., Leung, T.M., Xu, J.M. and Tang, S.K. (2018). Modelling Noise Annoyance Responses to Combined Road Traffic and Sea Sounds while Exposed to Composite Neighborhood Views. The Journal of the Acoustical Society of America, 144(6):3503-3513

3. Leung, T.M., Kukina, I.V. and Lipovka, A.Y. (2018) A parametric design framework for spatial structure of open space design in early design stage. Proceedings of the 25th ISUF International Conference. Krasnoyarsk, Russia.

4. Leung, T.M., Kukina, I.V. and Lipovka, A.Y. (2018). On the formulation of green open space planning parameters: A parametric tool. In 24th ISUF International Conference - Book of Papers, 1685-1682, València.

5. Leung, T. M., Chau, C. K., Tang, S. K., & Xu, J. M. (2017). Developing a multivariate model for predicting the noise annoyance responses due to combined water sound and road traffic noise exposure. Applied Acoustics, 127: 284-291.

6. Leung, T. M., Xu, J. M., Chau, C. K., Tang, S. K., & Pun-Cheng, L. S. C. (2017). The effects of neighborhood views containing multiple environmental features on road traffic noise perception at dwellings. The Journal of the Acoustical Society of America, 141(4): 2399-2407.

7. Leung, T. M., Xu, J. M., Chau, C. K., & Tang, S. K. (2017). Effects of visual environment with multiple environmental features on noise annoyance induced by road traffic noise. In INTER-NOISE and NOISE-CON Congress and Conference Proceedings, 255(2): 5978-5984, Hong Kong.

PREFACE

This work was performed at the Institute of Architecture and Urban Design, Siberian Federal University, Krasnoyarsk, Russia.

Comments on the author's contribution to the papers. Leung, Tze Ming was responsible for data analysis, graphical representation of data as well as illustration of the design scenarios, scripting the parametric urban design models and writing the text of the articles.

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1 INTRODUCTION

1.1 Overview

The task of urban design has become more complex and challenging today. Urban designers do not only have to consider the morphological form but also aesthetic, social, economic, as well as environmental dimensions of cities. The non-static nature of cities renders the need to have more responsive urban design solutions. Besides, more people live in urban areas than in rural area nowadays. The scale of urban design tasks has become larger. Due to various agendas of different stakeholders, it is also a challenge for designers to ensure effective communication among different parties during the design process. In response, urban designers seek to explore how the notion of digital design can help deal with these challenges.

In fact, computers have long been considered a tool for design representation. With CAD software, designers would produce drawings on computers. It has been a common practice for designers to create 2-dimensional or even 3-dimensional representations of urban design solutions by using computers. Due to the advance in computer technology and scripting techniques, the notion of digital design has also become more sophisticated. Computers are no longer a tool solely for design representation. It is also possible to utilize computers as a tool to stimulate design ideas and generate design solutions. The idea of parametric urban design, which is a digital design method to generate design solutions by defining parameters and the relationships and rules among them, emerges to this end. With parametric design thinking, a design can be decomposed into a number of parameters. When performing a design task, designers will manipulate various parameters and different values of them in order to generate a design solution.

Although parametric urban design has been explored for some time by both practitioners and academics, it is still considered at its infancy. There are a lot of aspects of parametric urban design which have not been fully explored. Specifically, although the performative approach of parametric design has been suggested in previous studies [1] to integrate design performance into the design generation process, few attempts have been made to adapt this notion to develop parametric urban design models. Design performance evaluation was still considered a process after the generation of design solutions in most studies concerning design performances and parametric urban design.

On the other hand, there is another stream of studies which focus on exploring the notion of inverse simulation, which is a method to generate design solutions with a given performance goal. It has even been shown in a recent study that with inverse simulation, building envelope design solutions could be generated by a given energy consumption target [2]. To this end, it will be natural to ask whether it is feasible to combine inverse simulation and parametric urban design so as to better integrate design performance into the design generation process.

As a result, the current study aims at exploring the possibility and feasibility of incorporating inverse simulation into performative parametric urban design models. The principles and steps of developing such a parametric design model will be formalized.

1.2 Problem Statement

In recent years, the idea of parametric design has been actively explored in the realm of urban design. Both practitioners and researchers have actively investigated how the notion of parametric urban design can be utilized in the design process. Of all the efforts devoted to parametric urbanism, the works from architecture office MVRDV and Patrik Schumacher, principal of Zaha Hadid Architects are probably the most well-known. In MVRDV, the "Function-mixer" in the form of software application was created. With different settings of program parameters, various programs or uses in 3D space would be mixed by the urban design scheme. With the idea of parametricism, Patrik Schumacher has engaged in various award winning master planning projects such as Kartal-Pendik Masterplan in Istanbul, Turkey and One North Masterplan in Singapore.

Meanwhile, different aspects of parametric urban design have also been examined in previous studies. It has been suggested that parametric models can be utilized for urban design tasks of different scales [3], [4]. Efforts have also been put on exploring the different parameters [5] and algorithm [6]–[8] related to parametric urban design models .

Although there are a number of advantages when parametric urban design models are utilized [9], there have also been critiques about the use of parametric models in urban design tasks. In particular, it has been argued that ideas such as "*Parametricism implies that all architectural elements and complexes are parametrically malleable*" [10] would render the notion of parametric urbanism limited to the formal viewpoint [11]. On the other hand, researchers also suggested that the use of computer model for design performance assessment in early design stage can help enable the design solution to achieve a higher level of environmental sustainability [12], [13]. To this end, there were studies which explored how parametric urban design models can be combined with the actual performances of the urban design solutions [11], [14]. However, there are still a number of common shortcomings when considering these previous studies:

- Only one type of performance of the design was considered
- Environmental and social dimensions of the design were seldom explored in combination
- Performances of the designs were usually evaluated after a design has been generated by the parametric urban design model

Consequently, this study mainly aims at dealing with the above shortcomings.

1.3 Research Questions

The primary objective of this study is to investigate the combination of inverse simulation and parametric urban design model as a strategy of performative approach. With this strategy, multiple performances of designs can be incorporated into a parametric urban design model. This study is based on the following research questions:

- How the performances of designs can be included as inputs into the parametric urban design models by adapting the notion of inverse simulation?
- What are the steps and principles to develop a performative parametric urban design model including multiple performances of the design solutions?
- Is it feasible to include both environmental performance and spatial structure of the urban design solution in a single parametric model?

To address these research questions, a parametric urban design model development framework would be formalized in this study. Within this framework, the steps to develop a performative parametric urban design model by using inverse simulation as the strategy would be laid out. Multiple performances can be treated as input to the model. As an experiment, this framework would be utilized to develop a parametric design model for green open space design.

1.4 Method

The current study can be divided into three different stages. The first stage of the study is primarily literature reviews. Different theories and streams of studies concerning parametric urban design would be reviewed. Algorithms and approaches adapted in previous studies for the development of parametric design models would also be examined. Besides, literatures related to performances of urban spaces would be reviewed so as to understand the types of performances to be included in the parametric design model to be developed in the experiment. Meanwhile, various computer programs for the development of parametric models in previous studies would be reviewed and tested.

In the second stage, the theoretical framework to develop a parametric urban design model which embraces the notion of inverse simulation and multiple performances of the design as inputs would be laid out. Mathematical concepts and logic of the model development framework would be discussed. The steps to develop a parametric model including performance inputs would also be laid out within the framework.

For the third stage of the current study, a parametric model for green open space design would be developed as an experiment to demonstrate how the model development framework could be applied. Grasshopper for Rhino3D was chosen as the program to develop the parametric design model. The model would be developed according the framework laid out in the second stage. The performances considered in the model were thermal performance, acoustic performance and spatial configuration of green open spaces. The Grasshopper addons Ladybug and Pachyderm Acoustic were utilized to quantify the thermal and acoustic performances of the design. Meanwhile, measures of Space Syntax were used as indicators for the spatial configuration in the open spaces.

1.5 Scope of Work

The current study would formalize the formulation of performative parametric urban design model with inverse simulation as a strategy. Theoretical framework of formulating the parametric design model would be laid out. The experiment to be introduced in the current study would be utilized to demonstrate how the model would be formulated under the framework. As per the experiment, only the performances within the site would be considered. Besides, neighborhood environment of the site would not be considered in experiment of the current study.

1.6 Thesis Outline

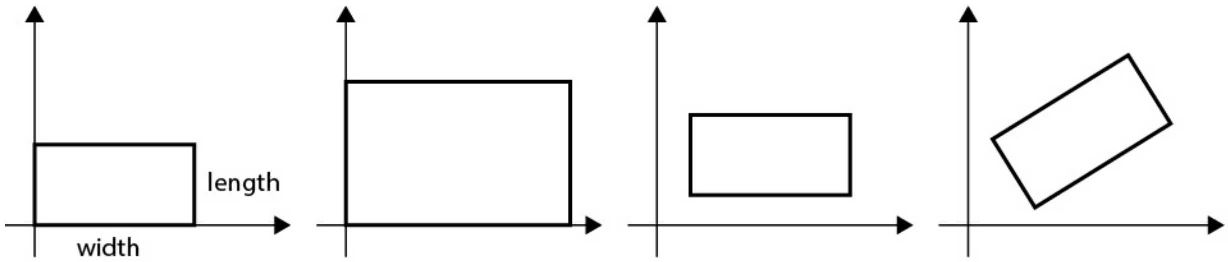
This chapter is a brief introduction of the study. The aims and methods of this study are briefly laid out. Chapter 2 is a detailed literature review on parametric urban design. The history of parametric design and previous efforts on parametric urbanism were reviewed. Approaches of parametric urban design would be discussed in this chapter. Various computer tools for parametric urban design and the criteria of choosing the tool in the current study were also discussed. Chapter 3 is a review on design parameters and performances of green open spaces. Chapter 4 lays out the parametric model development framework. Mathematical concepts and logic behind the framework were discussed. Chapter 5 is the experiment on the development of a parametric model for green open space design by utilizing the framework. The methods to quantity various performances and included in the parametric model would be shown. The steps to develop the model were based on the framework discussed in the previous chapter. Chapter 6 is the conclusions from this study. The directions of possible future studies were also discussed in this chapter.

2 PARAMETRIC DESIGN AND PARAMETRIC URBANISM

2.1 What is Parametric Design

In traditional CAD modeling, computers were usually used as a tool for design representation. Computers were considered a drawing tool. However, due to the advance in computer technology, the use of computer or digital tools in design is no longer limited to the production of drawings. Nowadays, designers can consider "*computer as a collaborative partner in the design process capable of generating ideas and stimulating solutions in response to robust and rigorous models of design conditions and performance*" [15]. To this end, parametric design is a way to utilize computers as a partner to generate design solutions.

In fact, parametric design means "*designing by means of objects which are defined by a set of constituent parameters*" [16]. Objects are declared by various parameters instead of the form of them [17]. Changing a parameter in a component of the design model will lead to relational transformation of the other components in the model [18]. When designing with a parametric model, the target form of the object being designed will not be specified. Instead, the procedure to generate the geometrical or design variations will be specified [19]. The designer will control the relationships among various components of the design and create the design object [20]. Taking a rectangle in a 2-dimensional space as an example, except that there are four sizes and four angles of 90 degrees, it can be defined by varying four different parameters. They are the length, width, position and orientation. Instead of specifying the object as a "rectangle", these four parameters will be specified and defined individually. The change in the value of any one of the parameters will lead to change in the form of the object (rectangle) (Figure 2.1). To this end, variations of a design element can be generated by altering the parameters related to it instead of drawing the them individually. The underlying concept of parametric design should be based on the relationship between data and variables and how the variables respond to the input data [21]. The notion of parametric design can be applied to various design fields such as product design, engineering, architecture and so on.



left to right: altering width and length; altering position; altering orientation

Figure 2.1 Defining a rectangle in a 2-dimensional space by using parameters

2.1.1 Parametric design thinking

Basically, there are three characteristics associated with parametric design thinking. They are "*thinking with abstraction*", "*thinking mathematically*" and "*thinking algorithmically*" [22]. Thinking with abstraction is considered the base of parametric design. It can help generate parallel design alternatives. It also helps to enable some parts of a parametric design models to be reused in other design projects. Thinking mathematically means that designers may have to consider the theorems and mathematics behind the script language to generate design solutions. On the other hand, thinking algorithmically refers to the idea that the script of the parametric design model will enable the possibilities of adding, modifying and removing parts in the model.

Considering the actual operation of parametric design models, parameters and algorithms are the primary components. Parameters are the input to a parametric design model. They can be geometrical or non-geometrical [23]. As mentioned, a change in the value of a parameter can generate a different variation of a design element. On the other hand, algorithms are the predefined rules governing the generation of a design and the relationships among different elements of the design. Usually, these rules and relationships are defined by mathematical formulae [24].

2.1.2 Difference between traditional paper-based design and parametric design

Instead of a conventional design strategy with a new form of media, parametric design could be regarded as a new form of design [25]. New ways of design thinking were provoked due to the integration of sophisticate digital design media throughout the design process [17], [26]. Traditionally, design process was based on implicit knowledge of the designers. Knowledge was rarely formalized. In parametric design, however, designers deal with parameters and rules to generate the designs. Knowledge has to be well-formulated. To this end, information has become a new material when designers design with the technique of parametric design. Besides, paper-based design is considered deterministic. Designers will draw the forms and shapes directly on paper or computers using CAD software. On the contrary, parametric design can be considered non-deterministic as designers will be dealing within the non-deterministic logic of the scripts and parameters. Designers usually continuously re-define and change the logical parametric relationships of the objects in a parametric model so as to reflect the designers' intention and concept. To this end, an extra layer of design reasoning would be added compared to traditional paper-based design method [27]. Moreover, in a paper-based design environment, designers usually interact with the sketches drawn on paper or shapes of the physical models. Even when CAD is used as a medium of constructing design representations, designers still merely interact with the shapes or forms drawn by computers. As per parametric design, designers do not only interact with the shapes or forms but also the mechanism that generate the design. Designers will interact with both the parameters and the rules that govern the parameters to generate the design [25]. Table 2.1 shows the differences and similarities of the role of designers between traditional paper-based design and parametric design.

Table 2.1 Role of designers for traditional paper-based design and parametric design

	Paper-based design	Parametric design
Designers' interaction with forms and shape	√	√
Designers' interaction with parameters	X	√
Designers' interaction with rules generating the design	X	√

2.1.3 Conceptual framework of parametric design

According to Oxman [25], the four basic components of design activities are representation, generation, evaluation and performance. Here, representation refers to the media to represent the design. Generation is the process of generating the design. Evaluation is the evaluative analytical process and the actual performance of the design can be identified by simulation. Although evaluation and performance are important components of design activities, they were usually considered afterthought in traditional design process [28]. With parametric design, it will be possible to integrate these two components better in the design process. Besides, the flow between components should also be in both directions. Figure 2.2 shows the ideal framework of parametric design. Ideally, designers should be able to interact with the four components of the design process.

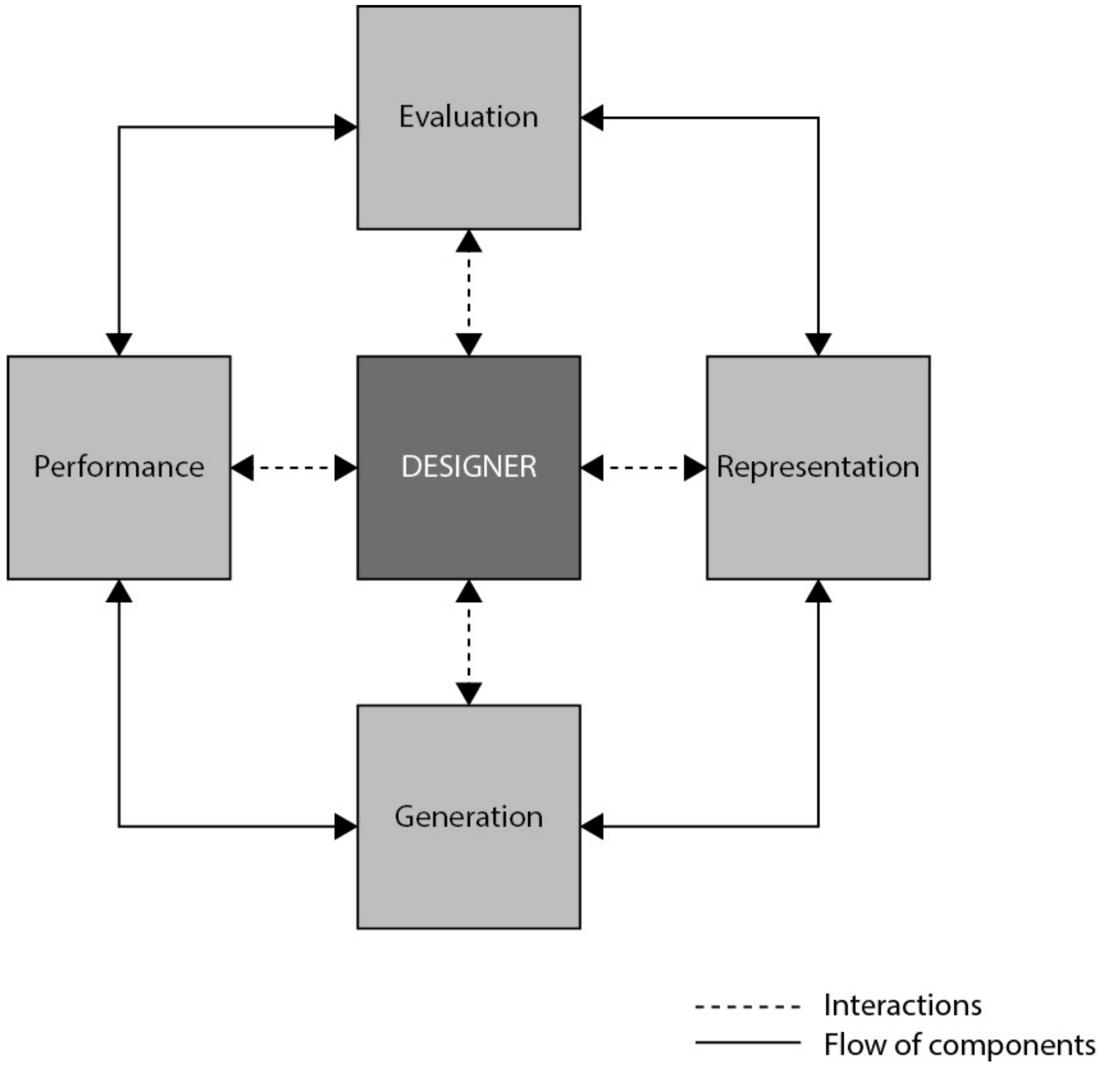


Figure 2.2 Ideal framework of parametric design (modified from [25])

2.1.4 Advantages of parametric design

There are different advantages associated with parametric design. Because the relationship among parameters to generate a design solution are pre-defined, designers can change the values of parameters and the design solution will be updated accordingly [29]. This helps reduce the time for making changes to a design [30]. Traditionally, designers could only consider a limited number of design alternatives simultaneously [31]. For parametric design, once the designer has defined the parameters and the relationships among them, it is possible to generate design alternatives in parallel. As the evaluation and performance components can be better integrated into the whole design process, it is possible to understand how the design will perform even during early design stage. The performances, or even the cost of the design can also be controlled as early as possible [32]. The integration of evaluation and performance in the design process also helps to enhance design optimization. For example, the structure of a roof truss system can be optimized with the aid of parametric design tools [15].

2.2 Parametric urbanism

In recent years, efforts have been put into exploring parametric design in the fields of architecture (e.g. [24], [33]) and urban design (e.g. [3], [34]). In fact, the notion of parametric urbanism can be referred to the work of Christopher Alexander. The idea of decomposing a design problem as subsystems and link variables was described in his book “Notes on the Synthesis of Form” [35]. This idea can actually be understood as the notion of parametric design. Later in his another book “A Pattern Language” [36], generative design patterns for creating classical and practical urban forms were defined. These design patterns can be and should be regarded as the parameters for parametric urbanism. However, these patterns were applied manually in the design process in the past while computers will be utilized when formulating a parametric design model nowadays. Meanwhile, various approaches of developing parametric urban design models were also suggested in order to formalize the theory of parametric urban design.

2.2.1 Why parametric urbanism

In his book “Masterplanning the Adaptive City: Computational Urbanism in the Twenty-First Century”, Verebes [37] argued that “*Urbanism has always been parametric, in that the city is comprised of complex associations and interactions of diverse and numerous agendas, systems* *and forces.*" Following this statement, it will be natural to lead to the application of parametric design in the field of urban design. It has also been suggested that all designs are parametric in a sense that designers are searching for design solutions based on parameters inherently [33]. In the realm of architecture and urban design, examples of these parameters include but not limited to legal aspects and environmental aspects such as solar radiation and wind [30], [38], [39]. As a matter of fact, there have always been critics that current urban design practices do not consider the notions of "time" and "processes". Urban design solutions are always "a fixed blueprint based on a snapshot of a situation" and this "snapshot" is usually pre-defined by the designer [8]. Consequently, it will be desirable if different "snapshots" can be considered. With parametric urban design models, parameters can be manipulated so as to reflect different possibilities of initial conditions. Hence, more dynamic designs can be generated [8]. Meanwhile, parametric design benefits the early stages of designs as initial design can be updated by means of adding new components or parameters. Modeling can even be started in the conceptual design phase [16]. Besides, it was suggested that parametric urban design tools could help to promote stakeholder participation in a more detailed and less time consuming way [9]. This means that a parametric urban design model can both generate design solutions and be used as a communication tool for various stakeholders. Steinø and Obeling [9] also concluded a number of advantages when utilizing parametric urban design models, they included:

- Capacity to quickly generate large number of generic designs
- Capacity to add detailing in the early stages of design with little effort
- Maintaining the model's "intelligence" throughout the different stages of design
- Facilitating easy testing by changing parameter settings

In summary, with parametric urban design models, designers can generate and explore design solutions in a way that can hardly be done by using traditional design approaches. However, designers will have to formulate the design model instead of drawing and interact with sketches when they begin the design process.

2.2.2 Parametric urban design models

Regardless of traditional design or digital design approach, a design task can be divided into three components (Figure 2.3). They are namely input, design synthesis and output. In the realm of urban design, the input can be various site, morphological, economic, social conditions and so on. Design synthesis is the process of generating the design. The output is usually the object generated. In most cases, the object will be presented in the form of drawings or physical models.

Figure 2.3 Basic components of a design task

During the design synthesis process, designers usually manipulate the input by their sense of style and experience when traditional paper-based design is in concern. The input will be processed implicitly by designers. However, the situation is different when designers treat computers as a partner to generate design. As Oxman puts - "*Information has become a new material for the designer*" [25]. This idea implies that input of design will no longer be implicitly manipulated. Instead, input can be manipulated explicitly with the help of computers and scripts. Meanwhile, information can also be the output of a design task when computers are utilized to generate designs [40]. The output of an urban design task does not have to be confined to an object as in the case of traditional design. Both information and objects can be regarded as design solutions.

On the other hand, the general rules of parametric urban design within the design synthesis process have been discussed by Schumacher. It was suggested that parametricism is "*a new style rather than merely a new set of techniques*" [41]. To this end, five agendas related to the design agent of parametricism were introduced:

1 Parametric interarticulation of subsystems

The goal is to move from single system differentiation to the scripted association of multiple subsystems. The differentiation in any one system is correlated with differentiations in the other system.

2 Parametric accentuation

The goal is to enhance the overall sense of organic integration by means of correlations that favour deviation amplification rather than compensatory adaptation.

2 Parametric figuration

Complex configurations in which multiple readings are latent can be constructed as a parametric model with extremely figuration-sensitive variables. Quantitative modification of parameters triggers qualitative shifts in the perceived configuration. Beyond object parameters, ambient parameters and observer parameters have to be integrated into the parametric system.

4 Parametric responsiveness

Urban and architectural environments possess an inbuilt kinetic capacity that allows those environments to reconfigure and adapt in response to prevalent occupation patterns. The real-time registration of use patterns drives the real-time kinetic adaptation. The built environment thus acquires responsive agency at different timescales.

5 Parametric urbanism

The goal is deep relationality, the total integration of the evolving built environment, from urban distribution to architectural morphology, detailed tectonic articulation and interior organization. Thus parametric urbanism might apply parametric accentuation, parametric figuration and parametric responsiveness as tools to achieve deep relationality.

In short, when performing urban design task with parametric models, the design agent should manipulate the input in a way that all the subsystems should be correlated with and accentuate each other. Besides, the parameters should not be confined to geometric ones. The real-time use patterns in urban environment can also be considered.

In terms of urban forms, the negative and positive heuristics were also suggested by Schumacher:

> ***Negative heuristics:*** *avoid rigid geometric primitives such as squares, triangles and circles; avoid simple repetition of elements, avoid juxtaposition of unrelated elements or systems.*
>
> ***Positive heuristics:*** *consider all forms to be parametrically malleable; differentiate gradually (at varying rates), inflect and correlate systematically.*

Although Schumacher claimed that his exploration in parametric urban design with Zaha Hadid Architects aimed at construct the logic between mutually correlated urban systems, there were critics that design solutions from them were mainly driven by the form and an aesthetic agenda instead of firm data or targets [42]. The "negative heuristics" suggested were primarily related to form and geometry. Meanwhile, it has also been argued that geometric form and style may not be a vital aspect of urban design [11]. Instead of generating design primarily driven by geometric form and aesthetics, it will be of paramount importance to develop a parametric urban design strategy that can help to bring urban space to life [43]. Despite the critics, the five agendas set by Schumacher should help to lay out a framework to develop a holistic parametric urban design model.

The challenge of parametric urban design is mainly on how the complex and ever-changing dynamics of urban conditions could be coded and parametrized. As commented by Christopher Alexander, "*the effort to state a problem in such a way that a computer can be used to solve it will distort your view of the problem. It will allow you to consider only those aspects of the problem which can be encoded and in many cases these are the most trivial and the least relevant aspects*" [44]. Although the power of computers and the ways to quantify and encode have become more advanced 50 years after the comments put by Alexander, defining the parameters and relationship among them should still be the most important task when developing a parametric urban design model. It is also important that the design output from the parametric urban design model can inform designers both visual lay-out of the design and associated analytical data [8]. Figure 2.4 shows a conceptual diagram on how a parametric urban design model usually work. Basically, it is a loop of "forward" searching for the most desirable design solution. In the first step, the values of the parameters will be defined. The next step is to construct the rules and relationship among the parameters. In the third step, a design option will be generated. The option will be analyzed to check if it meets the required performance levels. It will go back to the first step again if it does not meet the desired performance levels. The loop will end when a solution which meets the required performance levels is found.

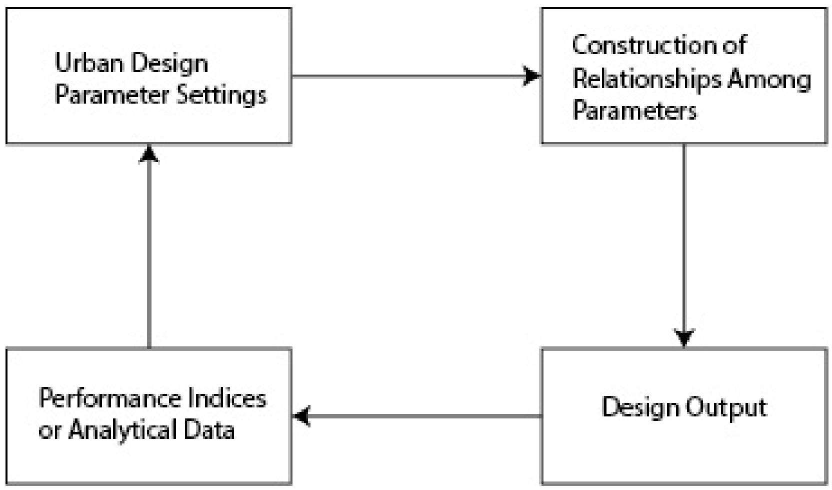


Figure 2.4 Conceptual diagram on the workflow of parametric urban design model

2.2.3 Parametric Urban Design Approaches

There are three main approaches for parametric urban design models. They are namely associative geometry, shape grammar and performative approaches. On the other hand, the input to a parametric design model can be geometric or non-geometric, or a combination of both [23]. Depending on the approach, the inputs are usually either geometric or a combination of geometric and non-geometric in the field of urban design. Usually, the input will only be geometric when associative geometry and shape grammar approaches are adapted. On the other hand, the input will be both geometric and non-geometric when performative approach is in concern. Table 2.2 summarizes the relationship between various parametric urban design model approaches and the model input.

As a matter of fact, the non-geometric input of performative approach is usually the desired performances of the design solution. More details about this will be discussed in a later section.

Table 2.2 Relationship between Parametric Urban Design Approaches and Model Input

Model Input	Model Approaches
Geometric	Associative Geometry Approach
	Shape Grammar Approach
Combination of Geometric and non-Geometric	Performative Approach

Associative Geometry Approach

Although Burry equated parametric design to associative geometry in his early literature [45], it should be considered an approach under the umbrella of parametric design. Associative geometry, or associative urbanism approach is an approach to generate designs by considering the geometric forms and the relationships within them. In the field of urban design, it is about the relationship, or associations of the forms of the elements in a site. For example, the curvature of a river in a site will affect the sizes and locations of the blocks near it. If the curvature of the river changes, the sizes and locations of these blocks may also change. When applying this approach, relationships within the geometric forms have to be explicitly described (mathematically).

This approach has been adapted in various studies. For example, in a study concerning the design of Ezbet El Matar, Egypt, generator nodes (Alexandria Agriculture Road, Airport Lake, formal housing units and El Nozha Airport) were defined and used as main drivers to generate geometric variations within the site. Combining with Voronoi tessellations as a dynamic grid system, designs of the site were generated [46]. Associative urbanism approach was also experimented in the Architectural Association's Design Research Laboratory (DRL). DRL Egloo team used an algorithm which simulated growth in natural forms for a project of mixed-use housing zone in Shanghai, China. Space Syntax measures were adapted to analyze the performance of the design proposal [34].

By considering the geometric relationships of various elements in cities, it is possible to generate promising design solutions with associative geometry approach. However, one drawback is that the design solutions cannot be evaluated within the approach itself. Although the proposal of the DRL Egloo team was coupled with the measures of Space Syntax, the use of Space Syntax was an evaluation procedure after the design was generated by the parametric model. Design evaluation was not an integrated part of the approach.

Shape Grammar Approach

Introduced by Stiny and Gips, shape grammar is a method of shape generation by applying specific transformational rules to shapes [47]. It is well known that shape grammars can be adapted to create designs [48]–[51]. Attempts have also been made to generate urban design solutions with shape grammars (e.g. [52]).

To this end, there were studies devoted to adapting shape grammar in parametric urban design models. An example was City Induction [53]. It aimed at developing an urban design tool which can formulate, generate and evaluate urban design solutions. In this project, shape grammars are one of the "starting points" to develop the tool to generate design solutions.

In fact, shape grammar approach shares the same drawback as associative geometry approach. The approach itself cannot be used to evaluate the design generated. This explains why there was a separated evaluation module in the City Induction project.

Performative Approach

Traditionally, design evaluation is a step after the design solutions are generated. This is a "generate and test" approach. This is also the case for a more conventional parametric design model (See Figure 2.4). For the performative approach, the evaluation process will be integrated into the design generation process. The performance of the design will become a force to drive the design solutions. To this end, the desired performance can directly generate or modify the design [1] in a parametric model. Figure 2.5 illustrate the basic difference between treating evaluation as a step after the design is generated (Figure 2.5a) and performative approach. In fact, there can be two different scenarios for performative approach. The first one is that only performances are considered input to the model (Figure 2.5b). However, it may not be totally practical as designers may still want to control some of the parameters of the design. As a result, both the performances and parameters will be treated as input in the second scenario, which is more practical in most cases (Figure 2.5c).

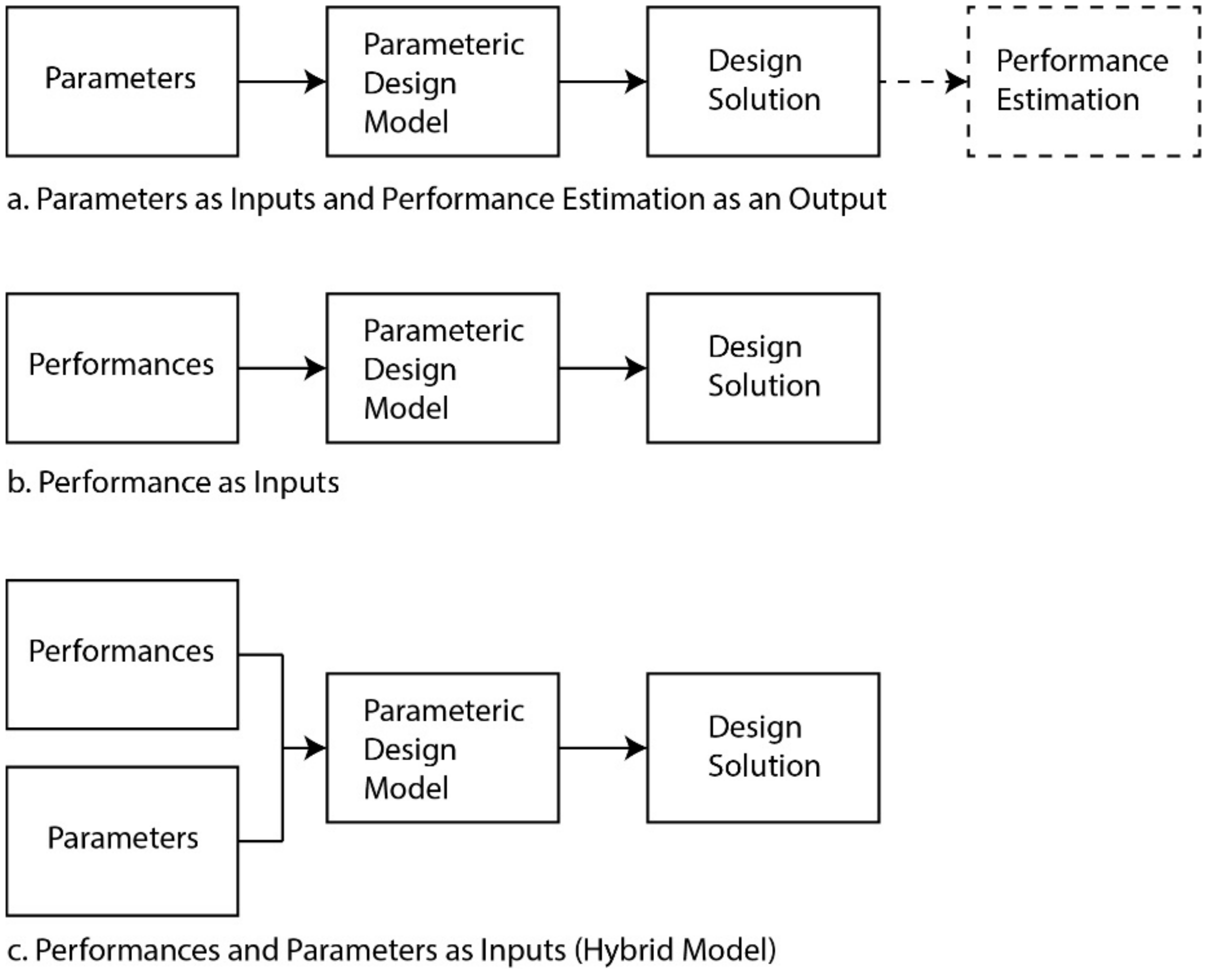


Figure 2.5 Concept of a Parametric Model with Performances as Inputs

The notion of performative approach is usually connected to the environmental quality of the urban area in concern. In a study in Borg El Arab, Egypt [54], the idea of solar envelopes were included and generated in the parametric model in order to assure the solar access of individuals in the urban spaces. The solar envelopes were then adapted as a regulation rule to generate the volumes of the buildings. By using this method, building volumes could be maximized while solar access was assured.

While performance of the design can become the force to drive the design solutions with performative approach, the idea of performative design was usually connected with the notion of evolutionary approach (which will be discussed in the next section) [1], [55], [56]. Different strategies of developing parametric urban design model by using performative approach have not been fully explored.

2.2.4 Evolutionary Approach of Digital Design

As stated in the book "An Evolutionary Architecture" by Frazer [57], the notion of evolutionary method is a process of form-generation "*paralleling a wider scientific search for a theory of morphogenesis in the natural world*". When applying evolutionary method, series of generations of design solutions will be created. Mutation rules will be applied to them so that the current generation will evolve into the next generation of design solutions. This process continues until the final design is obtained.

There are mixed opinions on whether evolutionary approach is an approach of parametric design. While some authors suggested that it should be one of the approaches of parametric design [46], [54], there are also authors who argued that this approach is different from parametric design [58], [59]. Usually, the relationships among the objects within the design solutions are consistent for parametric modelling. On the contrary, these relationships are not predefined but instead negotiated during the design process when evolution approach is adapted. Although it is possible to couple parametric models with the idea of evolutionary approach [55], this approach was considered different from parametric design in the current study because of the differences mentioned above.

Evolutionary approach has also been applied in studies related to urban design. Roche et al. [60] considered an urban system a biostructure. The system is "*a result of an ongoing movement*" and "*in a constant state of evolution*". Based on growth scripts and open algorithms, an idea of urban experiment about an unpredictable organic urbanism was laid out.

Although the evaluation of the design solutions is not necessarily included when adapting evolutionary approach, some types of fitness equations will usually be used to guide the evolution from one generation to another. This can be understood as evaluating the design solutions of each generation. As a result, design solutions with desired performance can be obtained from this approach.

2.2.5 Inverse Simulation Method

Conventionally, performance simulation is a "forward" procedure. The design is generated and then the performance will be simulated. A major drawback of this procedure is that designers have to determine the design before simulation can be performed. Quantified performances cannot be obtained before a design is generated. On the contrary, inverse simulation can be considered the reverse of this "forward" procedure. By interpolating pre-computed simulation results, design concept alternatives can be found with given performance goals. Designers will be able to consider the quantified performance goals even at early stage of the design process [2].

The idea of inverse simulation method has been adapted in a few studies concerning architectural design. By considering the natural lighting effects in the building, this method was utilized to generate the perforation design of the dome of the Louvre Abu Dhabi Museum [61]. In this real case study, Jean Nouvel, the architect who designed the museum, specified the desired lighting effects (intentions) rendered by natural light under the dome. A lighting intention map was created with respect to the lighting effects specified by the architect in the next step. With this map, the perforation of the dome was computed by a prototype called EEL (Espace En Lumière) earlier developed by Tourre [62]. In another recent study, it was shown that specifications of the building envelope design could be found by specifying the target thermal load of the building [2]. In order to reveal the inverse relationship between thermal load of building envelope specifications, scenarios of building envelope designs were generated and the relationship was examined by using regression technique. By utilizing the developed relationship, the required building envelope specifications such as U-value of windows and window-to-wall ratio could be identified by a given target thermal load of the building.

On the contrary, not much effort has been put to adapt inverse simulation for urban design tasks, although there have been studies on investigating inverse simulation of sunlight and shadow in urban spaces [63]. Moreover, there has been virtually no attempt to combine the idea of parametric urban design with inverse simulation. Although there have been investigations on urban procedural model with inverse simulation [64], this study primarily focused on computer graphic and optimization in terms of computing and generating the 3D model. In fact, combining the idea of inverse simulation with parametric design will help designers explore design alternatives by considering quantified objective goals. This should also be considered another strategy for performative approach of parametric design. Consequently, it will be of interest in the current study to examine the combination of these two aspects from the design perspective.

2.2.6 Approaches to Search for Design Solutions with Desired Performances

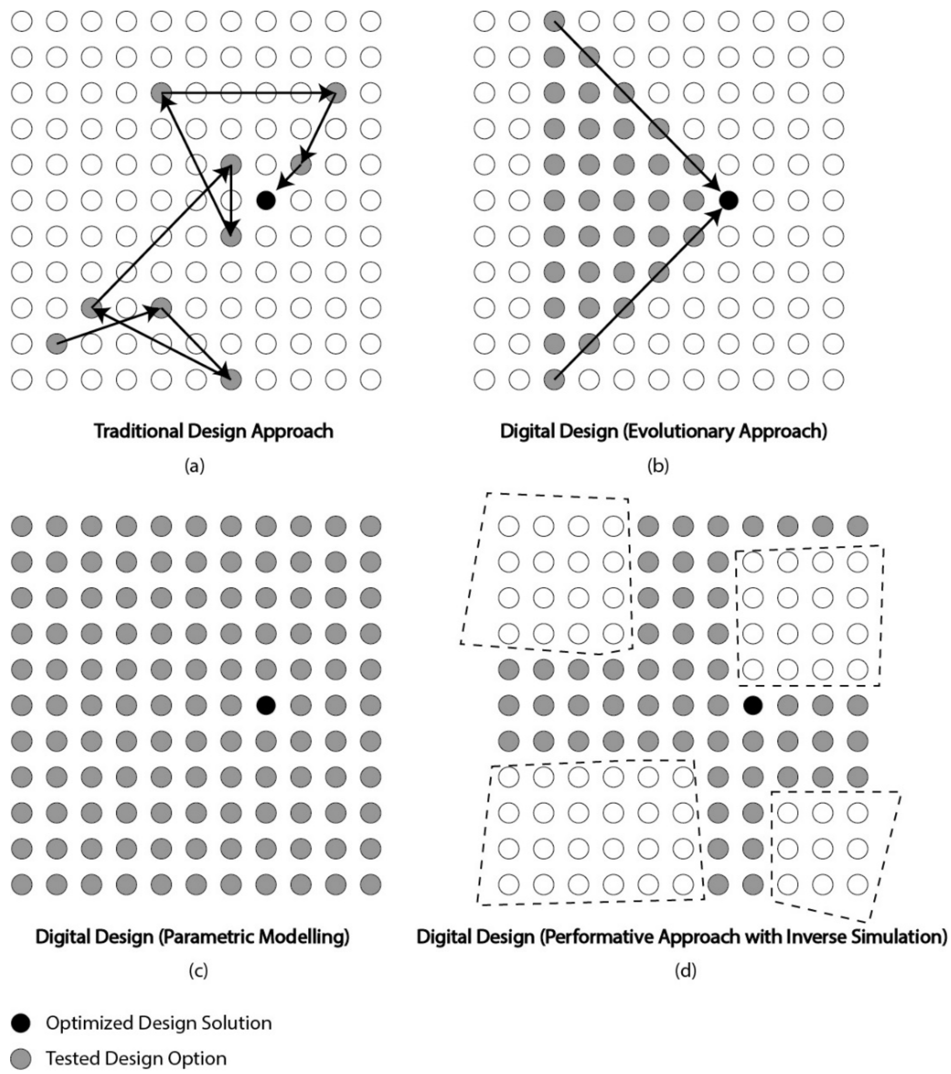
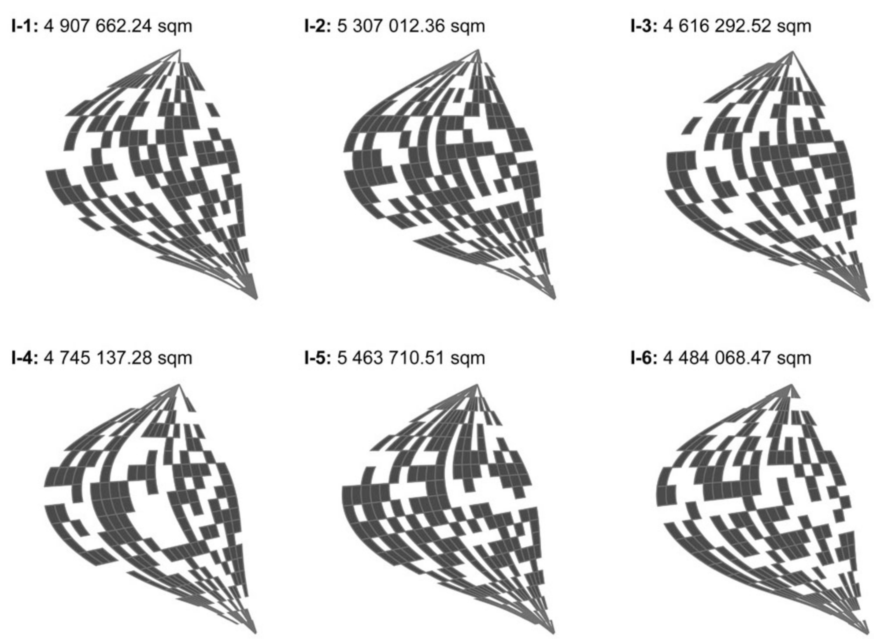


Figure 2.6 Different design approaches to reach design solution with desired performances

Figure 2.6 shows how different design approaches search for the design solution with the desired performance in the solution space. Traditional, designers interact with their sketches and drawings. They will inspect the design and create new sketches and drawings so as to improve the design. In this case, designers jump from one solution to another in the solution space and finally attain the design solution with desired performance (Figure 2.6a).

The situation will be different when digital design approaches are adapted. The two main approaches under the umbrella of digital design are evolutionary approach and parametric modelling. With genetic algorithm of evolutionary approach, various generations of design solutions will be tested against the desired performances. The solutions with performances closer to the desired ones will stay. Some of the attributes of these solutions will be mutated and the next "generations" of solutions will be formed and tested. This cycle continues until the design solution with desired performances is reached (Figure 2.6b). Evolutionary approach has been adapted to optimize the green area distribution in cities [65]. In this study, both the notion of parametric urban design and evolutionary approach were adapted. The masterplan was generated by using associative geometric rules. By using genetic algorithm, distribution of the green areas was generated with an aim to minimize built area and maximize green area (Figure 2.7). While a design solution with desired performances can be found by using evolution approach or genetic algorithm, only one optimized solution will be generated. Usually, only one or two types of performances will be included when using this approach, generating one solution only makes it less flexible when other types of performances have to be considered as there will only be one design solution to be tested against these performances. Unless there is a fixed performance goal which must be fulfilled, utilizing evolutionary approach or genetic algorithm for early design stage will be less appropriate because generating a number of conceptual design solutions is usually needed at this stage.



**I-1 to I-6: Iteration Number; Areas of built parcels are shown in the figure*

Figure 2.7 Genetic Iterations to Minimize Built Areas (and Maximize Green Areas) [65]

When it comes to parametric modeling, a number of solutions within the design space can be generated. These solutions will be evaluated and finally the desired solution will be obtained (Figure 2.6c). This idea of searching for the solution with desired performance levels can be illustrated by the City Induction model introduced by Duarte et al. [53]. There are three sub-models under the City Induction model – Formulation, Generation and Evaluation sub-models. The Formulation sub-model adapted the pattern language of Alexander [36] to formulate "*the specifications or the ingredients of a plan given a site and a community*". The Generation sub-model utilized shape grammars as a base to set the rules to generate urban design solutions. Using Space Syntax Theory [66] as the starting point, the Evaluation sub-model adapted various urban indicators to analyze design solutions generated. By using the City Induction model, design solutions could be generated, evaluated and ranked. As a matter of fact, generating plenty of solutions in a relative short period of time is one of the advantages of parametric approach [9]. This can even be done at early stage of design. As the design generation process does not integrate with the evaluation process, design solutions which do not match the required benchmarks may be generated. Although the evaluation process will eventually rule out these solutions, it can be an inefficient option as it is needed to evaluate these solutions to rule them out.

On the other hand, relationship between performances and various physical design parameters will be revealed when inverse simulation method is adapted into the performative approach of a parametric design model. The results from the pre-process procedure will help to generate filters to filter out some of the solutions in the solution space (Figure 2.6d). Solutions which are not filtered can be generated and evaluated so as to reach the desired design solution. The problems with the two former approaches can be addressed with this approach. First, more than one solution can be generated. This can serve the purpose of generating a number of conceptual design options at the early design stage. Second, solutions which do not fulfil the preset benchmarks can be filtered out from the solution space. Assuming that there are other performances which are not included in the model, which will be a highly probable case, designer will have to further inspect the design options generated by the parametric model. As design solutions which do not match the preset benchmarks have been filtered, the designer does not have to spend the time on evaluating and discarding the design solutions which do not fulfil the pre-defined requirements.

2.2.7 Previous Efforts on Parametric Urbanism

In recent years, both practitioners and researchers have actively engaged in parametric urbanism. To this end, the works from Patrik Schumacher, principal of Zaha Hadid Architects are probably the most well-known and architecture office MVRDV. With the idea of parametricism, Patrik Schumacher has engaged in various award winning master planning projects such as Kartal-Pendik Masterplan in Istanbul (Figure 2.8), Turkey and One North Masterplan in Singapore [41]. In MVRDV, the "Function-mixer" in the form of software application was created. By different settings of program parameters, various programs or uses in 3D space would be mixed by the urban design scheme. Besides, both building typology and program were defined parametrically in the competition entry for the Myllypuro Dynamic Masterplan by Haff-Jensen [16] (Figure 2.9).

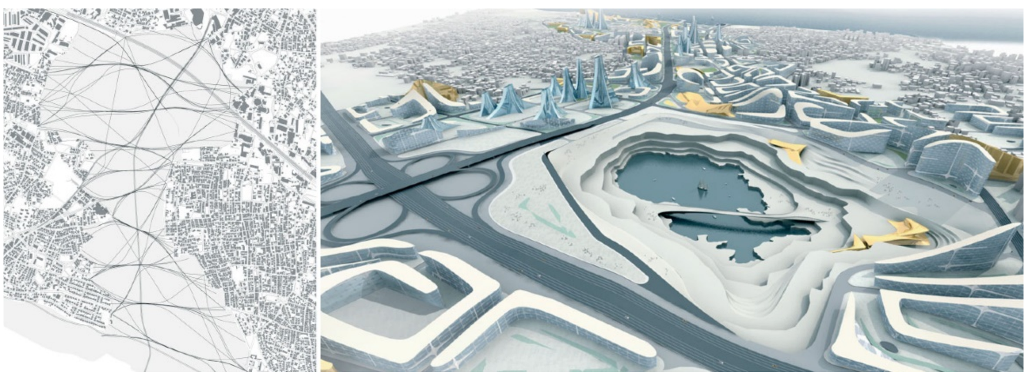


Figure 2.8 Kartal-Pendik masterplan in Istanbul [41]

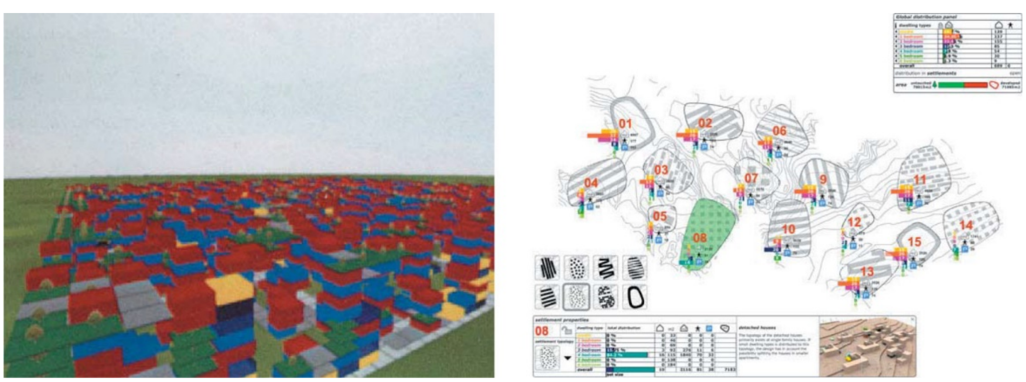


Figure 2.9 Function-mixer (left) and Myllypuro Dynamic Masterplan by Haff-Jensen (right) [16]

For academe, Koltsova et al. [3] demonstrated the possibility of applying parametric model for large scale urban planning. By adapting elements around the site, namely 1950's socialist housing, the new urban Moscow City and the Moscow river, as influencers, the master plan in a 253-hectare industrial site in Moscow was generated (Figure 2.10). On the other hand, Schnabel et al. [67] proposed that parametric modelling could be adapted to support the generation of "Form-based Code", which is considered urban design code emphasizing form instead of land-use, as a place-making approach in the urban design process of cities with high density such as Hong Kong. In smaller urban scales, a series of parametric design tools which supports urban design tasks at pedestrian scale in early design stage was developed by Koltsova et al. [4]. The tools developed in this study could be used in sequence. The first one was used to divide the lots and parcels in the site (Figure 2.11a). The next tool helped to decide the location of an open space in the site by considering major functions in the site and the shortest paths from these functions to the open space (Figure 2.11b). After this step, another tool would be applied to alter the building envelopes by considering various pre-defined view points in the site. The volumes of buildings would be cut based on positions of the view points and view angles (Figure 2.11c). The last tool helped analyze the view points and check the intersections of the view sections. This would help to define the location of landmarks in the site.

Figure 2.10 Master plan iteration by using parametric urban design model [3]

Efforts have also been put to investigate the algorithm of parametric urban design models. In a study by Beirão and Duarte [5], urban design students were asked to utilize the patterns developed by Christopher Alexander [36] and the shape grammar introduced by G. Stiny [68] to create urban design solutions. It was concluded that the approach of coding the pattern developed by Alexander could help to deal with complex urban design problem while leaving room for design creativity. Steinø [7] attempted to utilize an associative geometry approach in a parametric model to organize urban blocks (Figure 2.12). As an experiment, only simple geometrical operations such as rotation and reflection were adapted to demonstrate the possibility and feasibility of parametric urban design. While adapting the idea of pattern languages in the study by Beirão and Duarte [5] might help to improve the performances of the designs, the common shortcoming of these studies is that only geometry forms of the urban design solution were considered. On the other hand, Schneider et al. [6] developed an algorithm to organize street network in a parametric urban design model. When generating the street network, factors such as the shortest distances between major urban functions and the building density of different functions were considered in this study. However, the performances of the design solutions generated were not included in the model.

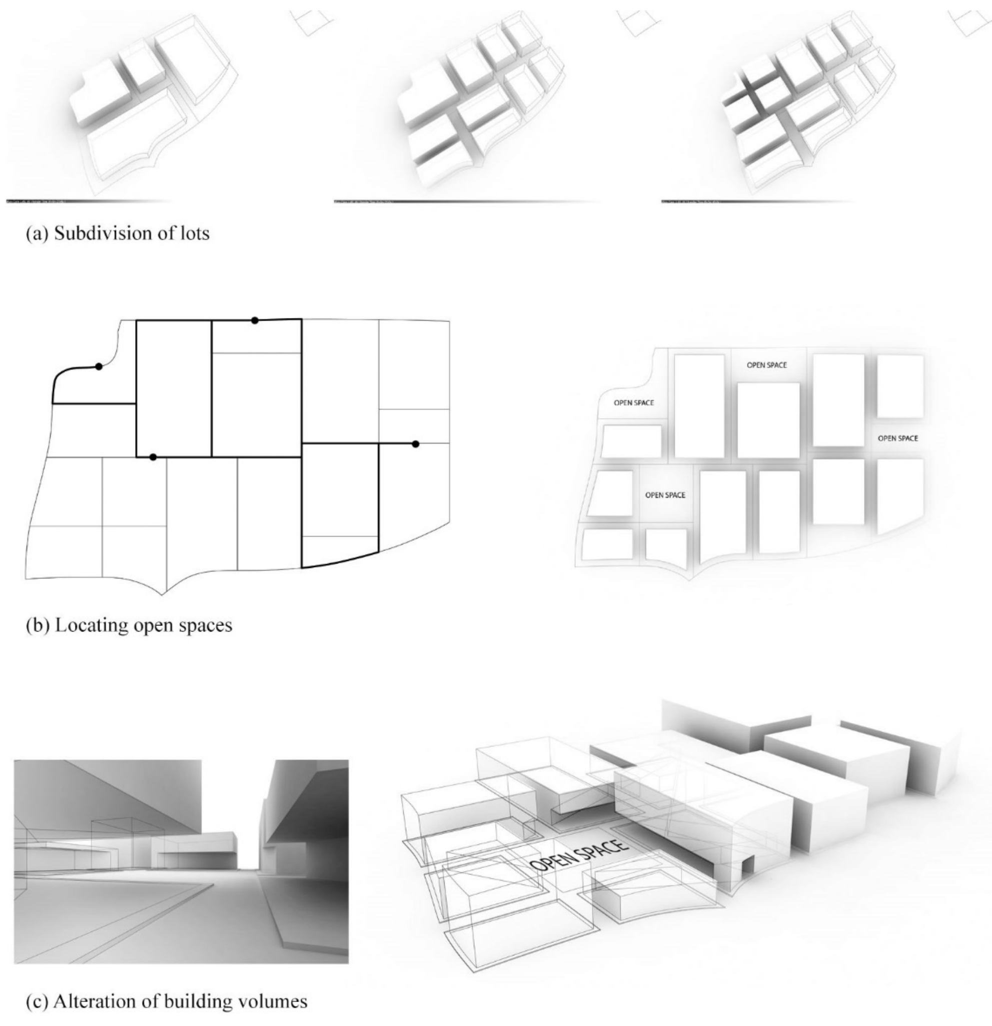


Figure 2.11 Parametric design tools supporting urban design tasks at pedestrian scale [4]

Figure 2.12 Generation of designs of plots by applying various geometrical transformations of identical buildings in a parametric design model [7]

When performing urban design task, it is always important to understand the current urban conditions of the site. To this end, it should be important to consider various urban and site conditions when utilizing parametric urban design models. To better integrate urban data with parametric urban design, researchers also revealed the possibility of combining GIS tools with parametric models. Methodology to generate initial mass and density in master plan by combining parametric model and GIS tools was explored by Pitts and Luther [69]. Because the main purpose of the study was to test the methodology, GIS data was imported to the parametric tools manually. It was suggested in the study that automated process of reading the data by parametric tools should be utilized and explored. In another study, Tang and Anderson [70] made use of GIS data such as demographical, social and spatial data as input data to control urban morphological parameters. As GIS data was integrated into the parametric model, environmental input could be used to generate morphological output from the model. The authors coined this integration of GIS data and parametric urban design "Information Urbanism". By extracting the features of existing urban fabric, Duarte et al. [71] identified "grammar" for a parametric system for urban solutions in Morocco. Here, urban data was analyzed and translated into the grammars for design generation of the parametric model. Although it is suggested from these studies that urban data can be integrated into parametric urban design models, how the output (the design solutions) would perform was not discussed in these studies.

Meanwhile, a design model will only be comprehensive if it can inform the designer about the performances of the design solutions. It has been suggested that a parametric urban design models should be able to generate both visual outputs and performance indicators associated [8]. Studies have been conducted to investigate parametric design models which could generate urban indicators as model output. To this end, Beirão et al. [72] described a structure to integrate spatial data from GIS tools and parametric model to aid urban design process. Within this structure, urban data would be stored in a database. The parametric tool (Grasshopper in this particular study) read the data including the shape files of the existing site construction, thoroughfares and site boundary. A parametric model was developed with these initial conditions. The output of the model developed included graphical representation of the design, as well as urban indicators such as building footprint, gross floor area (GFA), open space ratio (OSR) and floor space index (FSI). Another study by Canuto and Amorim [43] adapted the idea of "Measure of Urbanity" from Holanda [73] and attempted to reveal the degree of urbanity of the design generated by parametric model. In this study, urban block placement scenarios were generated in hypothetical sites and urbanity measures such as number of spatial islands and mean convex space developed by Holanda [73] were used to analyze these design scenarios. Besides, there have also been attempts to develop parametric models which can optimize the environmental performances of the design. A parametric urban comfort envelope was developed in order to optimize thermal comfort of urban spaces [54]. Parametric model was used to generate an urban design option and natural ventilation within the site was in turn evaluated. Optimized solar envelope was then generated and the solar envelope was translated into building volumes so that optimized solar access could be obtained in the urban spaces (Figure 2.13). In another study, a workflow of parametric modelling to optimize the solar potential of cities was developed [74]. By combining Ecotect, an environmental analysis tool developed by Autodesk, and Grasshopper, the photovoltaic (PV) solar electricity potential of installing PV panels on building roof tops was revealed (Figure 2.14). In these studies, the urban indicators or performance values of the designs were essentially the output of the models, which means that the design solutions were only evaluated after the design has been generated by the parametric model. Performances were not an integrated part of the design synthesis process.

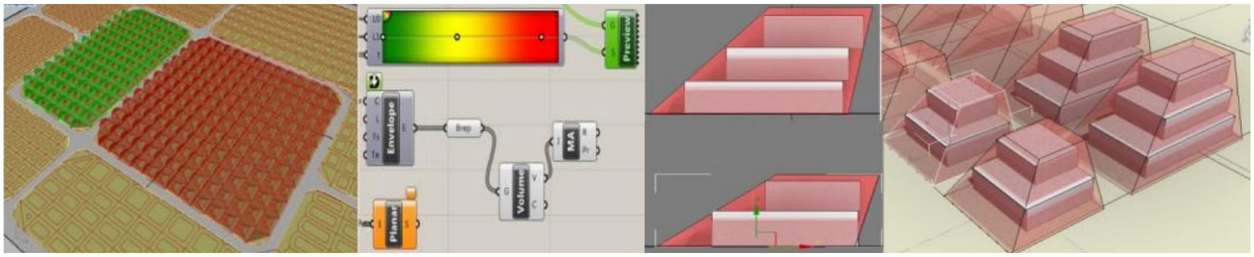
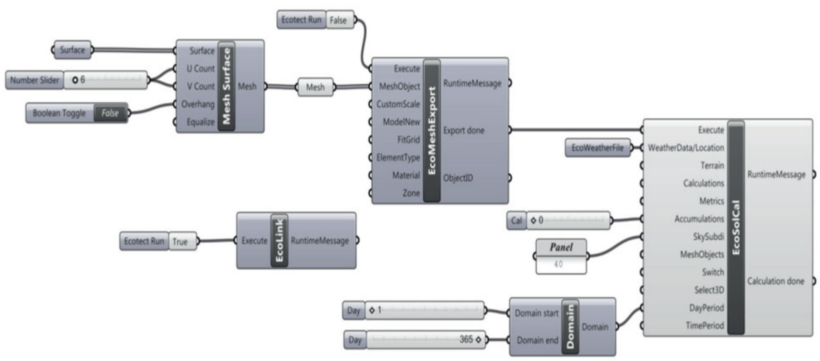
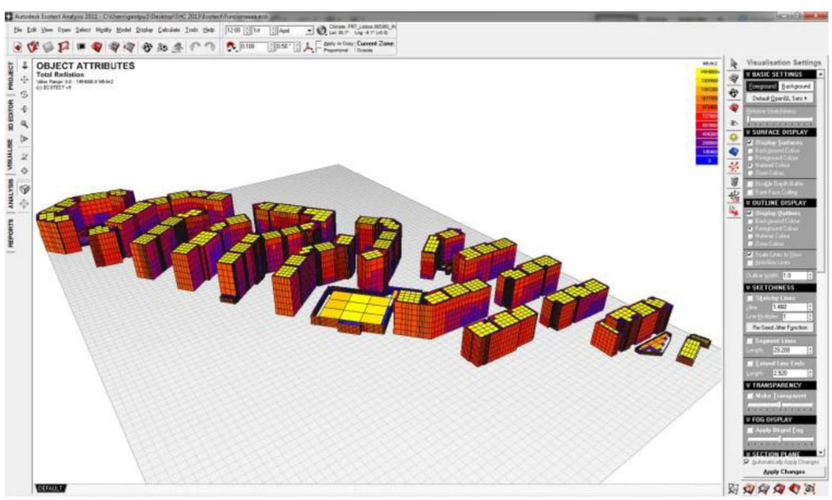


Figure 2.13 Parametric model to generate solar envelope and create building forms by using the solar envelope [54]



(a) Solar Analysis Generative Algorithm



(b) Solar Urban Model (by considering PV installation on rooftops)

Figure 2.14 Revealing solar potential of installing PV panels on building roof within the urban scale [74]

On the other hand, Yazici [65] investigated the methodology for parametric models to optimize the distribution of green spaces within cities. As mentioned in a previous section, although performance of the design was integrated in the parametric design process, this study utilized the notion of evolutionary approach when attempting to search for the design solution with the desired performances. To this end, no attempt has been made to combine inverse simulation with parametric design as a strategy of performative approach of parametric design. It will be beneficial to explore and formalize how inverse simulation can be combined with parametric design as another strategy of performative approach.

2.3 Parametric Model Development Tools

2.3.1 Options of Tools for Parametric Model Development

Various tools or software can be adapted when it comes to parametric design in architecture and urban planning. Maya Mel, Grasshopper and CityEngine were widely used in different research and urban design projects. Table 2.3 shows examples of previous studies on parametric urban design which adapted these tools. These tools were also explored in the current study so as to choose the most suitable one for the development of a parametric urban design model which combined inverse simulation and performative approach. The exploration of these tools did not directly relate to the parametric model development framework and experiment to be introduced in the current study. Instead, the user environment and workflow when using the tools were investigated so as to search for the best option for the current study.

Table 2.3 Examples of previous studies adapting various parametric design tool

Parametric Tool	Studies that used the tool
Maya Mel	[70]; [34]; [75]; [41]
Grasshopper	[8]; [4]; [70]; [33]; [24]; [76]; [6]
CityEngine	[9]; [77]; [78]; [79]; [80]; [81]; [82]

Maya Mel

Mel (Maya Embedded Language) is the script language of Maya, a 3D modeling software developed by Autodesk. The user environment is a scripting environment. This means that it is needed to somehow change the script in order to change the value of a parameter in a parametric model developed using MEL. There is no preset workflow when using Maya MEL. The workflow will depend on the intention of the designer and how the script is written. Since MEL is developed for Maya, 2-dimensional and 3-dimensional geometrical operations can be performed with the predefined syntaxes. As a matter of fact, all the graphical user interface (GUI) of Maya was written with MEL [83]. Graphical elements created by using the Maya GUI can be controlled by MEL directly and vice versa. Consequently, it is easy to choose a particular object or element in the design. In order to run the MEL script, it is a must to have the Maya software. Results can be seen directly after the script is run. However, one drawback of this tool is that in order to view the results, the script has to be run again whenever the value of a parameter is changed. Figure 2.15 is the user environment and an example of design explored with Maya Mel.

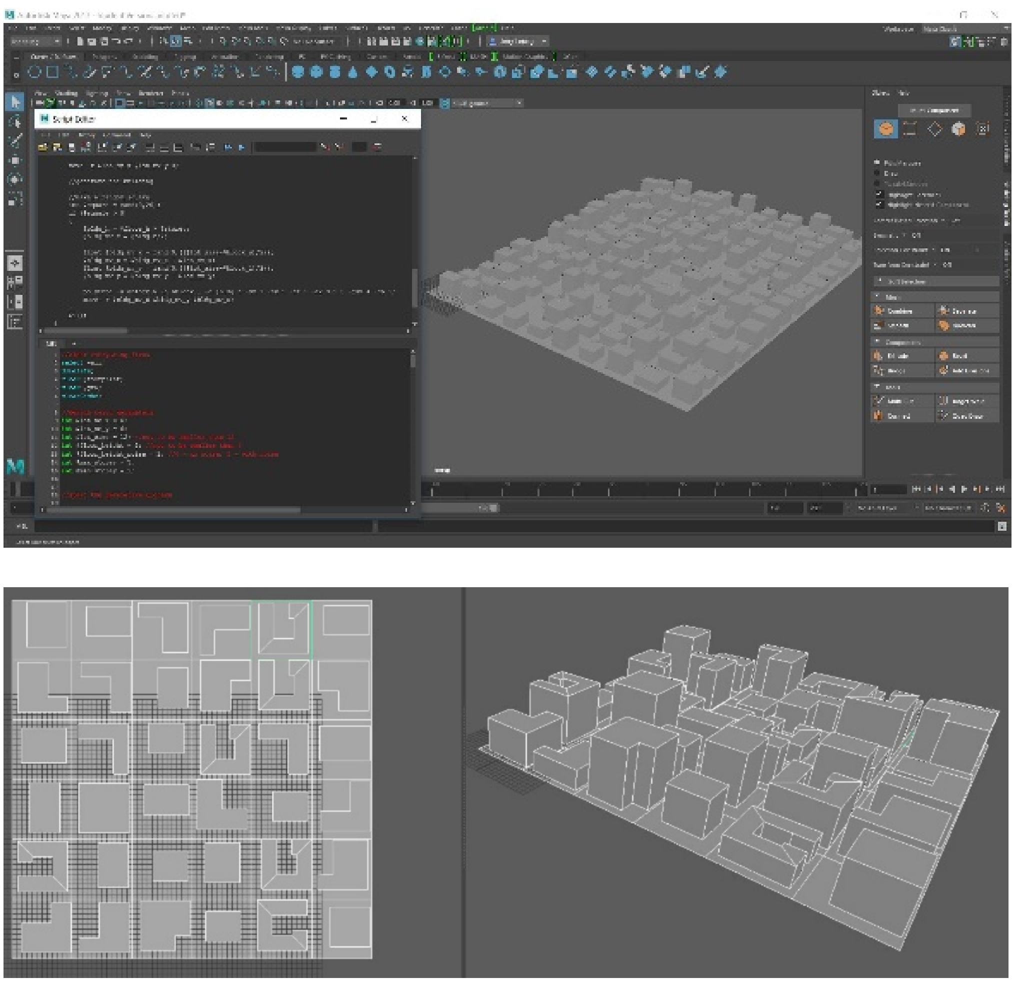


Figure 2.15 User environment and example of design explored with Maya Mel

Grasshopper

Grasshopper is a parametric design plugin in for Rhino 3D by McNeel. One of the most prominent features of Grasshopper is the node-based visualization interface. Instead of a conventional scripting or programming environment like Maya MEL, the user environment of Grasshopper is a visual-scripting environment. This environment was designed specifically for architects and building design professionals to create parametric models. In this user environment, the flow of relations of components is in a format of graph, which is a mathematical term used to describe flowchart [84]. Values of different parameters can be changed by using the pre-defined "number slider" component in this interface. Results can be obtained and visualized in the Rhino 3D viewport immediately after changing the value of a parameter. Because of the node-based visualization interface, it is relatively easy to manipulate the script. As in the case of MEL, there is no specific workflow when working with grasshopper for parametric modelling. Objects created within Rhino 3D can be selected in Grasshopper with a simple "BREP" command. The "BAKE" command can be used to translate objects created in Grasshopper to Rhino 3D. Meanwhile, there are also ready-to-use plug-in's of Grasshopper for performance analysis such as outdoor thermal [85] and acoustic [86] analysis. The software Rhino 3D will be needed in order to work with the model developed in Grasshopper. The node-based visualization interface and sample results from Grasshopper is shown in Figure 2.16.

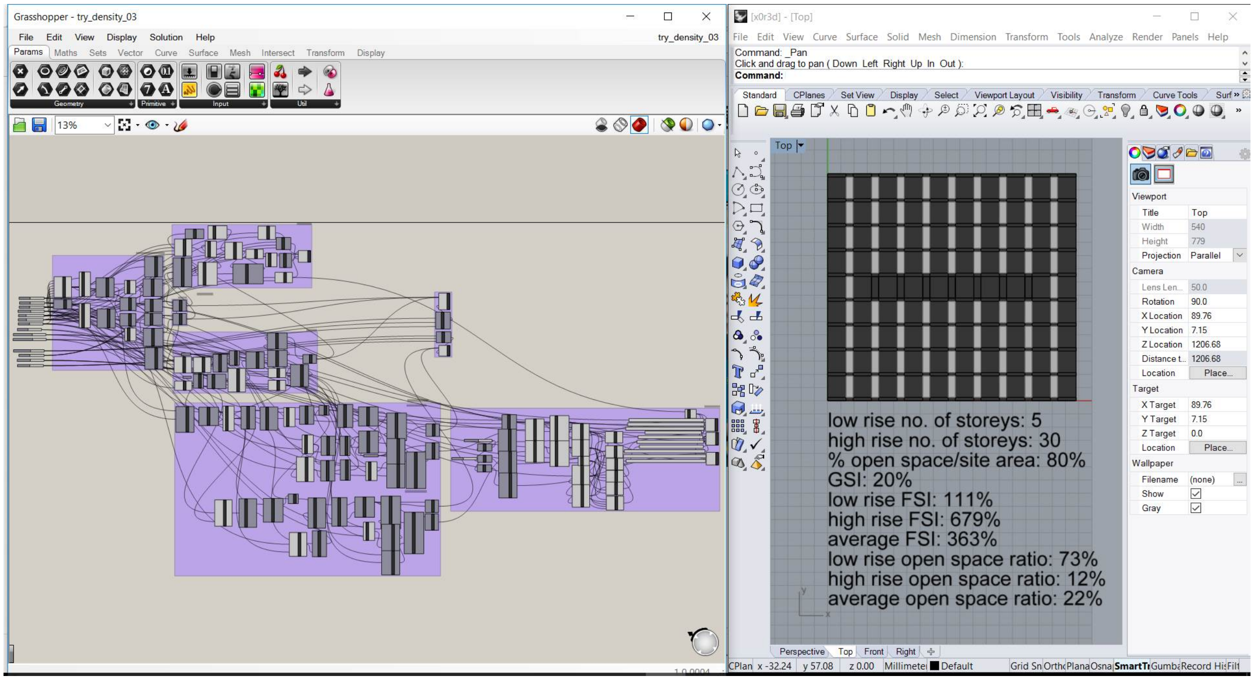


Figure 2.16 Node based visualization interface (left) and sample results (right) from Grasshopper

<u>CityEngine</u>

CityEngine, developed by Esri, is widely used in various urban planning projects. It is a procedural modelling tool based on L-systems [87]. Shape grammar is utilized in CityEngine to perform geometrical operations such as scaling and rotation. This tool has been adapted in the realm of urban design research. Unlike Maya MEL or grasshopper, CityEngine can be operated by using the GUI. Changing the values of parameters can also be done within the GUI. However, there is a pre-set workflow when working with CityEngine. Figure 2.17 shows the workflow of CityEngine [88]. Besides road networks and lots, it is also possible to create detail building façade using the GUI of CityEngine. To this end, the façade design is also parametric. A parametric model of an urban area can be created in CityEngine without any scripting technique. While some of these features make it perfect for urban planning projects, the pre-set workflow can be a drawback for research purpose. The flexibility in terms of workflow may be required in research projects. Moreover, designers will need to have CityEngine installed in the computer so as to work with the parametric urban design model. Sample results of CityEngine is shown in Figure 2.18.

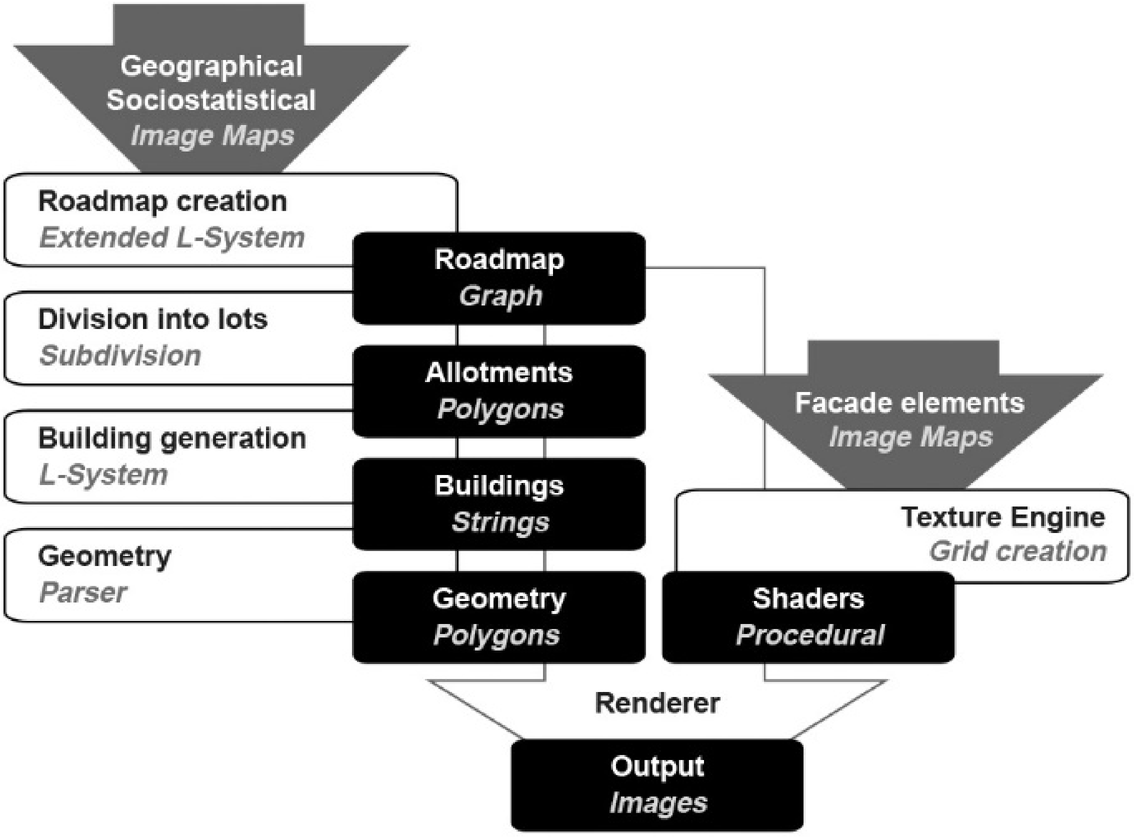


Figure 2.17 Workflow of CityEngine [88]

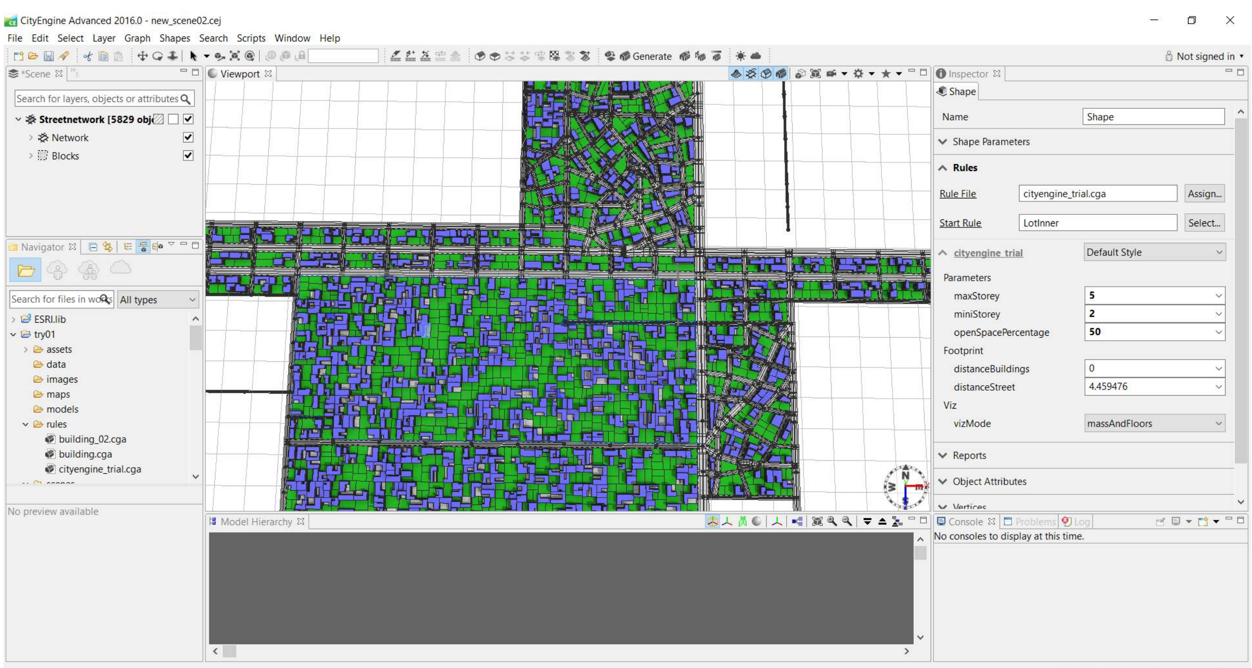


Figure 2.18 Sample results of CityEngine

PHP and Javascript

Besides the most common tools that were usually adapted in studies concerning parametric urban design, it is also possible to create a parametric model with programming languages. In this study, the feasibility of utilizing PHP and Javascript have been investigated. PHP and Javascript are programming languages primarily for website development. The user environment will be a scripting or programming environment. The main advantage of using this PHP and javascript is that the model could be shared online easily. The model could be distributed as a webpage in this case. It is also possible to control the whole workflow of developing the model as the tools and models are going to be built from scratch. After the parametric model is developed, no specific software will be needed in order to work with the model. The designer will only need a web browser when designing with a parametric model developed by using PHP and Javascript. However, these languages are not developed primarily for creating geometries. As a result, some types of addons for geometrical operations will be needed in order to build a parametric urban design model with these languages. Besides, these languages are not developed for intensive calculation. It can render the generation of model extremely slow if intensive calculation is needed. Figure 2.19 shows a parametric urban design model for green open space developed earlier by the author with PHP and Javascript addon framework three.js [89].

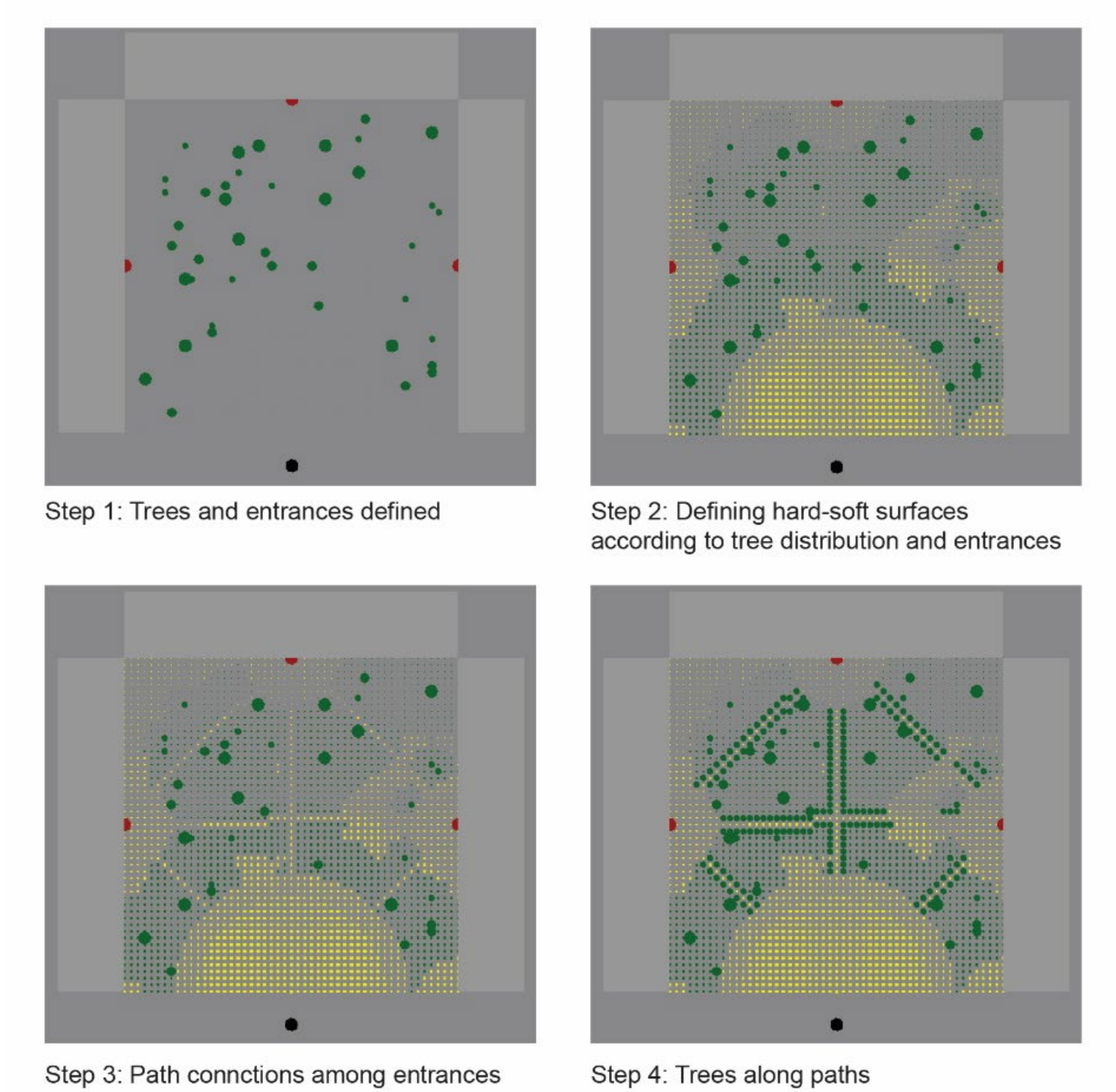


Figure 2.19 Possible parametric urban design model developed by using PHP and Javascript [89]

Table 2.4 shows the comparison of features of the tools tested in the current study.

Table 2.4 Comparison of features of parametric model development tools

Parametric Tool	User Environment	With a Preset Workflow	Specific Software Needed when working with the model	Able to use the model Online
Maya Mel	Scripting Environment	No	Yes; Maya	No
Grasshopper	Visual Scripting Environment	No	Yes; Rhino 3D	No
CityEngine	Graphic User Interface	Yes	Yes; CityEngine	No
PHP with Javascript	Scripting Environment	No	No	Yes

2.3.2 Parametric tool adapted in this study

The primary aim of this study is to investigate the principles of developing a parametric urban design model coupling with performative approach and inverse simulation. To accomplish this goal, there are some criteria to choose the parametric tool adapted. First of all, it has to be flexible in a sense that there is no preset workflow when performing the investigation. Second, obtaining results right after changing the values of parameters immediately is preferable. Third, the time required to generate a design option must not be too long. As mentioned previously, there is a fixed workflow for CityEngine. For Maya Mel, results cannot be obtained immediately after changing a value of parameter. Although using programming languages such as combining PHP and Javascript would be the most flexible option, it may take too much time to generate a design option as relatively intensive calculation might be required when generating the option.

As a result, it has been determined to utilize Grasshopper as the main tool to develop the parametric urban design model. First of all, it can fulfil all the criteria mentioned above. There are also Grasshopper add-ons which can help to simulate and estimate the performances of the design option. Furthermore, the visual interface would make it easier for designers or even laypeople to use the model. Users of the model will need to deal with the script directly if tools such as Maya MEL is used. This could be difficult for some users who are not familiar with a scripting and programming environment.

3 GREEN OPEN SPACES IN CITIES

3.1 On Open Spaces

Within cities, public open spaces can usually be categorized into streets, squares, plazas and parks. They are considered one of the basic elements of urban morphology [90]. Rogers et al. even suggested these essential parts of urban landscape should be understood as "outdoor rooms" in cities [91]. To this end, researches have been devoted to understanding the relationship between open spaces and urban fabric. Wu and Plantinga [92] investigated how locations and sizes of open spaces would affect urban spatial structure. It was found that city might encompass the open space if it was close to the city center. On the contrary, leapfrog development might occur if open space was far from city center. There were also studies which attempted to understand how public open space would affect residential developments. By considering indices such as the ratio of open space area to building footprint in UK in different eras, Hanson and Zako [93] argued that the existences of open spaces, as one of the spatial factors of cities, might correlate to poor liveability and antisocial behavior. It was also found in the same study that the most common open spaces were paths. On the other hand, Sandalack and Uribe [94] suggested that typology of open spaces should be utilized as a framework for design of the public realm.

3.2 Green Open Spaces

According to the EU project "Development of Urban Green Spaces to Improve the Quality of Life in Cities and Urban Regions" (URGE) [95], urban green spaces or green open spaces can be defined as:

> "*public green spaces located in urban areas, mainly covered by vegetation (as opposed to other open spaces) which are directly used for active or passive recreation, or indirectly used by virtue of their positive influence on the urban environment, accessible to citizens, serving the diverse needs of citizens and thus enhancing the quality of life in cities or urban regions*".

To this end, various types of vegetation and natural settings will usually be found in open spaces. Individuals usually have preferences on natural settings in urban areas and a tendency to be in touch with nature. Here, natural settings in urban areas were usually referred to greenery and water body. It has been suggested that greenery and water features were preferred components for green open spaces such as urban parks [96], [97]. Trees were rated to be one of the most desired elements in urban spaces [98]. Individuals were more likely to visit parks with water feature [99].

Indeed, studies suggested that green open spaces could bring multiple benefits to cities and the public. Social, economic and environmental benefits could be brought by these spaces. Socially, green open spaces can be considered urban oasis for people to escape from pollution, traffic and noise in cities [100]. Studies also suggested that the existence of green open spaces can help promote health and well-being of individuals [101]. Level of physical activities, which could help improve individuals' health, was found to be positively correlated to the access of green open spaces [102]. On the contrary, the risk of stroke mortality was found to be higher when the exposure to these open spaces was low [103]. Apart from physical health, green open spaces could also provide restoration effect and help relieve the stress of individuals [104]. It was even suggested that green open spaces could play a role for the education of school students. In a recent study concerning access to green environment in school attendance areas and academic performances, it was revealed that percentage of tree coverage was positively related to the reading performance of primary school students [105].

Besides, there are also economic advantages associated with green open spaces. It was suggested that green open spaces within neighborhood was related to property prices. For instance, it was previously found that prices of houses were positively correlated to the proximity of green open spaces in Spain [106]. Similar results were also found in another study in Netherlands. It was even revealed that property prices increased if there was a view to green open spaces [107].

The environmental benefits brought by green open spaces should also be mentioned. Various studies have confirmed that green open spaces could bring mitigation effects to the problem of urban heat island as they can help to regulate micro-climate [108], [109]. It was also suggested that these spaces could help to mitigate air pollution in cities [110].

Due to the multiple benefits brought by green open spaces, more efforts should be put on different methods and techniques to design these spaces. As a result, the design of green open space was chosen as the subject of experiment of the current study. To this end, a performative parametric model would be formulated by utilizing the model development framework to be developed.

3.3 Performances of Green Open Spaces

The performances of urban spaces have become more important when performing urban design tasks. In fact, urban designers have become more aware of the performances of the designs. There are two different streams of studies when performances of green open spaces are concerned. The first stream mainly refers to the existence of green open spaces in relation to the urban area. For instance, Levent et al. [111] suggested that the level of performances of green open spaces is related to factors such as ratio of green area to total urban area and proportion of green spaces per inhabitant. On the other hand, there were also studies which focused on the benefits of green open spaces as the performances. An example of this stream of study connected performances of green open spaces to five broad categories – responsiveness to actual issues, sustainability, natural environmental benefits, economic benefits and socio-cultural benefits [112]. In the current study, the performances of open spaces would also be about the benefits brought by green open spaces. It was mainly referred to the benefits within the spaces brought by the natural features. In fact, there were also studies which devoted to understanding how natural settings in green open spaces could help improve the performances of the space. Thermal and acoustic performances in green open spaces are constantly investigated by researchers. It was also the interest of the current study to include thermal and acoustic performances in the performative parametric design model for green open spaces. Meanwhile, the spatial structure of the spaces will affect the usage of the spaces. As a result, the current study also aimed at investigating the feasibility of including spatial structure as a performance of green open spaces in the performative parametric design model.

3.3.1 Thermal Performance

In most cases, thermal performance in green open spaces refers to the cooling effect of it in hot summer. Two different aspects of thermal performance were usually considered in studies. They were the ability to cool the open spaces themselves [113], [114] and the surrounding spaces (e.g. streets and roads) [115]–[117]. As the focus of the experiment in the current study was mainly on benefits within the green open space and the internal design of the space, only the ability to cool the spaces themselves would be considered.

Both morphological attributes such as sizes, shapes and spatial patterns of green open spaces [114], [116], [118] and natural features of the spaces can affect the thermal performance. When natural features in open spaces are concerned, thermal performance of green open spaces is largely related to tree planting. It was found that the mitigation effect on urban heat island was brought by urban tree planting [119]. The cooling effect in green open spaces was also found to be related to the trees in these spaces. It was suggested that tree shading was an important factor affecting the quality of open spaces [120]. Shadows casted by trees could help to reduce direct solar radiation and thus help to cool the open spaces [121]. Air temperature of green open spaces could be reduced by the planting of trees [122]. This would help enhance thermal comfort in urban spaces [123], [124]. Meanwhile, user behaviors could also be affected by the planting of trees in green open spaces. Research has revealed that individuals tend to stay under the shaded area rendered by trees in open spaces [125].

Various indicators have been developed to quantify the thermal performance in outdoor spaces. Universal thermal climate index (UTCI) , Standard Effective Temperature (SET), Physiological Equivalent Temperature (PET), Predicted Mean Vote (PMV), Predicted Percentage Dissatisfied (PPD) and Web-bulb Globe Temperature (WBGT) are some of the most used indicators for quantifying outdoor thermal performance [126], [127]. Each of these indicators possesses its own advantages and drawbacks [128]. In the current study, UTCI has been chosen as the indicator for quantifying thermal performance in the parametric model. There were two main reasons for this decision. First, the aim of the current study was not comparing these indicators but investigating the feasibility of including thermal performance as one of the performances in the parametric model. To this end, the advantages and drawbacks of the indicators used was out of the scope of this study. Instead, the indicator being chosen should be integrated into the model development procedure without complications. Second, Grasshopper add-on Ladybug can estimate UTCI values of the design generated in the Grasshopper environment. This would make the process of model development smoother in a sense that no third-party software application would be needed in order to quantify thermal performance.

3.3.2 Acoustic Performance

Acoustic performance is usually about the preference of the acoustic environment. It refers to whether users of the open space will feel acoustically comfortable. To this end, the notion of soundscape emerges. Soundscape can be defined as "*an acoustical composition that results from the voluntary or involuntary overlap of different sounds of physical or biological origin*" [129]. With the soundscape approach for the evaluation of acoustic environment, types of sounds and the characteristics such as sound level of them will be considered. When adapting this approach, descriptors such as "noise annoyance" and "pleasantness" would be used to evaluate the quality of the acoustic environment [130].

As per the soundscape in green open spaces, people inside the spaces usually feel less annoyed, or prefer the acoustic environment more if there is water sound in the spaces [131]. Water is not only a type of natural sound that individuals prefer, various studies have confirmed that water sound could provide masking effect on environmental noise [132], [133]. The masking effect of water sound could even reduce the perceived loudness [134] or the annoyance [135] brought by traffic noise. Of various water sounds in open spaces, fountain sound has always been a subject of study when researches about urban water sound was concerned [136]–[138]. A previous study conducted by the author of the current study even revealed the statistical relationship between probability of being annoyed and properties of combined sounds of water fountain and traffic noise [139]. Due to the preferences of water features in green open spaces and the capability of improving acoustic environment of water sound, it will also be of importance to examine the feasibility of incorporating sound masking capability of fountain in green open spaces as a performance in the performative parametric model for green open space design. The statistical model developed by the author of the current study previously [139] would be used to quantify the performance.

3.3.3 Spatial Structure

In the experiment of the current study, spatial structure of green open spaces mainly referred to the internal structure of the space. The connection between the spaces and the surrounding environment was not considered in this study. Here, the relationship between tree distribution and spatial structure was the focus. Trees have always been treated as an element to define the spatial structure of outdoor spaces. Trees would define the spatial framework and affect both visual and physical experiences in urban spaces [140]. Urban spaces could be defined by trees both vertically and horizontally [141]. Horizontally, trees define the visual enclosure of spaces while a ceiling of canopy would define the spaces vertically. In fact, similar idea was also suggested by Strom [142]. Trees functioned like architecture in a sense that "*canopy acts like a ceiling and trunks are analogous to columns*". Spaces inside the open spaces, as well as the degree of enclosure of the open spaces could be defined by trees [143]. Urban landscape with trees enclosed could also help to create a separation from the "*hectic urban environment*" [144].

To understand the spatial structure of urban spaces, Space Syntax [66] can be utilized. With Space Syntax, organizations of architectural spaces at both building and urban levels can be quantified [145]. Space Syntax is also a graph-based theory which can be used to reveal how spatial configurations in buildings can influence human movement and interaction [146]. In fact, there are two underlying ideas within the Space Syntax theory [147]. First, space should not be considered the background of human activity like background of objects. Instead, space should be an object itself where human beings will move and interact with one another within it. Second, human spaces should not be just properties of individual spaces. They should be understood as the interrelations between many spaces. These spaces will in turn make up the spatial layout or configuration of a city or a building. Studies also confirmed that Space Syntax could be used to reveal both the perception and behavior of people in architectural spaces [148]–[152]. For example, Space Syntax measure integration values were found to be correlated to the movement of people in rooms in Tate Britain Gallery [153]. This also suggested that people in the gallery are using the spaces, rather than merely attracted by the exhibits. A recent study in U.K. also found that areas with lower integration values in open spaces tended to be under-used [154].

Researchers have also attempted to investigate the effects of tree planting on spatial structure of open spaces by using Space Syntax measures. A study on tree planting design suggested that planting trees in a symmetric and rectangular array manner would render lower connectivity value. In the same study, it was shown that a curved composition or a configuration of tree planting design would render higher value of connectivity, which was more preferable [155]. However, when considering outdoor thermal effect and the influences on connectivity and visual integration of trees together, it should be obvious that more trees will render better cooling effect but lower connectivity and visual integration. As a result, it will be of interest to include both spatial structure and thermal effects brought by trees in a parametric model for green open space design so as to understand how interrelated performances can be included in a performative parametric urban design model.

3.4 Attributes for Green Open Space Design

When designing green open spaces, there are a number of attributes to be considered. Basically, they can be categorized as physical and performance attributes. Physical attributes are the actual design features of the green open spaces. These attributes can be translated to the physical parameters of a parametric model for green open space design. Meanwhile, performance attributes are about the performances of green open space. Unlike physical attributes, performance attributes are not design features that are actually put in the open spaces. Instead, they are affected by the physical attributes (design features put in the open spaces), as well as external factors such as climate condition (in the case of thermal performance). Table 3.1 summaries the attributes which are usually considered for green open space design.

3.4.1 Physical Attributes

Site

Location

Location of the open space can be referred to two different ideas. In a broader sense, it can be referred to the climatic zone where the open space is located. This will affect factors such as temperature and the needs for shadow provisions in the space. On the other hand, it can also mean where the open space is located within the city. This will mainly affect the relationship of the open space to the neighborhood. In fact, the location of the open space in the neighborhood could affect functions such as walkability of the space [102].

Size

The size of the open space is the area occupied by the space on the ground surface. Although size of open space had no effect on activities such as walking [156], a bigger open space would usually lead to better cooling effect for the urban environment [157], [158].

Geometry

The geometry of an open space is mainly affected by the immediate surroundings such as the roads and buildings. Microclimate of open spaces could be affected by the geometry of it [159], [160]. A more regular geometry which is closer to a circle was suggested if the open space was located in city center. On the other hand, irregular shape or geometry would be preferred for open spaces in other districts [161].

Buildings surrounding the open space

Buildings at the immediate surroundings of the open space do not only affect the entrances to the open space, but also the solar access of the space in general. Specifically, the position of the buildings relative to the open space and the height-to-width (H/W) ratio would affect the solar access or shadow provision and hence influence thermal comfort in the space [162], [163].

Greenery and planting

Trees

Spatial structure of open spaces can be defined by trees. Trees can also provide shadow and affect thermal comfort in open space [164], [165]. They also possess the power of restoration which can help open space users to relieve stress [166], [167]. In fact, previous studies have shown that natural features were very important to the users of urban open spaces [168].

Hard-soft surface relationship

Soft surfaces mainly referred to grass or greenery. As in the case of trees, grass possessed the power of restoration [169], [170] that is beneficial to the well-being of open space users. Open spaces with "a lot of grass" might lead to a higher rating of restoration likelihood [99]. On the other hand, hard surfaces are paved surfaces. The relationship between hard and soft surfaces would help to define the internal paths, focus and entrances of an open space.

Facilities

Amount of seating

Studies showed that open spaces with more sitting areas could attract more people to use the space [171]. Sitting areas should be considered with the placement of trees due to the effects of shadow provision of them.

Integral sitting

Features such as ledges and steps could be treated as secondary sitting areas [171], [172]. This would increase the amount of seating and help attract more people to the space.

Seating materials

Seating materials would affect the comfort when sitting in the open space [173]. It has been suggested that seating materials should be chosen in a way that they do not respond to temperature change and damage clothes [172]. Researchers suggested that wood was a preferred material for seating in open spaces [172], [174].

Orientation of seating

Clusters of seats with various orientations could help to attract population with wider backgrounds to sit in the open space [175]. Variety of orientations of seats could also provide different views for people who were sitting [172]. Seats with different orientations were preferred over a linear configuration [175].

Sitting height

Sitting height is mainly related to the comfort of people. Height of seats should be set according to standards such as Architecture Graphic Standards [176]. On the other hand, height of integral sitting was recommended to be approximately between 400mm and 800mm [172].

Sculpture

Sculptures and public artworks could help to create a sense of joy and delight and promote communication of people [177]. However, research by Lo et al. [168] suggested that it was the least important attribute for open space design.

Fountain

A fountain can be served as a landmark in open spaces. Water features such as fountains could have restoration power [99], [178] and enhance the well-being of open space users. Water sounds from fountains could also help to mask the unwanted noise and improved the acoustic environment of the open space [135], [139].

Focus

Focus could create a center of the open space and help people navigate and be a spot for gathering [179]. To this end, a sculpture or fountain can be put in the focus so as to reinforce the function of it.

Paving

Paving or pavement in open spaces could affect both the thermal comfort [180], [181] and walkability of the spaces [182], [183]. Good paving was found to be one of the important attributes of neighborhood environment for elderlies [184].

Internal connections

Internal connections refer to the paths inside the open spaces. With smooth paths connecting one place to the other (e.g. from one entrance to another), the walkability of the spaces would be enhanced [185].

Amenities

Food

Food stalls could be the seed of activities in urban open spaces [171]. In fact, one of the activities people imagined they would do in small parks / urban spaces was found to be eating and drinking [99]. These results implied that open spaces with food provision could attract more users to the spaces.

Toilets

Although it is quite self-explained, toilets are usually considered one of the most important amenities in urban open space design. In fact, the existence or number of toilets was usually one of the amenities considered in park usage studies [186].

3.4.2 Performance Attributes

Thermal Performance

Solar access

People would tend to enjoy the sunshine in open space when temperature was not too high [171]. Solar access will also affect thermal comfort in open spaces. Shading should be provided in summer in hot climate regions as it could improve thermal comfort.

Temperature

Temperature affected microclimate conditions and in turn thermal sensation and thermal comfort in open spaces [187]. In fact, temperature is not the sole factor affecting thermal comfort. Other factors such as wind speed and humidity would also affect thermal sensation and hence thermal comfort [123], [188], [189].

Wind

Wind, in particular wind speed, was also one of the factors that would affect outdoor thermal comfort [187]. Strong wind would also discourage people to use open spaces [171]. The optimal wind speeds were suggested to be 0 – 2.6 m/s for sitting and 0 – 5.4 m/s for walking. Wind speed greater than 5.4 m/s was uncomfortable for any types of activities [190].

Acoustic Performance

Soundscape

Sound levels directly affect acoustic comfort. Usually, sound level would have a direct correlation with noise annoyance. Higher sound level would lead to higher noise annoyance [191], [192]. It was also suggested that good soundscape quality could only be achieved if the sound level from traffic noise was less than 50 dB(A) during daytime [193].

Table 3.1 Attributes for green open space design

Attributes			References
Physical Attributes	***Site***	Location	[102]
		Size	[156], [157], [158]
		Geometry	[159], [160], [161]
		Building surrounding the open space	[162], [163]
	Greenery	Trees	[164], [165], [166], [167], [168]
		Hard-soft surface relationship	[99], [169], [170]
	Facilities	Amount of seating	[171]
		Integral sitting	[171], [172]
		Seating materials	[172]–[174]
		Orientation of seating	[172], [175]
		Sitting height	[176], [172]
		Sculpture	[168], [177]
		Fountain	[99], [135], [139], [178]
		Focus	[179]
		Paving	[180], [181], [182], [184], [183]
		Internal connections	[185]
	Amenities	Food	[99], [171]
		Toilets	[186]
Performance Attributes	***Thermal***	Solar Access	[171]
		Temperature	[187] [123], [188], [189]
		Wind	[187] [171] [190]
	Acoustic	Soundscape	[191], [192] [193]

4 PARAMETRIC MODEL DEVELOPMENT FRAMEWORK EMBRACING PERFORMANCES AS INPUTS

4.1 Basic Concept

The primary purpose of the current study is to develop a model development framework which can guide the development of performative parametric urban design model. The notion of inverse simulation will be adapted so that designs can be generated when the required performance levels are input. To this end, the model developed under this framework will be different from a more conventional parametric design model, which mainly comprises physical parameters as input. As discussed in Chapter 2, both performances and physical parameters will be adapted as input to the model. Figure 4.1 shows the basic concept of such a model. Basically, by use of inverse simulation, values of a set of physical parameters will be estimated. With the values of the other physical parameters input to the model, a design option will be generated.

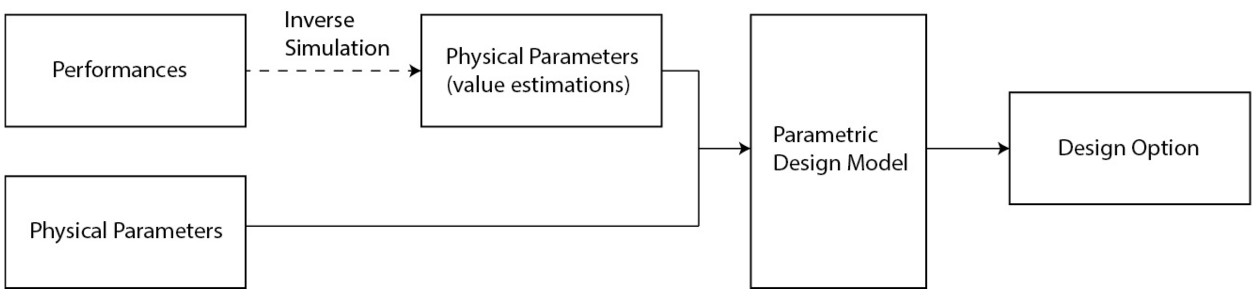


Figure 4.1 Basic concept of the parametric model

4.2 Mathematical Concept behind the Framework

4.2.1 Parameters and Performances

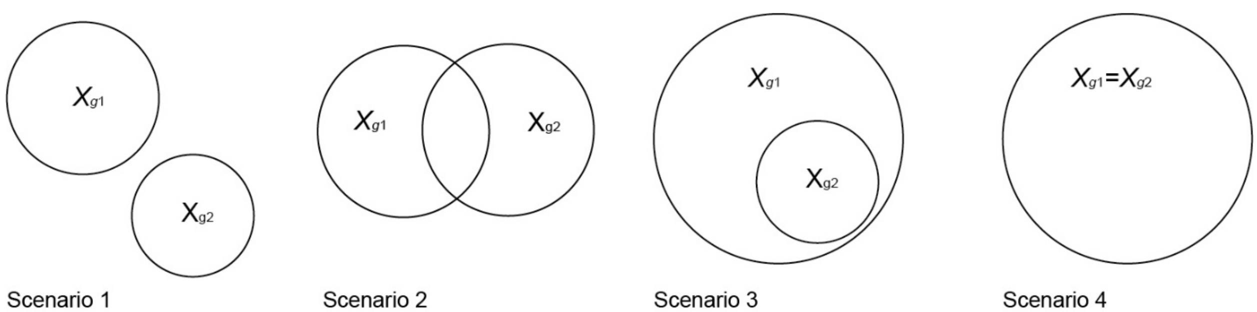
Mathematically, every single performance of a design option can be express as a function of physical parameters related to it. When multiple performances are considered, there will be a system of functions. The performances of a design option in a parametric urban design model can be expressed as:

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

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) influencing the corresponding performances; k is the total number of types of performances considered.

Interactions among performances

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. Assuming X_g is a set of parameters rendering a particular performance, 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}) rendering two different performances p_1 and p_2 – (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 4.2 shows these four possible relationships.



**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}.*

Figure 4.2 Possible relationships between two given sets of parameters X_{g1} and X_{g2} rendering 2 different performances

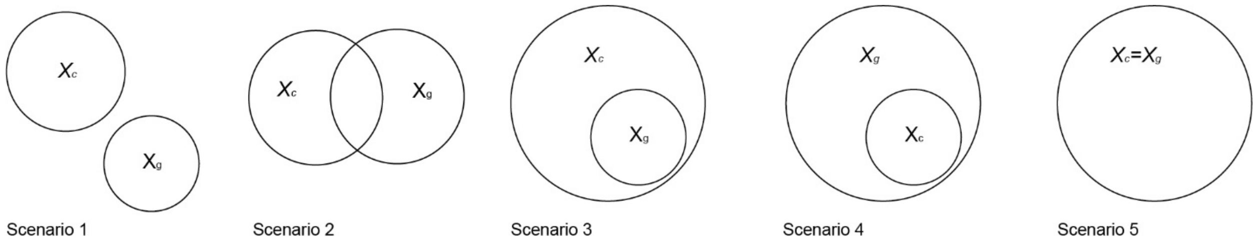
Considering these relationships, when there is no intersection between X_{g1} and X_{g2}, changes in the values of any parameters in the X_{g1} will never affect performance p_2, and vice versa. The performances in this case will not be interrelated. While developing the parametric model, the performances can be considered separately if there are no intersections among the parameters. It also means that the designer can alter the performance level inputs of these performances independently.

On the contrary, the same parameters can affect different performances if the two sets of parameters are not disjoint (scenarios 2 to 4 in Figure 4.2). Different performance goals may yield different values of the same parameter. Conflicting values of parameters may be obtained when different performance values are required. In this case, it will not be viable to allow the designer to set the values of these performances independently in the parametric model. When developing the parametric model, it will be essential to inform the designer that these interrelated performance values cannot be set independently. The designer should also be informed about how the other interrelated performance values change when the value of one performance is defined.

Interactions among constraints and performances

There will be a number of constraints (e.g. design brief and practical issues) for any design task. They have to be included in the parametric design model when generating a design solution. It is because these constraints do not only affect the design solution, but also some of the parameters in the parametric models. The range of values of a parameter can be restricted due to the constraints. For instance, the range of possible footprint of buildings inside a site will be restricted by the site dimensions. In this case, the site dimensions are the constraints, which must be included in the parametric urban design model.

Parameters influenced by the constraints can also be parameters affecting the performances. Suppose X_g is a set of parameters which will affect the performances 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 4.3 shows the possible relationship of these parameters.



**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.*

Figure 4.3 Possible relationships between the set of parameters influenced by the constraints and the set of parameters affecting performances

When there is no intersection between X_c and X_g, the performances in concern and the constraints are independent. They do not have to be considered together when developing the model. However, there are also cases that there are intersections between X_c and X_g. From Figure 4.3, 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). The constraints may restrict the ranges of values of these parameters. These ranges will in turn affect the ranges of values of the performances. As a result, the ranges of parameter value and performance value input should be restricted by these constraints while developing the parametric model.

There can also be direct interactions between the constraints and performances. The constraints can affect the performance of the design directly. In the realm of urban design, one example of such cases is the location of the site. The climatic zone where the site is located will affect the temperature inside the site directly. When there are interactions between constraints and performances, the ranges of values of the performance levels will usually be restricted. Again, this should become the maximum and minimum input values of the performance levels when developing the parametric design model.

4.2.2 Inverse Simulation

Equations (1) describe the relationship between performance levels and values of parameters. In a "forward" procedure, the performance p will be estimated by given values of a set of parameters X. Suppose $x_1, x_2 \dots x_n$ are the parameters in the set of parameters X, a "forward" procedure can be understood as:

Given values of parameters ($x_1, x_2 \ldots x_n$) → performance p (2)

To this end, the performance will be estimated when all the values of the parameters are defined. This means that the design has to be generated in order to estimate p.

On the contrary, equation (2) will be inversed in an inverse simulation problem:

Given value of performance p → parameters ($x_1, x_2 \ldots x_n$) (3)

For equation (3), unless there are ready-to-use computer applications or formulae to perform the estimation of values of parameters, it will be needed to develop the mathematical relationships among various performances and parameters when developing the parametric design model. In this case, a "forward-backward" strategy will be needed. The "forward" procedure is essentially the use of equation (2). There are basically 2 steps for this procedure:

1. Generate design scenarios with various combinations of parameter values
2. Evaluate performances of the design scenarios with simulation tools

After these two steps, the "backward" procedure follows. The primary task of this procedure is to develop equation (3). After it has been developed, there are two options to include it as a form of inverse simulation. As there are a lot of pairs of scenarios and performance values, they can be stored as a database. The parametric model can search for the combinations of parameters values from the database with a given performance value. The main advantage is that computers can complete the search within a second. However, the disadvantage of this method is that the performance value being input may not exist in the database. In this case, the performance value which is the closest to the input one in the database can be used.

On the other hand, mathematical relationship between the parameters and performances can be formulated as another way of tackling the problem. With the mathematical formulae developed, it will be possible to find the combinations of parameter values by a given performance level. However, it can be a resource intensive and time-consuming task for the computer to find the combinations if the relationship is very complicated. To this end, a less complicated equation such as a linear relationship will be preferred so as to ensure that the model can generate results within seconds. Figure 4.3 shows the idea of this "forward-backward" strategy.

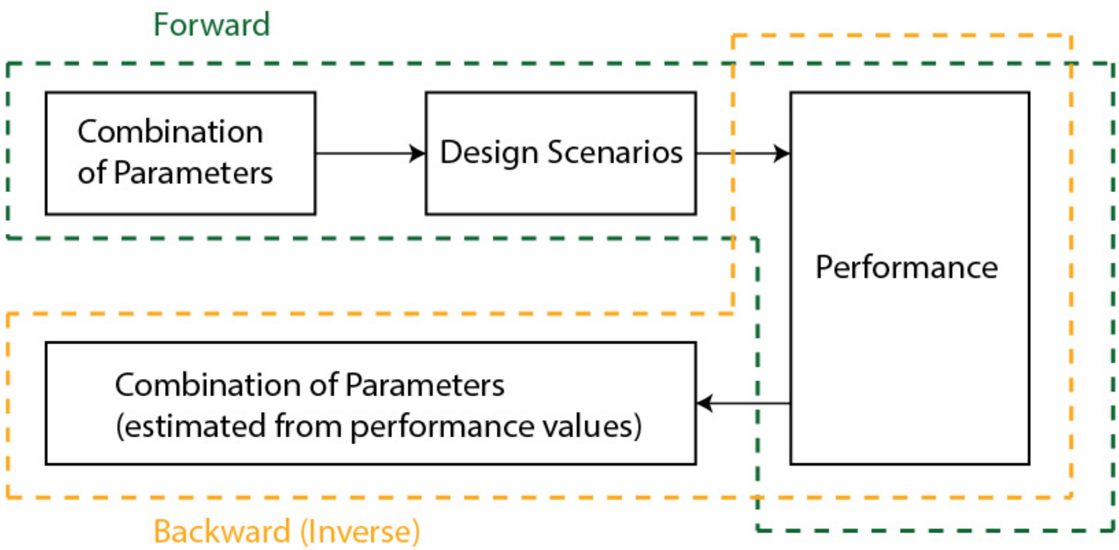


Figure 4.3 "Forward-Backward" Strategy of Inverse Simulation

4.2.3 Generation of Design Options

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

$$DO = F(x_1, x_2, \cdots, x_n, C) \qquad (4)$$

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 (4) when a non-performative 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. Assuming that x_1 *to* x_m ($m<n$) are the parameters affecting the set of performance goals *P*, equation (4) can be redefined as:

$$DO = F(P, x_{m+1}, x_{m+2}, \cdots, x_n, C) \qquad (5)$$

With equation (5), designers will control the performance levels *P* and the parameters x_{m+1} to x_n as input to the parametric design model. Values of x_1 to x_m will not be defined by the designers. Instead, the notion of inverse simulation will be implemented in this part of the parametric model.

By incorporating equation (3) in this part of the model, the parameter values x_1 to x_m will be estimated. Consequently, equation (5) will become:

$$DO = F(x_1, x_2, \cdots, x_m, x_{m+1}, x_{m+2}, \cdots, x_n, C) \qquad (6)$$

By using equation (6), the design option will be generated with the estimated values of x_1 to x_m, input values of x_m+1 to x_n, and C.

As mentioned above, conflicting values of x's (x_1 to x_m) could be obtained due to the different performance goals. There are two ways to deal with this issue. The first way is to allow the designer to define the values of the parameters which will be in conflict. The assumption with this method is that the designer should perform the trade-off of performances and make decisions on the parameters. In this case, the designer should be informed about the values of the performances when one defines the values of these parameters. The second ways will be to use a weighing or optimization mechanism to generate sets of values of x_1 to x_m. Contrary to the first method, the assumption behind is that the model will perform the trade-off by utilizing the optimization mechanism. However, this mechanism is out of the scope of the current study. It will not be discussed here. Meanwhile, it is further assumed that the influences of constraints on the parameters have been considered when the ranges of possible values of x's, as well as the performance levels, are defined.

4.3 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. As an extension of Figure 4.1, Figure 4.4 shows the logic and flow of these components and subcomponents.

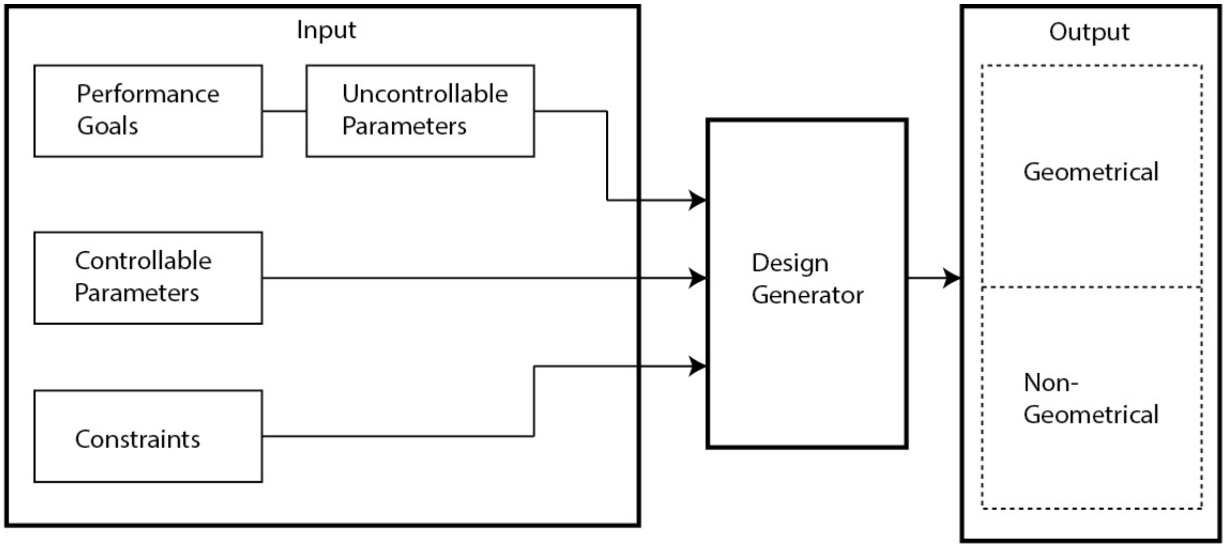


Figure 4.4 Flow and logic of the framework

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)). The constraints can come from issues such as design brief and site conditions. For example, zoning, programs, neighborhood geometry, building height and location of the site are some of the factors that should be considered as constraints. As discussed in pervious section, constraints can affect both the parameters and performances.

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 of the parameters. In a smaller scale such as small open space design, the dimensions of seating spaces can be a parameter. In fact, these parameters do not have to be all physical. To this end, time dimension can also be parameters of the model. When time is treated as a parameter, it will be possible to consider life cycle impact of the design as a performance.

Meanwhile, 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 (6)) are parameters that the designer will define and control the values of them. This is similar to the parameters in any non-performative parametric urban design model. By changing these values, different design options will be obtained.

Uncontrollable parameters

Uncontrollable parameters (x_1 to x_m in equation (6)) 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 when using the model to generate design options. Instead, the values of performance goals will be defined. With the notion of inverse simulation, 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 mainly about the design synthesis process and 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 (6), will be defined. These relationships and rules are usually defined by mathematical formula. They can be overlapped or co-dependent [194].

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 performance levels for further exploration. On the other hand, the designer can also choose to explore options with different performance levels. Besides, the output of the model can be geometrical, non-geometrical, or a combination of them. Geometrical output mainly refers to the graphical representation of the design options. In the realm of urban design, plans or maps of the site would be preferred as geometrical output. In fact, according to Le Corbusier, "plan is generator" of cities [195]. This explains the importance of generating plans or maps as output of the model. Meanwhile, non-geometrical output is primarily data related to the design. An example of non-geometrical output is the performance levels of the design that are not defined by the designer.

4.4 Procedure to Develop a Parametric Model under the Model Development Framework

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

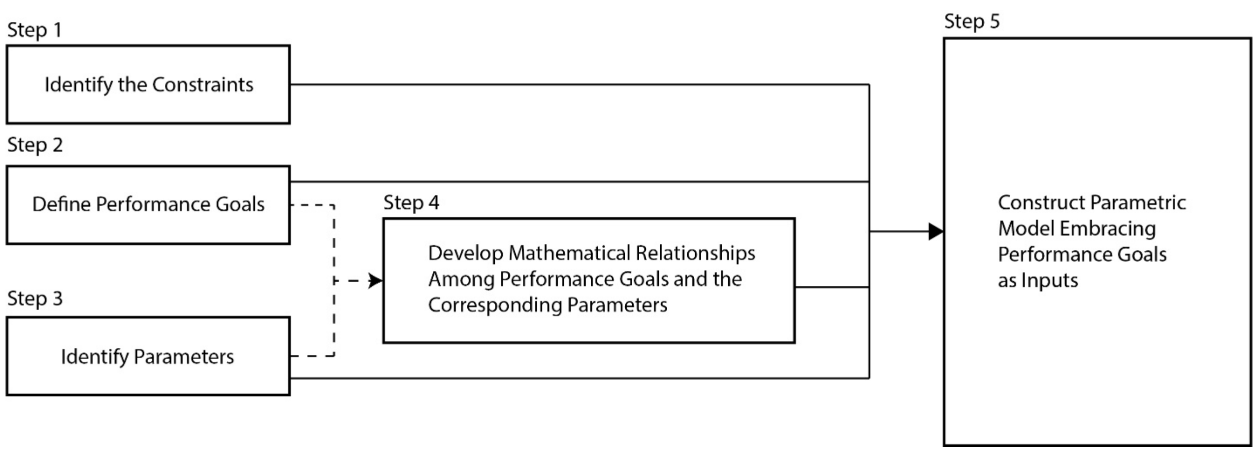


Figure 5 Procedure of developing a parametric model embracing performance goals as inputs

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. Besides, it is also needed to quantify the performance goals. It is not feasible to include performances which cannot be quantified.

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 affecting the performances 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 (6), different possible values of x_1 to x_m will be obtained by defining the values of p's. Ideally, it would be preferable if there are simple developed mathematical relationships between the performance 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. Different tools for performance simulations may be needed in order to develop the relationships. The "forward-backward" strategy will be adapted in this step. Inverse relationship between the parameters and performances will also be developed.

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.

5 EXPERIMENT: FORMULATION OF PARAMETRIC MODEL CONCERNING BOTH URBAN AND ENVIRONMENTAL PERFORMANCE

As a proof of concept of utilizing inverse simulation as a strategy of performative approach for parametric urban design model, an experiment was conduct. In this experiment, a parametric design model for generation of green open spaces (GOS) was developed. The performances considered in this model were thermal performance, acoustic performance and spatial structure of GOS.

5.1 Virtual Site

In order to demonstrate the development of the parametric model by applying the framework laid out in the previous chapter, it was preferable that site configurations of it would also be parameters of the model. This means that these site configurations should be alterable. As it was impossible to have a site with configurations, especially dimensions, that were alterable, it has determined that a virtual site would be adapted in the current study.

It was assumed that the virtual site was located in Hong Kong when formulating the parametric design model. The main reason for choosing Hong Kong as the location was the subtropical climate in this region. To this end, the thermal performance would be about how the design of the site can help cool itself down in hot summer. It was a rectangle with changeable dimensions. Three sides of it were enclosed by buildings while one side of it was facing a street. The side facing the street was facing south. The buildings were all of height 17.5 m (5 storeys). Meanwhile, trees and a fountain would be put into the site. They 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 5.1 shows the configuration of the virtual site.

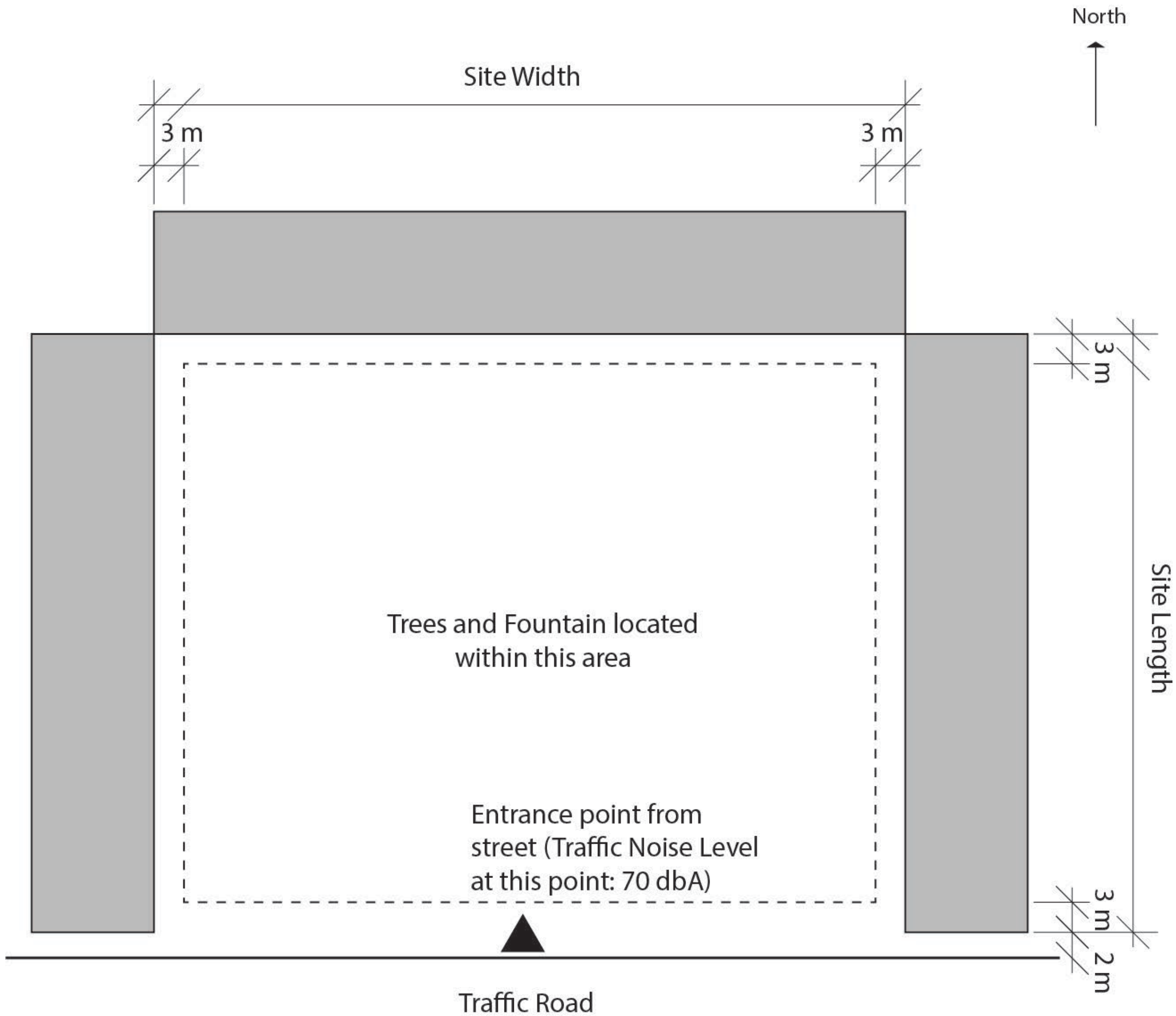


Figure 5.1 Virtual site defined in the parametric urban design model

5.2 Model Development Procedure

Following the model development framework laid out in Chapter 4, there should be 5 steps when developing the parametric urban design model.

Step 1: Identification of constraints

There were various site constraints in the virtual site. First of all, it was located in Hong Kong. The climate, which is directly related to the thermal performance of the open space, would be affected by this geographic location. Heights and positions of buildings were fixed. This would affect the shadow casted and hence thermal performance of the site. Besides, the traffic noise level should also be considered a constraint. All these constraints would be programmed into the parametric model. Table 5.1 lists the constraints that were considered when developing the model.

Table 5.1 List of constraints considered in the current experiment

Constraints	Descriptions
Geographic location of the site (Hong Kong)	The climate zone where the site was located would directly affect the thermal performance of the design.
Site Orientation	Shadow casted by buildings would affect thermal performance of the design. The entrance of the site was facing south. Orientation of the site will affect the shadow casted in it and therefore the thermal performance.
Building Positions and Height	As in the case of site orientation, the building positions and height of them were fixed, the thermal performance of the design would be restricted by the shadow casted by the buildings.
Traffic Noise Level	The traffic noise level at the street would affect the noise level in the site. Hence, it will directly affect the acoustic performance of the design.

Step 2: Defining the Performances

In the current experiment, the performances considered were thermal and acoustic comfort, as well as the spatial structure in GOS. Various performance indicators would be needed to quantify these performances in order to script them into the parametric urban design model. Table 5.2 summaries the indicators used to quantify these performances. Details of quantifying the performances will be discussed in the next section.

Table 5.2 Performances considered and the related indicators

Performance	Indicator to quantify the performance
Thermal Performance	Universal Thermal Climate Index (UTCI)
Acoustic Performance	Probability of having low noise annoyance [139]
Spatial structure	Connectivity value (Space Syntax measure)

Step 3: Identification of Physical Parameters

As mentioned in Chapter 3, there are a lot of physical design attributes that will affect the design of GOS. As the parametric model to be developed was assumed to be used 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 the aim of the current experiment was to demonstrate the steps to develop a performative parametric model guided by the model development framework, physical parameters not related to any of the performances considered were not included. Table 5.3 shows the physical parameters considered and the performances being affected.

Table 5.3 Physical Parameters and Performances being Affected

Physical Parameter	Performances		
	Thermal Performance	***Acoustic Performance***	***Spatial structure***
Site Width	√	√	√
Site Length	√	√	√
Tree Density	√		√
Fountain Location		√	

Step 4: Developing Inverse Relationship

Mathematical relationships among physical parameters and performances would be developed. In fact, the aim of this step was to develop the inverse relationship among the performances and various parameters. As mentioned in the pervious Chapter, there are two ways to develop the inverse relationships after the mathematical relationships among physical parameters and performances are revealed. In the current experiment, linear regression models would be formulated to describe the relationships among the parameters and performances. The inverse relationship could be obtained after the relationships among parameters and performances were revealed by regression analysis.

Step 5: Final Model Development

With all the parameters and mathematical relationships, the model could be developed using Grasshopper. Regarding the output of the model, both geometrical and non-geometrical output would be generated by the model. 2-dimensional and 3-dimensional graphical representations of the designs would be generated. Besides, the performances and basic information of the design would also be shown as output of the model.

5.3 Inverse Relationship among Performance Levels and Parameters

One of the keys of developing the parametric urban design model is to derive the inverse relationships among the performance levels and parameters (Step 4 of the model development procedure). To this end, it would be essential to estimate the performance levels corresponding to various design scenarios. With these estimation results, relationships among the performance level and parameters could be derived by regression technique.

5.3.1 Design Scenarios

Before developing the inverse relationship, design scenarios had to be generated. In the current experiment, the dimension of site, tree density in the site and the location of fountain are alterable. When constructing the design scenarios, both the width and length of the site increased from 50m to 200m, in a step of 50m. On the other hand, tree densities were set to be from 0.025 to 0.1 tree/m^2, in a step of 0.025 tree/m^2. Trees were distributed in the site with a random function. Depending on the size of the site, location of center of fountain was from 20 m from the edges of the site, in a step of 20 m. Meanwhile, there were some values of parameters which were fixed in the current experiment. They are the tree crown diameter, tree shape, tree height, fountain diameter and water sound level generated by the fountain. Table 5.4 summarize the parameters to construct the design scenarios.

Table 5.4 Parameters for generating design scenarios

Parameters		**Description**
Alterable	*Site Width*	50m to 200m
	Site Length	50m to 200m
	Density of Trees (Tree Number / m^2)	0.025 to 0.1
	Fountain Position	Center of fountain was not closer than 20 m from the edge of site
Unalterable	*Tree Crown Diameters*	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	20 m (The fountain was assumed to be of a circular shape)
	Water Sound Level	65 dbA at the edge of the fountain

With these parameters, Grasshopper was used to generate the design scenarios. The thermal performance and acoustic performance could be estimated within Grasshopper once a design scenario is generated. Besides, 2-dimensional representation of the design scenarios were exported to the software application DepthMap to reveal the connectivity value of the scenarios.

5.3.2 Thermal Performance

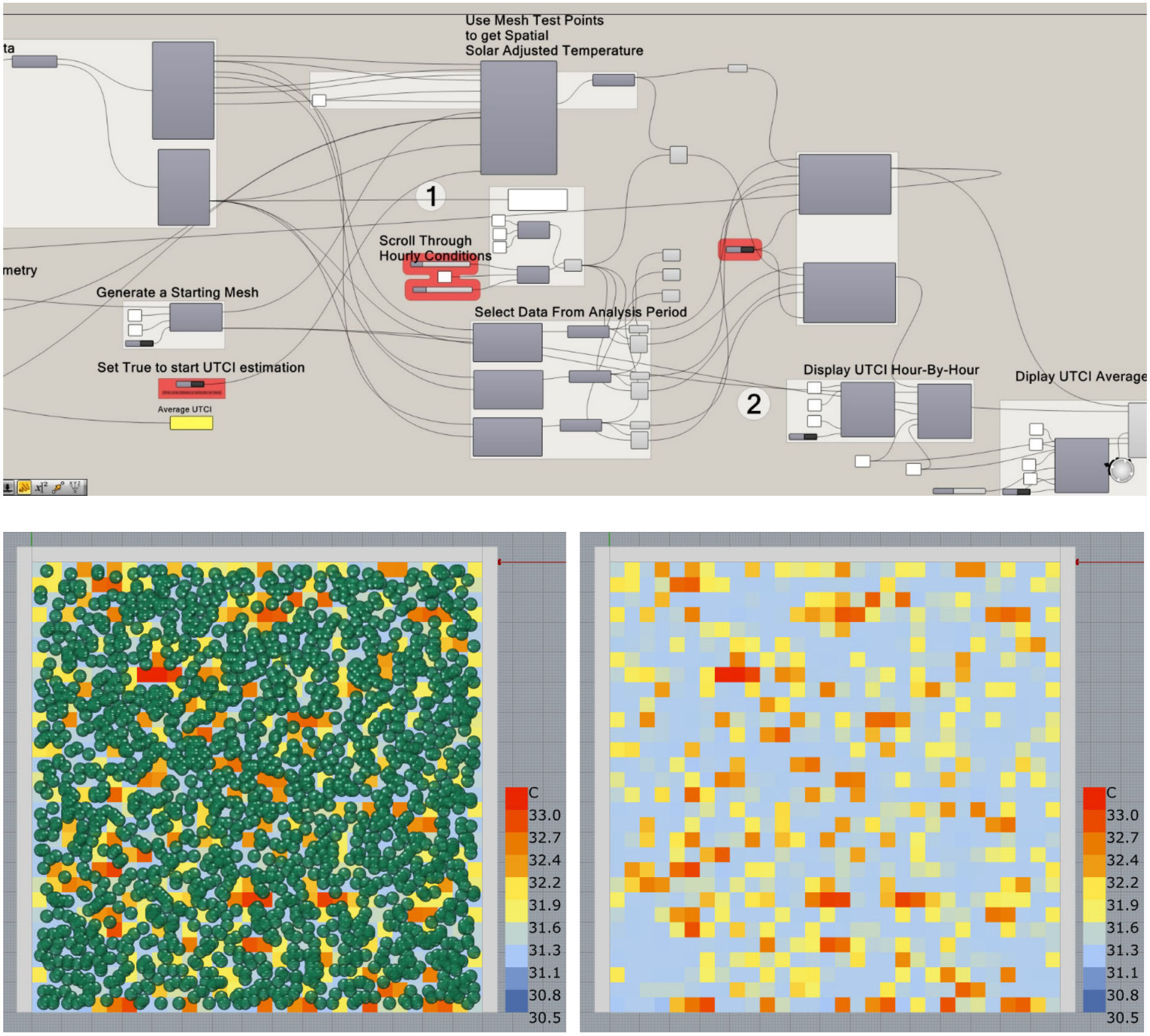
The thermal performance in the GOS was quantified by using Universal Thermal Climate Index (UTCI) developed by the European Cooperation in Science and Technology [196]. UTCI has been widely used in studies concerning outdoor thermal performance [197]–[199]. The index is expressed in terms of degree Celsius. When estimating average UTCI, the time period considered was the hottest week of the year in Hong Kong (22 July to 28 July). Meanwhile, average wind speed and humidity within the hottest week of the year were adapted for the estimation.

UTCI values were estimated by using Ladybug, which is an add-on of Grasshopper. The advantage of Ladybug is that UTCI estimation results can be obtained directly after changing the parameter values in Grasshopper. It is not needed to export the design scenarios from Grasshopper to other third party software tools. In fact, exporting the scenarios to other third party tools could be an extremely time consuming process. When a designer or the model development personnel is developing a parametric model, procedures which will help consume less time is always preferred. Figure 5.2 shows an example of UTCI value estimated by using Ladybug and the graphical representation of it.

The reduction in average UTCI value in the site due to tree shading was adapted as a performance goal. To this end, the UTCI value of the site without any trees and the value of the same site dimension with various tree density would be compared. The UTCI reduction value $\Delta UTCI$ is given by:

$$\Delta UTCI = UTCI_0 - UTCI_T \quad (7)$$

where $UTCI_0$ is the average UTCI value of the site when there is no tree and $UTCI_T$ is the UTCI value when trees are planted in the site.



Above: Calculation of UTCI value in Grasshopper Interface

Below: Graphical representation of UTCI values in the site generated by Ladybug (left: with trees drawn; right: without trees drawn)

Figure 5.2 Example of UTCI value estimation by Ladybug in Grasshopper and the graphical representation of it

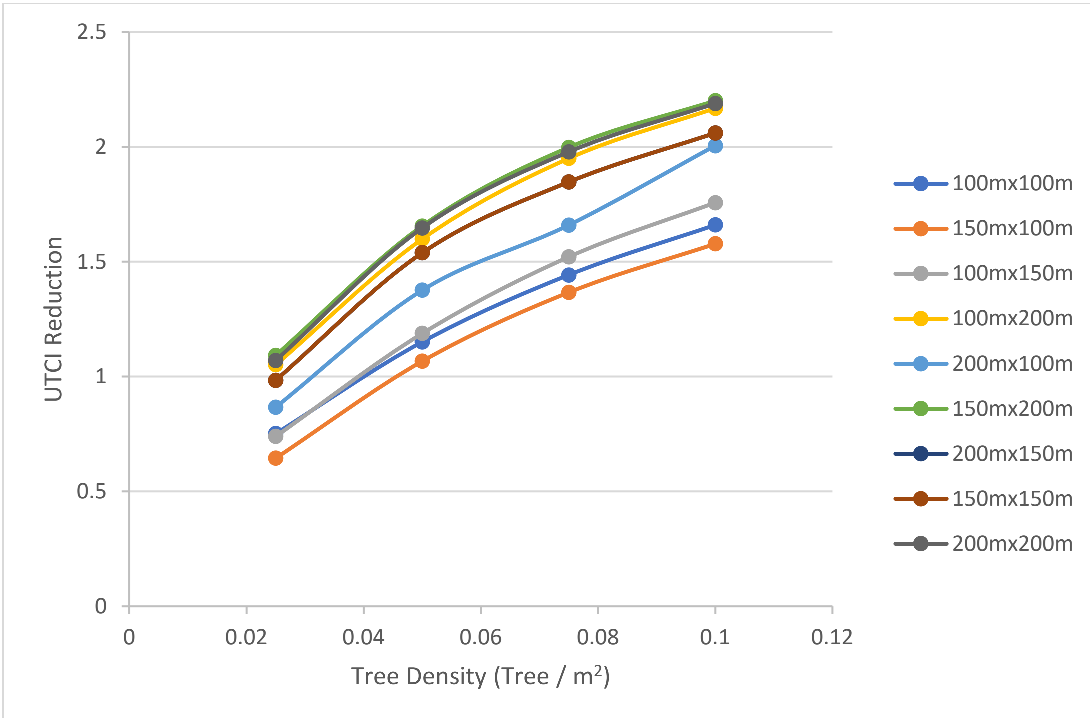


Figure 5.3 Relationship between UTCI reduction and tree density corresponding to various site dimensions

Figure 5.3 show the relationship between tree density and UTCI reduction with respect to various site dimensions. As expected, a higher tree density would lead to a greater UTCI reduction value. Meanwhile, UTCI reduction values would also be affected by site dimensions. Upon correlation analysis, it was found that both site width and length exhibited a positive correlation with UTCI reduction (Table 5.5).

Table 5.5 Correlation between UTCI reduction and site dimensions

	Site Width	**Site Length**
UTCI Reduction	0.828**	0.369*

**significant at 0.05 level; ** significant at 0.01 level*

From the observation of Figure 5.3 and the correlation analysis, it was determined that UTCI reduction value could be expressed as a function of tree densities, site width and site length:

$$\Delta UTCI = \alpha_0 + \alpha_1 TreeDensity + \alpha_2 SiteW + \alpha_3 SiteL \qquad (8)$$

where *TreeDensity* is the tree density; *SiteW* is the site width; *SiteL* is the site length; α_0 is the constant term; α_1 to α_3 are the coefficients of the independent variables.

Meanwhile, regression analysis was performed to derive the mathematical relationship among UTCI reduction values, tree densities and site dimensions. Table 5.6 shows the results of the regression analysis.

Table 5.6 Regression results for thermal performance

Parameters	Coefficient	Standardized Coefficient	Significance
Tree Density	13.94**	0.869**	<0.001
Site Width	0.004**	0.382**	<0.001
Site Length	0.002**	0.170**	0.001
(Constant)	-0.271*	-	0.031

**significant at 0.05 level; **significant at 0.01 level*

The adjusted R^2 of the regression model was found to be 0.924. The independent variables (tree density, site width and length) could explain the dependent variable (UTCI reduction) very well. The absolute values of standardized coefficients of tree density, site width and length show that UTCI reduction was mostly affected by tree density, followed by site width and site length.

In order to generate graphic representation of the design options, the values estimated from the inverse relationship had to be deterministic. As a result, there would be three equations for the inverse relationship:

$$TreeDensity = \frac{\Delta UTCI - \alpha_0 - \alpha_2 SiteW - \alpha_3 SiteL}{\alpha_1} \quad (9)$$

$$SiteW = \frac{\Delta UTCI - \alpha_0 - \alpha_1 TreeDensity - \alpha_3 SiteL}{\alpha_2} \quad (10)$$

$$SiteL = \frac{\Delta UTCI - \alpha_0 - \alpha_1 TreeDensity - \alpha_2 SiteW}{\alpha_3} \quad (11)$$

Equations (9) to (11) were the actual equations which would be scripted into the thermal performance part of the parametric design model. This means that the designer would have to input the required UTCI reduction value and values of some parameters in order to generate the design option. Taking tree density as an example (Equation (9)), in order to get the value of tree density and generate the design option, the designer would have to input the UTCI reduction value, as well as the site width and length.

5.3.3 Acoustic Performance

It was assumed that only the fountain sound and traffic noise would affect the acoustic performance of the site. Acoustic performance was defined by using the research results published previously by the author of the current study. In this previous study [139], questionnaire survey has been used to elicit the noise annoyance induced by an acoustic environment with both fountain sound and traffic noise. Combined sound scenarios with various fountain sound and traffic noise levels were generated. These scenarios of acoustic environment were shown to the respondents and they were asked to rate the annoyance levels of the scenarios. By using ordered logit regression model, it was found that the probability of having low noise annoyance could be derived by traffic noise level, fountain sound level and the difference between these two sound levels. This means that the probability of having low noise annoyance could be estimated at any given fountain location in the site.

Meanwhile, the location of the fountain was defined by using a conventional 2-dimensional coordinate system. The south-west corner of the site was set to be (0,0), the x-axis was parallel to the East-West direction while the y-axis was parallel to the North-South direction. As it was assumed that the fountain was circular in shape, the coordinates of the centers of the fountain were utilized for deriving the relationship between fountain location and acoustic performance of the site. Figure 5.4 illustrate how the location of the fountain was defined in the site.

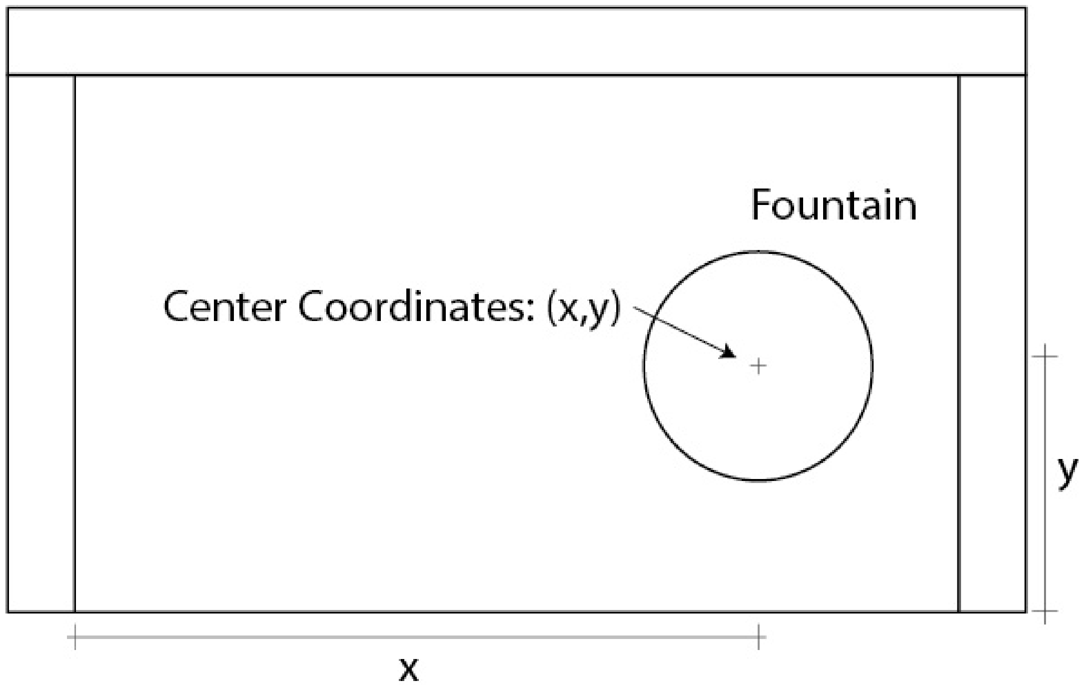
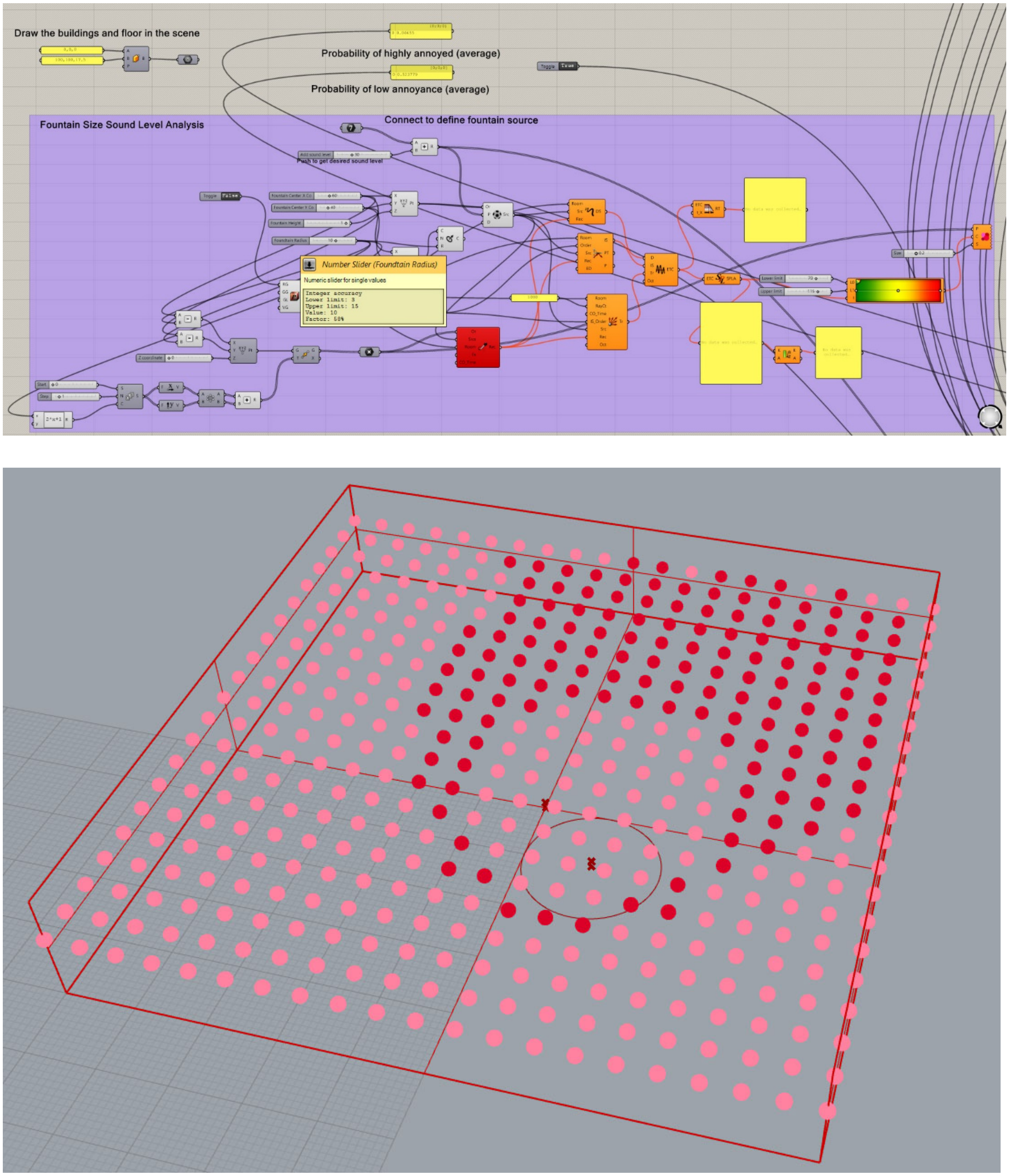


Figure 5.4 Defining the location of fountain

When evaluating the acoustic performance of the urban design scenarios, the site was divided by using a 5m x 5m grid system. The traffic noise level and fountain sound level at each grid was estimated. Afterwards, the probability of having low annoyance at each grid was calculated. Pachyderm, which is a Grasshopper add-on for acoustic simulation, was used to estimate the sound levels at each grid. As in the case of thermal performance, the advantage of using Pachyderm was that sound level calculation, as well as the probability of having low annoyance, could be calculated within Grasshopper so that it was not needed to export the design scenarios to third party software tools. The average probability of having low noise annoyance in the site of each design scenario was also calculated within Grasshopper to represent the acoustic performance of the design. Figure 5.5 shows an example of estimation of the probability within Grasshopper and the graphical representation generated by using Pachyderm.



Above: Estimation of probability of having low annoyance in Grasshopper interface

Below: Graphic representation of acoustic performance in the site

Figure 5.5 Example of estimation of the probability of having low noise annoyance in Grasshopper and the graphical representation generated by using Pachyderm

The basic hypothesis was that position of fountain and dimension of the site would affect the probability of having low noise annoyance in the site. Upon correlation analysis, it was determined that site area, the ratio of x-coordinate of fountain to site width, and the ratio of y-coordinate of fountain to site length would be included into the mathematical model to estimate the probability of having low noise annoyance in the site. Table 5.7 shows the correlation analysis.

Table 5.7 Correlation between probability of having low annoyance and parameters

	Ratio of x-coordinate of fountain center to site width	**Ratio of y-coordinate of fountain center to site length**
Probability of having low noise annoyance	-0.465**	0.404**

*** significant at 0.01 level*

With the variables shown in Table 5.7, the relationship between probability of having low noise annoyance and site area, the ratio of x-coordinate of fountain to site width, and the ratio of y-coordinate of fountain to site length was expressed as:

$$Pr = \beta_0 + \beta_1 SiteArea + \beta_2 \frac{xcor}{SiteW} + \beta_3 \frac{ycor}{SiteL} \qquad (12)$$

where *Pr* is the probability of having low noise annoyance; *xcor* and *ycor* are the *x* and *y* coordinates of the center of the fountain; β_0 is the constant term; β_1 to β_3 are the coefficients of the independent variables.

Table 5.8 shows the regression results, the adjusted R^2 was found to be 0.927, meaning that the independent variables could be used to explain the probability of having low annoyance well. It can be seen that a bigger site would render higher probability of having low annoyance. Meanwhile, a higher ratio of x-coordinate of the center of fountain to site width would lead to lower probability. Conversely, ratio of y-coordinate of the center of fountain to site length increased with the probability.

Table 5.8 Regression analysis for acoustic performance

Parameters	Coefficient	Standardized Coefficient	Significance
Site Area	0.00000451**	0.760**	<0.001
Ratio of x-coordinate of fountain center to site width	-0.063**	-0.230**	<0.001
Ratio of y-coordinate of fountain center to site length	0.064**	0.194**	<0.001
(Constant)	0.537**	-	<0.001

***significant at 0.01 level*

As in the case of thermal performance, the values output from the inverse relationship had to be deterministic. From Equation (12), 5 inverse relationships had been derived:

$$SiteArea = \frac{\left(Pr - \beta_0 - \beta_2 \frac{xcor}{SiteW} - \beta_3 \frac{ycor}{SiteL}\right)}{\beta_1} \quad (13)$$

$$xcor = \frac{\left(Pr - \beta_0 - \beta_1 SiteArea - \beta_3 \frac{ycor}{SiteL}\right) \cdot SiteW}{\beta_2} \quad (14)$$

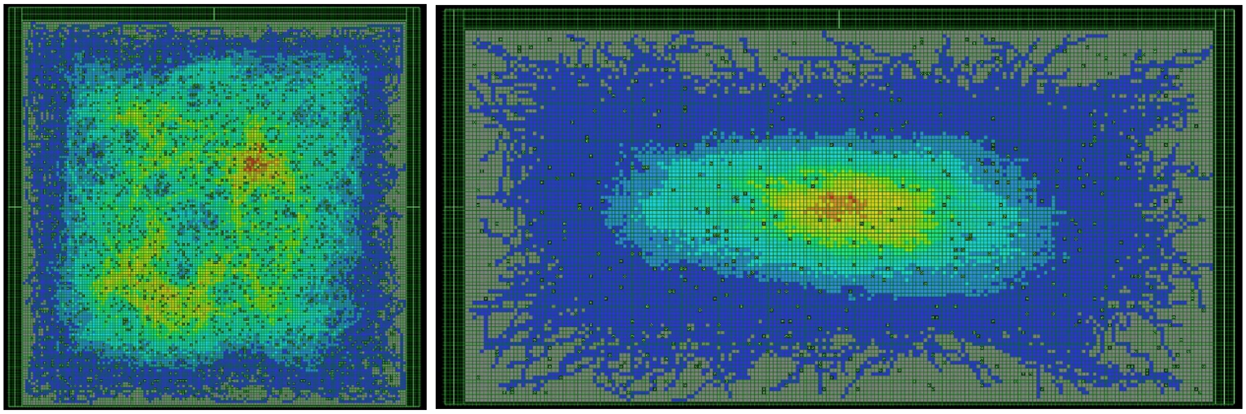
$$SiteW = \frac{\beta_2 xcor}{Pr - \beta_0 - \beta_1 SiteArea - \beta_3 \frac{ycor}{SiteL}} \quad (15)$$

$$ycor = \frac{\left(Pr - \beta_0 - \beta_1 SiteArea - \beta_2 \frac{xcor}{SiteW}\right) \cdot SiteL}{\beta_3} \quad (16)$$

$$SiteL = \frac{\beta_3 ycor}{Pr - \beta_0 - \beta_1 SiteArea - \beta_2 \frac{xcor}{SiteW}} \quad (17)$$

5.3.4 Spatial structure

In order to define spatial structure of the GOS, the notion of Space Syntax was introduced to the current experiment. Results from a previous study suggested that Space Syntax measure Connectivity could be used to understand the spatial structure of open space with trees [155]. As Connectivity values cannot be estimated within Grasshopper, the design scenarios have to be exported to the application Depthmap, which is a tool for Space Syntax analysis, for analysis. By generating visibility graphs, this application was utilized to reveal the average connectivity values of different variations of tree density and site dimensions. To this end, 2-dimensional representation of the design scenarios were generated in Grasshopper and exported to Depthemap. Figure 5.6 shows some examples of visibility graphs generated.



Left: tree density 0.1 tree/m², Site dimension 200m x *200m*

Right: tree density 0.025 tree/m², Site dimension 100m x *200m*

Figure 5.6 Visibility graphs generated by Depthmap

Figure 5.7 shows the relationship between tree density and average connectivity with respect to various site dimensions. Basically, average connectivity values decreased when tree density increased. The slopes of the curves also decreased when tree density rose. When tree density was small, a change in tree density would lead to greater drop in connectivity value. When the density increased, the same amount of change in tree density would lead to a smaller drop in connectivity value. Besides, it can be seen that different site dimensions would render different connectivity values. A larger site would lead to a higher connectivity value even when the tree density was the same. However, the gaps between connectivity values with respect to different site dimensions were found to be larger when the tree density was smaller. The gap actually became smaller when tree density increased. When tree density was 0.1, the percentage difference of average connectivity values between site dimension 100mX100m and 200mX200m was 3.78% while the percentage difference was found to be 139.39% when tree density was 0.025.

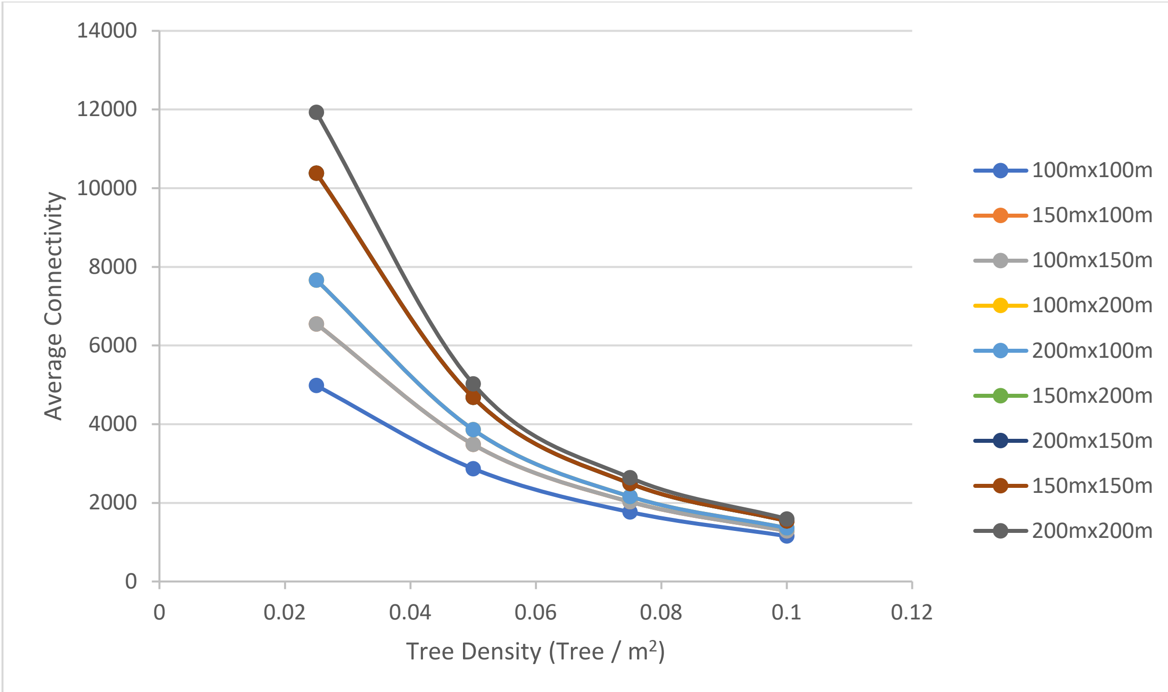


Figure 5.7 Relationship between tree density and average connectivity

Meanwhile, average connectivity value could be expressed as:

$$Con = \gamma_0 + \gamma_1 SiteArea + \gamma_2 TreeDensity \qquad (18)$$

where *Con* is the average connectivity value; γ_0 is the constant term; γ_1 and γ_2 are the coefficients of the independent variables.

Regression analysis technique was utilized to reveal the statistical relationship between connectivity and tree density, as well as site area. The adjusted R^2 was estimated to be 0.82, which means that the model could explain the data reasonably well. The regression results are shown in Table 5.9. The relative effects of the parameters on connectivity could be revealed from the absolute magnitude of standardized coefficients. The absolute standardized coefficients for tree density and site were 0.871 and 0.268. These results suggested that connectivity was mainly affected by tree density, followed by site area.

Table 5.9 Regression results for Connectivity

Parameters	Coefficient	Standardized Coefficient	Significance
Tree Density	-90378.13**	-0.871**	<0.001
Site Area	0.088**	0.268**	0.001
(Constant)	7657.12	-	<0.001

***significant at 0.01 level*

The inverse relationships for connectivity value, tree density and site area were:

$$SiteArea = \frac{Con - \gamma_0 - \gamma_2 TreeDensity}{\gamma_1} \quad (19)$$

$$TreeDensity = \frac{Con - \gamma_0 - \gamma_1 SiteArea}{\gamma_2} \quad (20)$$

As tree density would greatly affect both UTCI and Connectivity values, it was expected that thermal performance was interrelated to spatial structure rendered by trees. It was vital to understand the actual quantitative relationship between them in order to develop the parametric model. Figure 5.8 shows the relationship between average connectivity and UTCI reduction values at various site dimensions. As expected, a higher UTCI reduction value would mean a lower average connectivity value. This is because more trees will render more shaded areas and at the same time lower the average connectivity value. Meanwhile, site dimensions would also affect the relationship between connectivity and UTCI reduction.

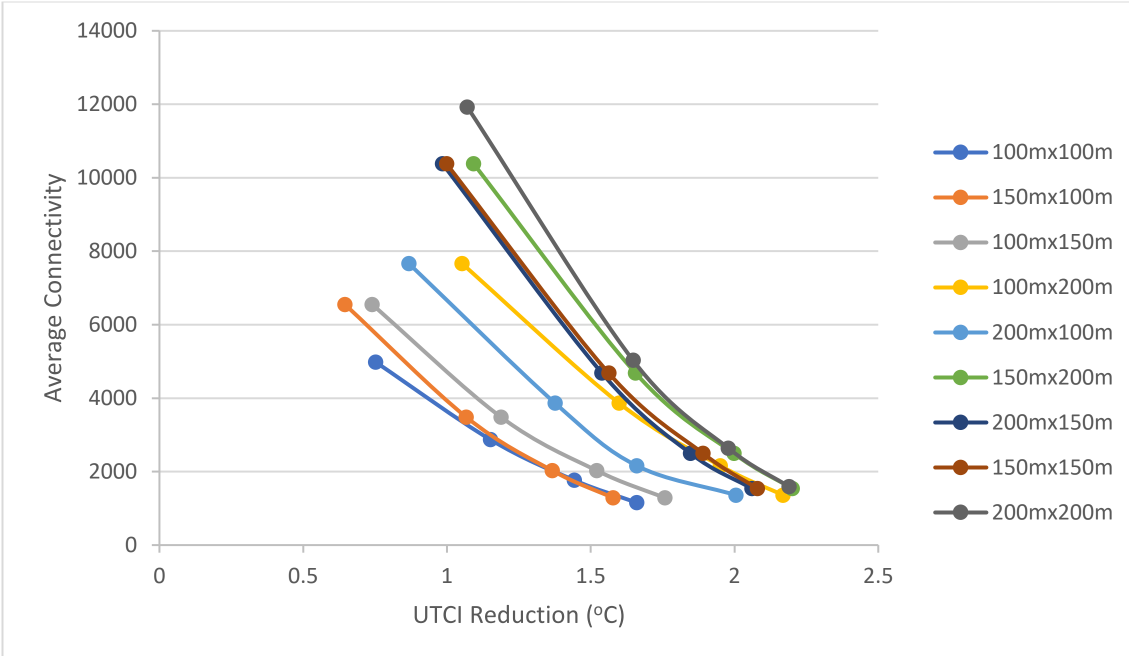


Figure 5.8 Relationship between Connectivity and UTCI reduction

Consequently, UTCI reduction could be expressed as:

$$\Delta UTCI = \delta_0 + \delta_1 Con + \delta_2 SiteArea \qquad (21)$$

where δ_0 is the constant term; δ_1 and δ_2 are the coefficients of the independent variables.

The relationship between UTCI reduction and average connectivity was further reveal by using regression technique. UTCI reduction values were regressed against average connectivity values and site area. Table 5.10 shows the regression results.

Table 5.10 Regression results for UTCI reduction and average connectivity

Parameters	**Coefficient**	**Standardized Coefficient**	**Significance**
Average Connectivity	-0.000136**	-0.879**	<0.001
Site Area	0.00003077**	0.605**	<0.001
(Constant)	1.360	-	<0.001

***significant at 0.01 level*

5.3.5 Parametric Model Development

After formulating the inverse relationships, the final step was to develop the parametric model by using these relationships. The basic idea was that the model would generate design options according to the desired performance levels. There were three major considerations when developing the model. First of all, there were boundaries for the performances. Second, there would be interrelated performances. Thermal performance and spatial structure were interrelated. Third, one performance might be related to multiple physical parameters.

Boundaries of Performances

There were boundaries for each of the performance considered. These boundaries were determined during the process of developing the inverse relationships. When scripting the final parametric model, it was vital to get the values of the boundaries of the performance levels. First of all, they were needed to set the ranges of performance inputs to the model. Designers will not be allowed to set the performances beyond these ranges. Besides, these values would also help to inform the designer about the performance boundaries of the design that was going to be generated. Taking thermal performance as an example in the current experiment, if a particular combination of site width, site length and tree density would lead to a UTCI reduction value which exceeded the boundaries, the model would inform the designer that the results were "out of range". The upper and lower boundaries of the performances are shown in Table 5.11.

Table 5.11 Boundaries of performance levels

Performance	Lower Boundary	Upper Boundary
Thermal Performance (UTCI reduction)	0.645	2.201
Acoustic Performance (Probability of having low noise annoyance)	0.519	0.743
Spatial structure (Connectivity)	1155	11927

Interrelated Performances

When the performances were interrelated, defining the value of a performance might fix the values of other performances simultaneously. To this end, the designer might define conflicting values of performances if it was not taken care in the parametric design model. The values of them should not be allowed to be defined independently. In the current experiment, there was a correlation between thermal performance and spatial structure rendered by tree planting. The input of the model should be scripted in a way that the designer can only define the value of either one of the two performances. The designer will not be allowed to define the value of average connectivity if one defines the value of thermal performance level, and vice versa. Meanwhile, the average connectivity value will be estimated after the designer define the desired thermal performance level and the estimated average connectivity value will be shown to the designer. On the other hand, UTCI reduction value will be estimated when the designer chooses to define the desired connectivity value.

Performances affected by Multiple Physical Parameters

Usually, performances would be affected by more than one physical parameter. The same performance level might render various combinations of physical parameters. In the current experiment, all the performances were affected by the site dimensions. However, it was assumed that the designer would define the site width and length. It is because the dimensions of the site are usually affected by other factors other than the performances of the site itself. On the contrary, when the designer of the model defines a particular performance value, it is needed to inform the designer about the different possible combinations or have the designer to fix the values of the physical parameters in concern in order to generate the design. In the current experiment, the latter was adapted as it will provide the designer with a greater degree of control on the possible design options to be generated.

Meanwhile, acoustic performance was affected by the position of fountain. Although the fountain position was considered one attribute, it comprised two physical parameters. They were the x and y-coordinates of it. Various pairs of x and y-coordinates might render the same probability of having low noise annoyance. As a consequence, designer will be allowed to choose which coordinate (x or y) to define so as to obtain the position of the fountain.

With all the above considerations, the performative parametric model for designing GOS was developed by using Grasshopper. There were basically four components of the model. The inputs of the model were the performance levels and values of controllable parameters. The estimation component estimated the values of the uncontrollable parameters. There was also a component to visualize the design. This component was developed during the scenario generation process and was reusable in the parametric model. A component to display the data related to the model generated was also included in the model. In the current experiment, the data output was mainly the performance levels and parameter values estimated. Figure 5.9 shows the Grasshopper interface of the model and these components.

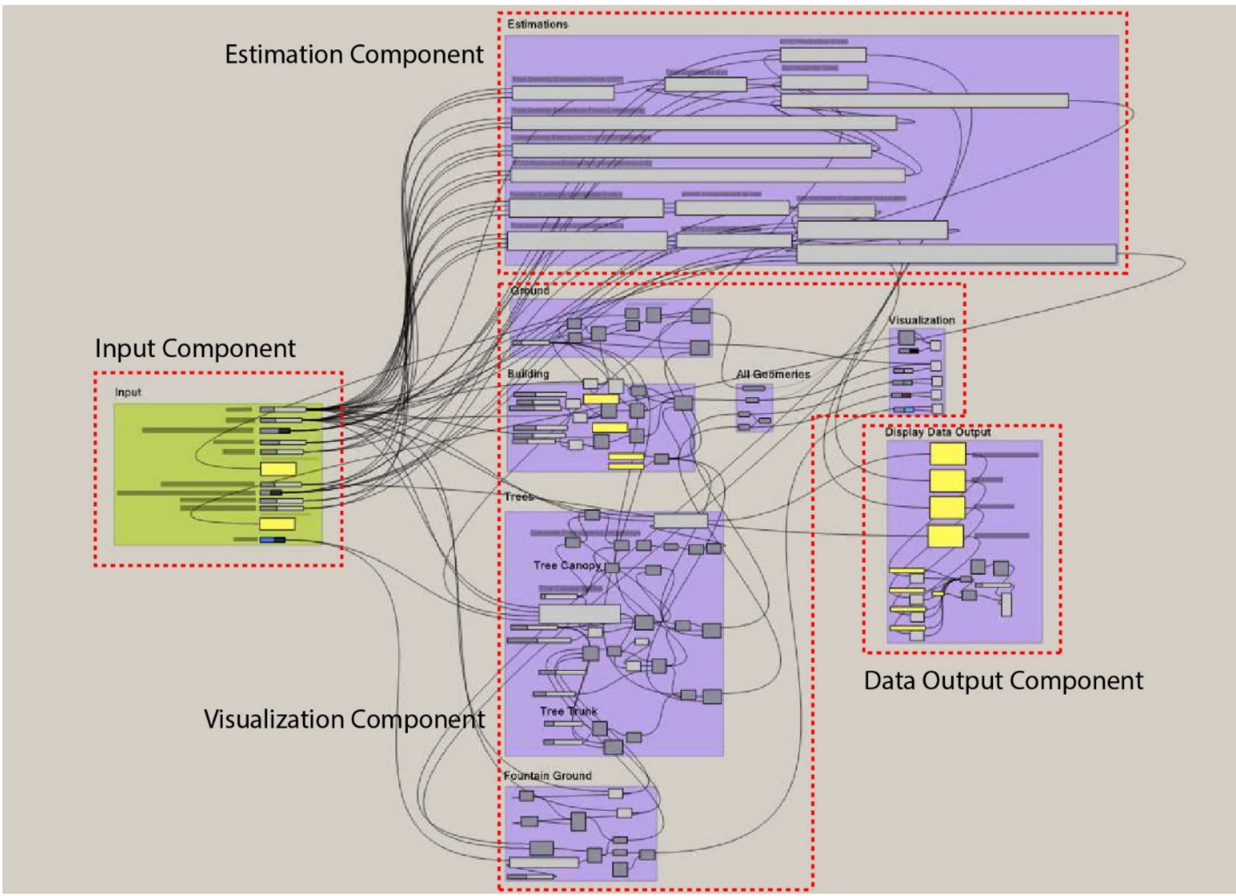


Figure 5.9 Grasshopper interface of the parametric design model and the components of the model

5.4 Design Generation by Using the Model

Basically, inputs that the designer can define in the model were:

- Site Width
- Site Length
- UTCI Reduction / Connectivity

- Probability of having low noise annoyance
- Fountain Center x-coordinate / y-coordinate

As mentioned, the designer has to choose to control either UTCI reduction or Connectivity value because these two performances were interrelated. Meanwhile, the designer has to choose to define x-coordinate or y-coordinate of the fountain center after one has set the probability value of having low noise annoyance. Figure 5.10 shows the input interface of the model in Grasshopper.

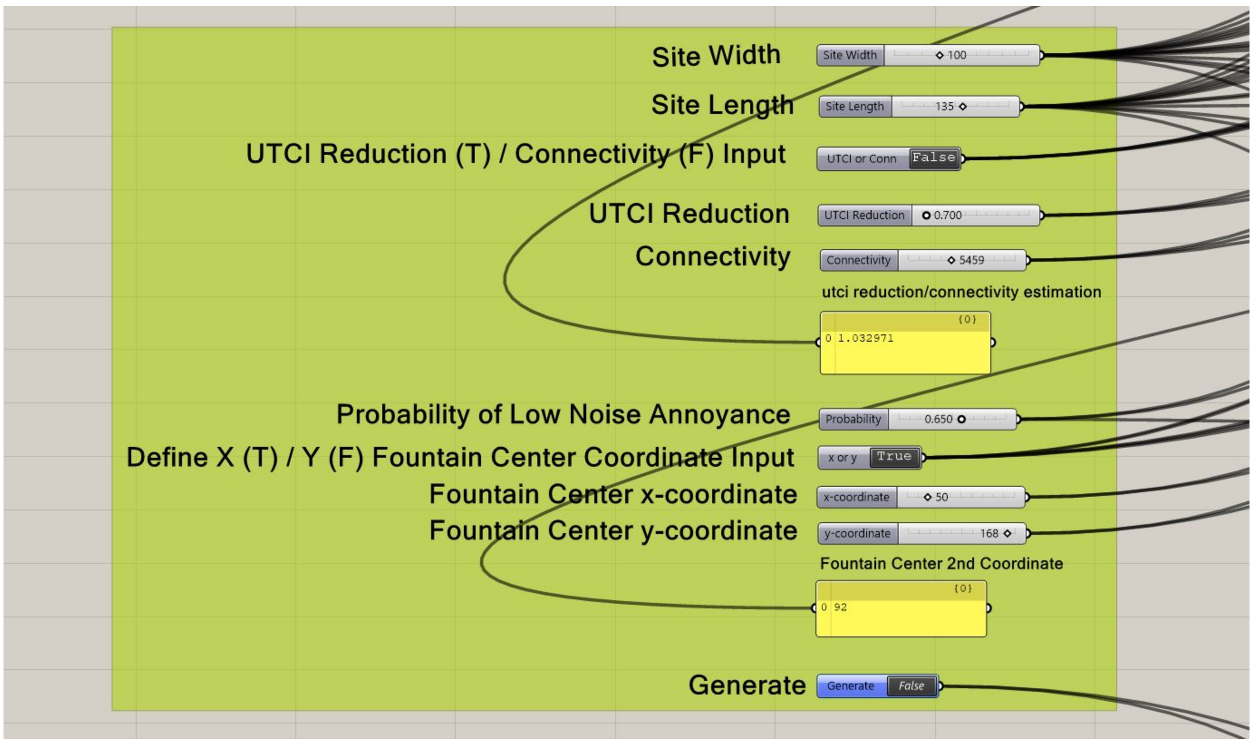


Figure 5.10 Input to the model in Grasshopper

It can be seen from Figure 5.10 that when the Connectivity value is set, the value of UTCI reduction would be shown to the designer. This is also the case for the location of fountain center. When the x-coordinate of the fountain center is set, the model will find the y-coordinate of the fountain center. As mentioned, there can be cases that it is not possible to have the desired performance values corresponding to the physical parameters / the interrelated performances. The model will show the designer that it is "out of range" in this case (Figure 5.11).

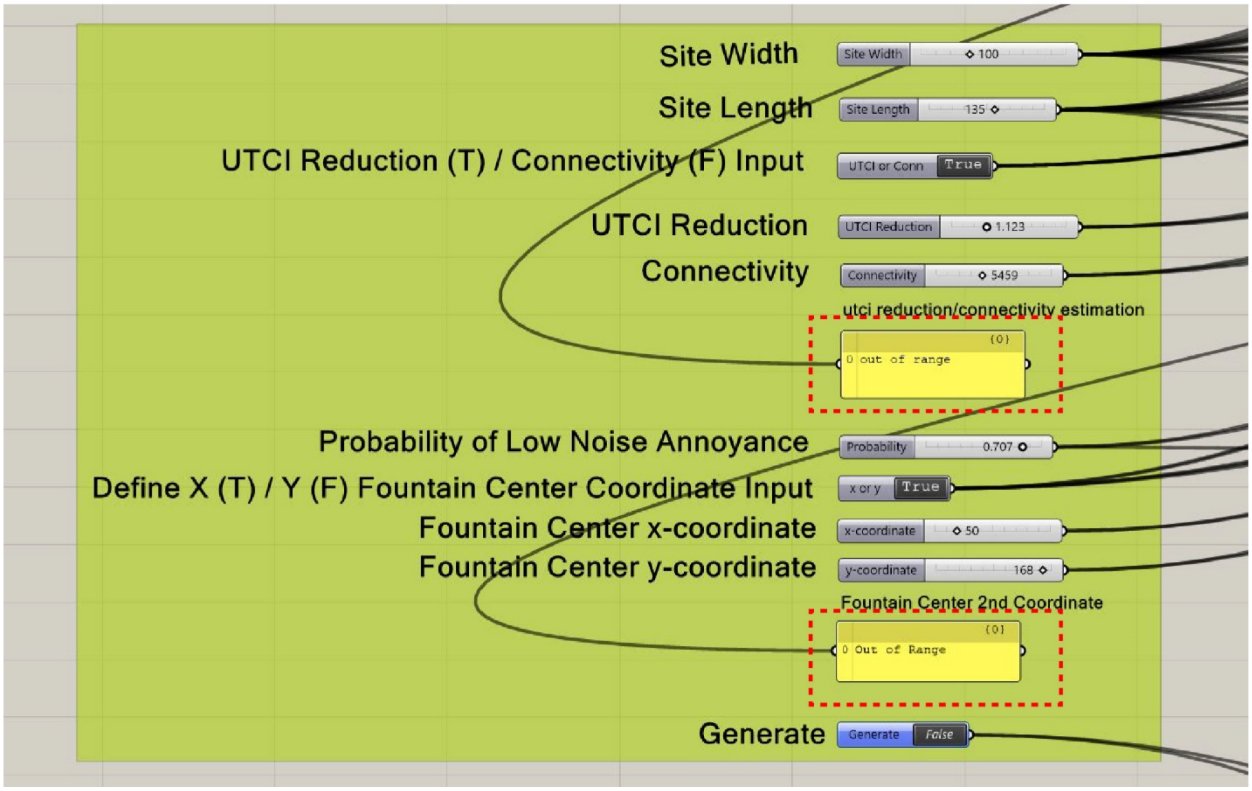


Figure 5.11 Model showing designer "out of range" when the desired performances corresponding to the physical parameters / interrelated performance cannot be found

After defining the input values, design options can be generated by the model if the values of UTCI reduction / Connectivity and x-coordinate / y-coordinate of center of fountain can both be found. Figure 5.12 shows two examples of the design generated by the parametric design model. Both graphic representation (geometrical output) and information related to the performances of the design (non-geometrical output) will be generated by the model.

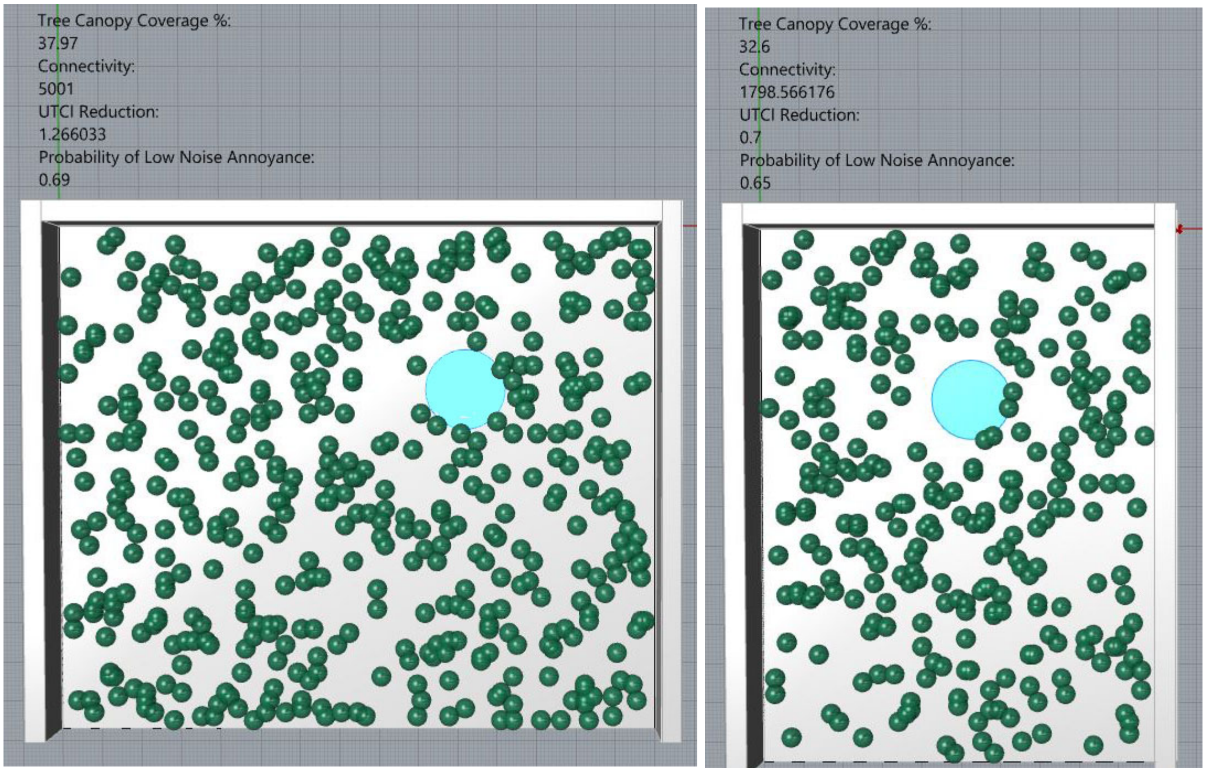
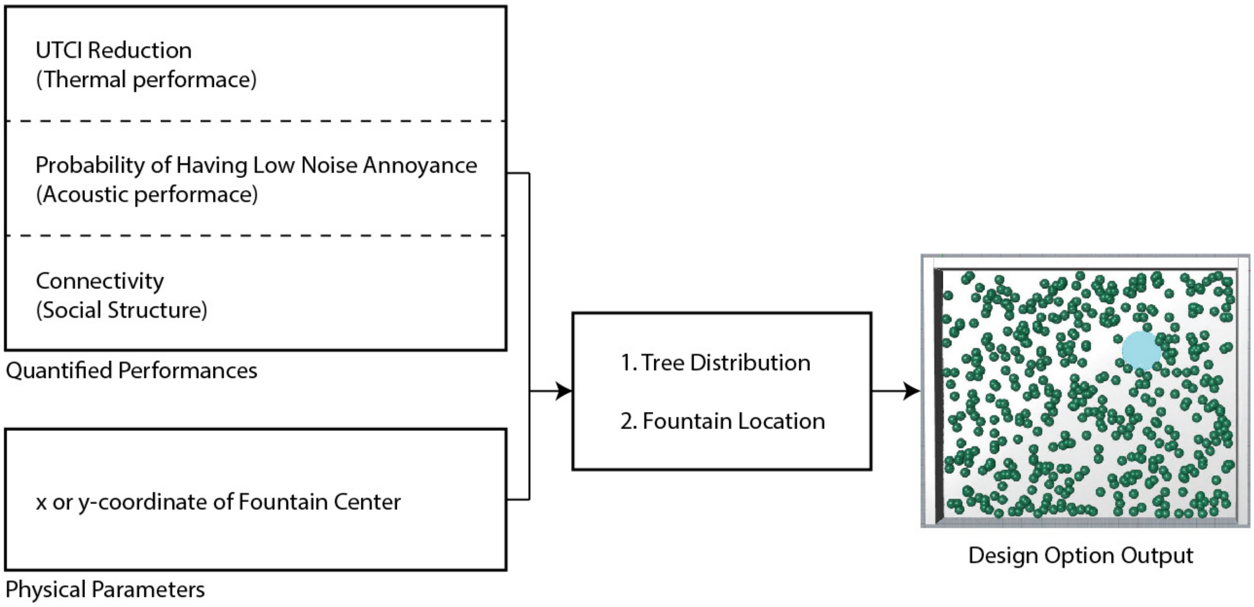


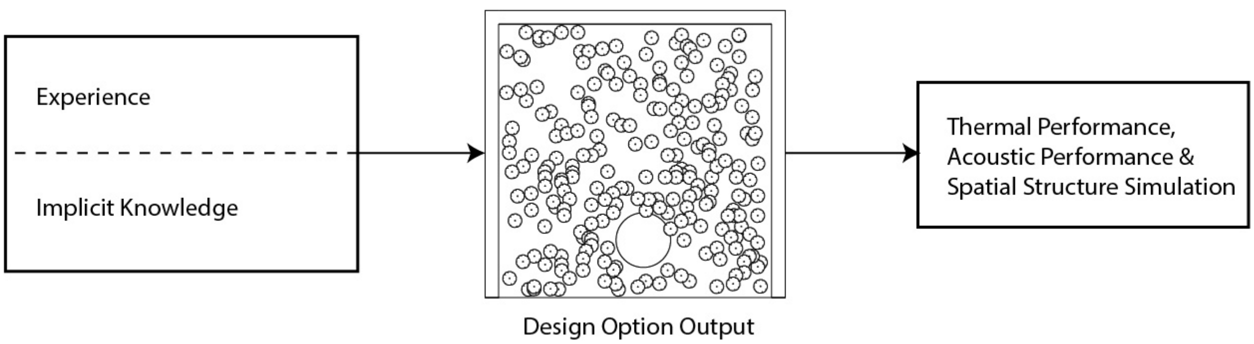
Figure 5.12 Examples of design options generated by the parametric design model

5.5 Comparison between the current model and traditional design method

Figure 5.13 compares the differences between designing the green open space by using the current model in the experiment and traditional design method. Assuming that the size of the site is fixed and only tree distribution and fountain location will be considered at the beginning of the design task, the designer has to consider the thermal performance (UTCI reduction) / spatial structure (connectivity) and acoustic performance (probability of having low noise annoyance) of the design when designing the open spaces with the developed model (Figure 5.13a). These performances are all with quantified values when the design task begins. Simultaneously, the designer has to determine either the *x* or *y*-coordinate of the fountain. The design option will be generated by the model. The performances are considered explicit knowledge to generate the design option. On the contrary, the way to generate a design option will be totally different when adapting traditional design method. In this case, the designer will create drawing, either by hand or computer drawings, of the design option with his or her experience (Figure 5.13b). The knowledge to generate the option is implicit and there will be no quantified performance when the design task begins. The performances can only be simulated or estimated when a concrete sketch of the green open space is created.



(a) Open space design by using the developed model



(b) Open space design by traditional design method

Figure 5.12 Difference between designing by using the model and traditional design method

6 PRINCIPLES OF DEVELOPING PERFORMATIVE PARAMETRIC URBAN DESIGN MODEL WITH INVERSE SIMULATION

From the experiment shown in the previous chapter, principles of developing a performative parametric urban model by using inverse simulation as a strategy were observed. Basically, they can be categorized as general, model scripting and model user interface and output principles.

General Principles

I Research about relationships among various performances and parameters must be conducted before generating urban design scenarios for developing inverse relationships

There are two possibilities when the inverse relationships of the parametric urban design model are concerned. The first possibility is that the relationships have been revealed in previous studies. The inverse relationships can be derived and scripted into the model directly. The second possibility is to generate design scenarios and identify the inverse relationships. In the experiment of the current study, the route of generating design scenarios was adapted. Green open space design scenarios with various tree densities, site dimensions and fountain locations were generated. This is because the relationships among the performances (thermal performance, acoustic performance and spatial structure) and physical parameters have not been revealed in previous studies. Although generating design scenarios for developing the inverse relationships should probably be the usual case, it is always preferred if the relationships have already been developed in previous studies. The main reason is that performance simulation can be an extremely time-consuming process. The time will add up if there are various types of performances to be revealed. Given that there is usually limited time for a design task, it will be a must to examine if there are relationships among the performances and parameters which have already been developed. This will help save the time needed to develop the parametric model.

II Performances have to be quantifiable urban, social, environmental, or economic indicators

According to the model development framework, there are 5 steps in order to develop the model. Of all these steps, the third one is to define and quantify the performances in concern. In fact, the success of developing the model will partly lie on the feasibility of quantifying the performances. Therefore, it is vital that all these performances are quantifiable urban, social, environmental, or economic indicators. In the experiment, thermal performance, acoustic performance, and spatial structure were performances which had been quantified in previous studies. The indicators, which have been developed before, of these performances could be adapted in the experiment. If a performance had not be quantified before, the designer or developer of the model will have to search for methods or indicators to quantify the performance. It will not be feasible to include a performance into the model if it is not possible to quantify the performance in concern.

III Parameters do not have to be physical urban features

In the experiment of current study, all the parameters were basically physical urban design features (e.g. trees and fountain). While it is usual to treat physical features as parameters, there can also be non-physical parameters. As discussed in Chapter 2, it is possible to include the notion of time into the parametric model. When it is included as a parameter, it will be possible to treat life cycle impact of the urban design project as a performance. This means that the parametric model will not only help to create the initial design of the urban spaces but also take care of the whole life cycle of the design.

IV Simple mathematical relationships are preferred for the inverse relationships among performances and parameters

There are two ways to deal with the inverse relationships among the performances and parameters. The first way is to store sets of performances and parameter values in a database. The parametric model can search for the set of parameter values corresponding to the performance value defined by the designer. If all the parameters are categorical, there will only be a limited number of combinations of parameter values. This also implies that there will only be a limited number of discrete values of performances in this case. All these performance values corresponding to various combinations of values of parameters can be stored in the database. Storing the performance and parameter values in a database will be a preferred option in this case as the operation of searching in a database can usually be completed within a second. However, this option will not be preferred if some of the parameter values are continuous. The reason is that there can be cases that the value of performance input does not exist in the database. Developing mathematical relationships among the performances and parameters will be a better option. In this case, simple mathematical relationships will be preferred. It is because the parametric model can perform faster if the mathematical relationships are simpler. This also explains why linear relationships were adapted in the experiment. This consideration will be even more important if the model will be used on the internet as individuals will expect to wait for a few seconds at most in order to have the design option generated.

V Not all parameters related to performances have to be uncontrollable

There were controllable and uncontrollable parameters according to the model development framework. Here, controllable parameters are parameters that the designer will define the values of them in the parametric model. On the other hand, uncontrollable parameters are parameters that the values of them will be estimated with respect to the performance values being input. The designer will not define the values of these parameters directly. It is worth mentioning that it is not necessary to define all parameters related to the performances as uncontrollable parameters. As demonstrated in the experiment, the dimensions of the site were considered controllable. This was because there would probably be considerations other than the performances included in the model. These considerations may affect the dimensions of the green open space. However, this does not mean that the site dimensions must be treated as controllable parameters. It was used to demonstrate the two types of parameters in the experiment. The decision on whether a parameter is controllable or not depends on other concerns of the design task which have not been included in the model. As a result, it will be the decision of the designer to choose what parameters should be controllable or uncontrollable.

VI Boundaries of performance values have to be clearly identified

Regarding the performances included in the model, the boundaries of the performance values have to be identified before formulating the model. The boundaries will be revealed during the process of developing the inverse relationships. These boundaries will in turn be scripted into the model. In fact, the relationship revealed may not hold beyond the boundaries identified. As a result, the designer should not be allowed to define performance values outside these boundaries. Besides, these boundary values should also be shown to the designer in the model because informing the designer about these values will help the designer to have an idea about the maximum and minimum performances of the design.

<u>Principles of scripting the parametric urban design model</u>

VII It is preferred that the components developed during urban design scenario generation are reusable when formulating the performative parametric urban design model

Although it is not a must to do so, it is preferred that both processes of urban design scenario generation and parametric model formulation are done in the same software application. When doing this, components developed during scenario generation process can usually be reusable when formulating the parametric model. In the experiment of current study, urban design scenario generation, performance analysis, and parametric model formulation were done using Rhino3D and Grasshopper whenever possible. The only exception was the spatial configuration analysis, which was done by using Depthmap. This was because there was no available add-on to perform this analysis on Grasshopper. Meanwhile, the component to visualize the design was reusable in the experiment. This component was used to generate the plans and 3D representations for both the design scenarios for performance analysis and design options of the parametric model. Making use of reusable components will help to save time when developing the parametric model.

<u>Principles of model user interface and output</u>

VIII Values of interrelated performances should be estimated automatically when the value of one of these performances is defined

Without doubt there can always be performances which are interrelated. These performances can even be competing with one another. In the experiment, spatial structure and thermal performance due to the planting of trees are two competing performances. When the value of thermal performance was set, the value of the Space Syntax measure Connectivity would be estimated and shown, and vice versa. This principle should apply regardless the number of interrelated performances. The relationships among all these performances should be revealed during the inverse relationship development process. The values of the interrelated performances should be changed simultaneously when the designer changes the value of a performance. Meanwhile, there may be more than one set of interrelated performance values which can fulfil the performance goal requirement when the designer defines the value of this performance. An optimization algorithm can be linked to the parametric design model to deal with this issue [200], [201]. With the algorithm, it will be possible to estimate sets of values of these interrelated performances. Some examples of such algorithms include applying a weighted factor for each performance and Pareto approach [202], [203]. However, optimization technique was out of the scope of the current study and it would not be discussed further.

IX Values of all parameters involved should be estimated automatically when the value of a performance affected by multiple parameters is defined

Usually, a performance will be affected by more than one parameter. In the experiment, all the performances were basically affected by multiple parameters. Taking acoustic performance as an example, it was affected by location of the fountain and site dimensions. There can be various combinations of parameters which can fulfil the same performance level requirement. In the current study, the proposed method to deal with the issue was to allow the designer to define the values of the other parameters connected to the performance in concern so that the model only had to search for the value of one parameter. It must be noted that this is only one of the ways to deal with the issue. In the study of Rezaee et al. [2] about inverse simulation of building cooling load and building envelope configurations, a range of values of the attributes such as window-to-wall ratio or u-value of windows could be obtained by a given target cooling load of a building. This method can be one of the ways to deal with the problem and incorporated into the parametric model if only non-geometric output is needed. However, regardless of the method to estimate the values of the parameters, the designer must be informed about these values so that the designer can understand what the design option will be like.

X Values of parameters estimated from performance input are preferred to be deterministic

The values of parameters have to be deterministic if graphical representations of design options are needed. As a result, the method adapted by Rezaee et al. [2] may not be a preferable method for the performative parametric design model in most cases as designers usually want to obtain graphical representation of the design in order to further develop the design options. In fact, all the values of parameters estimated were deterministic in the experiment. This was to make sure that graphical representations of the design options could be obtained from the model.

XI The model should generate both plans and data related to the design as output

As discussed, the output of the model can be geometrical, non-geometrical or a combination or both. A parametric model generating both geometrical and non-geometrical output will be preferred. There are a few reasons for it. In order to visualize the design option generated by the model, geometrical output will be a must. Designers will need the graphical representations in order to further evaluate or develop the design options. Here, one of the most important graphical output is the plan of the design. Indeed, "plan is generator" of cities [195]. On the other hand, it will be important to inform the designer about the performances and basic information (such as the tree density in the experiment) of the generated design option. When the scale of the design task is larger, indicators such as Floor Area Ratio (FAR) should be a part of data output. Outputting information and performance indicator values of the design from the parametric model can help designers to make judgement when further evaluating the design [8]. As a result, information of the design and values of the performance indicators should also be an output of the parametric design model.

7 CONCLUSION AND DISCUSSIONS

As per the best knowledge of the author, the current study was the first one which attempted to formalize the use of inverse simulation as a strategy for the performative approach of parametric urban design model. Principles and steps of developing a model by using this strategy was also laid out in the current study. Multiple design performances (both environmental performances and spatial structure) can be treated as input to the parametric urban design model. Indeed, integrating simulation and optimization techniques with parametric design is one of the major challenges for the performative approach. "*How can performative data be exploited directly as data input in parametric meta-models*" [204] should also be a challenge when developing performative parametric design models. To this end, the current study should help shed light on the way to deal with this challenge, as well as giving one of the possible answers to this question.

From the experiment, it can be seen that it is feasible to include performances of the design as inputs to the parametric urban design model. By scripting the inverse relationship between the performances and physical parameters into the model, design options can be generated by the model when the desired performance levels of the design are input. In the case of the experiment, the distribution of trees and fountain location could be found by specifying UTCI reduction value (thermal performance) / connectivity value (spatial structure) and probability of having low noise annoyance level (acoustic performance). To this end, a design option of the green open space can be generated when the desired thermal performance / spatial structure and acoustic performance are input into the model. Meanwhile, thermal and acoustic performances are environmental performances of green open spaces. The concept of including both environmental performances and spatial structure of an urban design solution within a single parametric urban design model was proved in the experiment. With such a parametric urban design model, it will be feasible to consider quantified performances of the design and utilize them as the actual driver to design. Compared to designing with traditional method, quantified performances can only be simulated after the design is generated and the design is usually created according to the implicit knowledge and experience about the performances of the designer.

Another primary result arisen from the current study was that the formalization of the procedure to develop a performative parametric urban design model with the notion inverse simulation. There are five main steps when developing such a parametric design model. These steps are 1) identifying constraints; 2) defining performance goals; 3) identifying parameters; 4) developing mathematical relationship between performance and parameters which affect the goals (inverse simulation); and 5) constructing the model. This procedure should be universal regardless the type or nature of the urban design tasks. Besides, three main categories of principles were identified for performative parametric urban design models incorporating inverse simulation. First, there are general principles for the model development. These principles are related to the quantification of the performances and parameters, as well as the relationship between the performances and parameters. Second, there are principles when actually scripting the model. It is preferable that the components developed can be reusable in different steps of developing the model. Third, principles for developing the user interface (UI) were also identified in the current study. The principles related to the UI development are about how the values of performances and parameters should be displayed and the output of the model.

Usually, the notion of combining evolutionary approach with parametric design aims at searching for the most optimized design solution [205]. For instance, by using evolutionary approach and parametric urban design model, the study by Yazici [65] aimed at optimizing the green areas in cities. The question being asked with this method is usually "what is" (the most optimized solution). When search for the most optimized solution, there will usually be one final solution generated, although it is possible to examine the solutions generated during the iteration process. However, the question asked is "what if" when adapting the strategy developed in the current study. Various design options corresponding to different performance levels can be generated with a parametric design model developed under the proposed framework. As a result, parametric model developed under the model development framework in this study will help designer to understand "What the design options will be if the performance requirement is…". In fact, divergent and convergent steps are repeated alternatively during the design process [206], [207]. Here, the divergent steps are about the generation of options or alternatives while convergent are about evaluating and selecting the best options. During the early or conceptual design stage, it is vital to generate a range of design concepts or options (divergent step) [206]–[209]. This will make sure that valuable concepts will not be over-looked and therefore increase the probability of getting to a better final design solution [210]. Parametric design model developed under the framework should serve this purpose of generating design concepts by considering the performances of the design.

As in the experiment of the current study, a forward-backward approach has to be taken when developing the performative parametric design model in this case. Different design scenarios have to be generated and the performances of these scenarios have to be quantified (forward) in order to build the inverse relationship between performances and physical attributes of the one. After the relationship are revealed, it will be possible to develop a parametric model which generates design solutions based on given performance levels (backward). In the current study, a more traditional parametric technique had been utilized for the forward procedure. Design scenarios were generated by changing the values of the parameters one by one. However, it should be noted that this is only one of the possibilities for the forward procedure. There can also be other methods to generate the design scenarios. For example, it is possible to use Monte Carlo method [211], [212] to generate various random combinations of physical design attributes so as to build up the design scenarios and identify the relationship between performances and physical parameters of the design.

On the other hand, parametric models can potentially be used as a tool for communication. The design and construction of Aviva Stadium in Dublin is an excellent example. By using a parametric model shared between architects and engineers, form, structure and facade of the building was optimized. The model also acted as a communication tool among architects, engineers, client, local planners, contractors and cladding sub-contractors [213], [214]. However, the model and construction process documented in these studies were mainly about the communication between AEC (Architecture, Engineering and Construction) professionals. On the other hand, Steino et al. [215] suggested that a parametric model can be an effective tool for communication among stakeholders even in public design workshops. Meanwhile, planners and politicians considered interaction with various parties in society vital because it can help ensure that the urban design process will be more democratic [216]. To this end, parametric models can potentially become a democratic tool for the communication between professionals and laypeople in an urban design task.

In the context of a design workshop with locals, there should be some considerations when using a parametric model as a communication tool. First of all, considering information visualization and communication, natural language is always preferred when explaining complicated ideas [217]. This notion should also apply to a parametric model as a communication tool. Specifically, the performances included in the model should be expressed in easy and natural languages. As per the experiment, it can be too complicated to communicate with laypeople about the acoustic performance by using the probability of having low annoyance. Translating the input to verbal description such as "Annoyed", "Slightly Annoyed" and "Not Annoyed at all" can be one of the ways to tackle the issue. With this type of translation, individuals who are not in the AEC field can play with the model to discover possible design options without difficulty. Besides, it will be important for the model to generate the design in a timely manner. Given the current power of computers, a model employing evolutionary approach may not be able to generate design solutions quickly. It is because simulation is a part of the model and it usually takes hours if not days in order to complete the simulation process [218], [219]. To this end, the strategy proposed in the current study will help develop parametric urban design models which can better serve the purpose of communication. As the inverse relationships are usually mathematical formulae, results can usually be obtained in seconds. This will help to make sure a smooth discussion about performances and design solutions in the context of public design workshops.

Although the procedure and principles of developing performative parametric urban design model by using inverse simulation has been formalized, the current study is not without limitations. First, while most of the principles were verified in the experiment, the particular principle of treating time as a parameter and life cycle impact as performance input to the model was not verified in the experiment. While it should be possible to treat life cycle impact as performance input if time dimension is one of the parameters, this was not verified in the experiment. In fact, the notion of performative parametric urban design is still in its infancy, it has not been fully explored yet. Meanwhile, it will not be possible to examine every possibility of utilizing this type of parametric model for urban design in a single study. However, this principle is listed in the current study so as to treat it as one of the possible directions of future study.

Besides, there are also some ideas about user interface of the parametric urban design model that were not demonstrated in the experiment. Due to the limitation of Grasshopper, the idea of showing the estimated values of interrelated performances was not fully demonstrated. In the current experiment, designer had to declare whether they would input UTCI reduction (thermal performance) or Connectivity (spatial structure) values so that the model will estimate the corresponding interrelated performance values. This was also the case for performances affected by multiple parameters. However, this does not mean that it is impossible to show the values of all interrelated performances or values of multiple parameters affects a performance simultaneously when the value of a performance is defined. This should only be a technical issue that can be solved.

Meanwhile, there are four main directions when further study is considered. The first direction would be extending the experiment so as to test the implementation of the model development framework. First of all, some more physical parameters can become alterable. For example, the size of the fountain or even the number of fountains in the green open space can be defined as alterable physical parameters. Meanwhile, more performances would be expected to be added to the model in further studies. Including the possible initial cost as performance in the model will help to understand more about how to deal with interrelated performances. This is because the cost will be related to all the physical attributes and therefore all the performances will become interrelated. It would also be of interest to apply the model development framework to develop a parametric design model for green open space design in a real site. As mentioned, how to include life cycle impact as performance and time as parameter in the model should also be examined in future studies. A parametric model embracing life cycle impact as performance can enable the model to take care of the whole life cycle of the green open space being designed.

On the other hand, creating a library of models for green open space design corresponding to different climatic zones will also be recommended. By doing this, the models can be used in various locations around the globe. Indeed, previous studies suggested that designers tend to rely on intuition and past experience, and followed by guidelines or guidebooks to aid the decision making process [220]. As Bambardekar and Poerschke pointed out, the popularity of using guidebooks is due to the time and cost effectiveness of using them. Besides, detailed information of the design will not be required when using guidebooks [12]. These are what a library of models developed under the proposed framework can provide. As a result, the library should be able to serve as an interactive guidebook for designers when performing green open space design tasks. An online version of this library of models will also help to test how these models perform in the context of public design workshop or how they can be used for public consultation on urban design process.

Besides, it will also be of interest to apply the model development framework to develop a parametric urban design model for a real site. In the current study, the model was developed for designing a virtual site. It was mainly for the sake of proving the concept of the model development framework. To this end, it will be natural to attempt to apply the framework in a real situation in the next step. Specifically, it will be preferable to develop a parametric urban design model with the aim to both design a green open space and communicate in a public design workshop. This will help to further demonstrate how to implement the model development framework when formulating a parametric urban design model.

Another direction of further study will be extending the model development framework. As mentioned, trade-off or optimization among various performances was not included in the model development framework. With an optimization or trade-off mechanism in the model development framework, the designer will not have to perform the trade-off. As an optimization mechanism can help to reduce the size of solution space [221], model developed under the framework will also aid the designer in selecting options during convergent steps of design after the mechanism is implemented.

While an alternative strategy of performative approach has been proposed in the current study, it should be noted that the comments by Christopher Alexander [44] still hold. Solely relying on the model may distort the views of the designer on the design problem. As a result, it may not be appropriate to use the models developed under the proposed framework to generate a "final design solution". Instead, it should be considered a tool for the designers to explore a larger solution space. As discussed, model developed under the model development framework will suit early design stage or divergent step of design well. It is expected that designers will further develop the options generated by a model developed under the development framework. Designers will still have to consider aspects which are not, or cannot be coded in the model.

Regardless the strategy adapted for developing performative parametric design models, a question needed to be asked is whether such a model is a new "form follows function" statement. As questioned by Oxman [1], "When and how does it become justified for the designer to intervene with the impact of physical law?" In fact, an extension to this question could be about the role of designers when more performances are included in the parametric design model. If form follows performances, should the designer really "intervene with the impact of physical law"? If Paramatricism, or Parametric Urbanism is a new design style [41], will performative parametric urbanism also a new design style? Will the designs generated by a performative parametric urban design model create a new form of aesthetics? These are the questions we may have to ask when designing with performative design models.

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