Decision-Making Support in Early Design Stage for High Performance Naturally Ventilated Buildings

HARVARD UNIVERSITY
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THESIS ACCEPTANCE CERTIFICATE

The undersigned, appointed by the Doctor of Design Program, have examined a dissertation entitled

Decision-Making Support in Early Design Stage for High Performance Naturally Ventilated Buildings

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candidate for the Doctor of Design degree and hereby certify that it is worthy of acceptance.

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Decision-Making Support in Early Design Stage

for High Performance Naturally Ventilated Buildings

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Abstract

While a lack of design decision-making support for natural ventilation evaluation in the early stage is noticeable, the interest in high performance naturally ventilated buildings has been rapidly growing in recent years. As a response, the target of this dissertation was to develop a design decision-making support system, including a new index and a calculation procedure, to help designers make better informed decisions in the early stage by taking natural ventilation into account.

To achieve this goal, the objective of this research had to be defined first. This meant defining the index to be used when evaluating natural ventilation in the early design stage. The study began by reviewing current practices of natural ventilation evaluation in the literature and identifying the problems of current indices. Considering the precision criterion was special for this stage and the available design information was limited, a new index had to be developed. A Design-Based Natural Ventilation Potential was proposed as the evaluation index of natural ventilation,

especially for the early design stage.

After defining the objective, a procedure for calculating the natural ventilation evaluation index was developed. The calculation procedure study consisted of two main parts, outdoor wind environment simulation and indoor natural ventilation calculation. For the outdoor wind environment simulation, an automatic process of computational fluid dynamic (CFD) simulation was suggested to provide a wind pressure coefficient database on the facade, including the influence of weather conditions and the urban context. Results would be used as boundary conditions for the indoor natural ventilation calculation. For the indoor calculation, a simplified calculation method was proposed as the solution to complete a quick natural ventilation evaluation during the early design stage. To achieve the simplified calculation method, similarity analysis was conducted, and then CFD simulation was employed to perform numerical experiments. Simplified calculation equations were built by regression of the numerical experiment results and were validated. The equations provided similar results to CFD simulation, but with much less time. Cross-ventilation was used to illustrate development of the simplified calculation method. In the end, a practical way to evaluate the Design-Based Natural Ventilation Potential was found using the automatic outdoor wind environment simulation and the simplified indoor natural ventilation calculation.

Lastly, a case study was employed to illustrate the possibility of this decision-making support system for natural ventilation evaluation in the early design stage. The design decision-making support system was embedded in the architectural modeling software to provide quick feedback on the design. Scripts were developed to carry out the natural ventilation evaluation calculations in Grasshopper. A building form optimization study was conducted based on the potential for natural ventilation evaluation in the early design stage, showing the advantages of this support system for designers.

In conclusion, a comprehensive and practical natural ventilation evaluation to help with decision-making in the early phase of design was developed in this research. This innovation enables better informed design decisions early in the design process.

Keywords

Building Performance Informed Design, Evaluation Index, Automatic Process, Simplified Calculation Method, Numerical Experiment, Regression, Evaluation Procedure, Embedded System

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Nomenclature

Variable	Description	Unit
ρ	Air density	kg/m^3
ν	Air kinetic viscosity	m^2/s
g	Gravity	m/s^2
ΔP	Pressure difference on openings	kg/ ms^2
H	Floor Height	m
A_i	Inlet area	m^2
A_o	Outlet area	m^2
z_i	Inlet elevation from floor level	m
z_o	Outlet elevation from floor level	m
w_i	Inlet width	m
w_o	Outlet width	m
h_i	Inlet distance from ceiling	m
h_o	Outlet distance from ceiling	m
a_T	Triangle side edge length	m
a_R	Rectangle side edge length	m
b_R	Rectangle side edge length	m
r	Circle radius	m
x	Outlet relative position x	m
y	Outlet relative position y	m
α	Outlet relative normal angle	π
A_f	Total floor area	m^2
L	Total wall length	m
$A_{0.2/1.2} \sim A_{0.6/1.6}$	Area with certain air velocity limits at different heights	m^2
$x_1 \sim x_{13}$	Input similarity criteria	m^2
$y_1 \sim y_{10}$	Target similarity criteria	m^2

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Chapter 1 Introduction

1.1 Background

Design is a problem-solving process. It can be understood as a decision-making process balancing information from different resources. It follows certain operations in a looping design sequence (Brawne, 2003; Herbert, 1966; Young, 1986). Traditionally, design was a negotiated solution taking into consideration functions, space quality, aesthetics, structure, cost, and other aspects (Moore and Design Methods Group, 1970). In recent years, more information regarding building performance has been part of the decision-making process, including but not limited to energy consumption, natural ventilation, thermal comfort, air pollution, walkability, daylighting, and noise. Building performance, especially building energy consumption, has received growing attention in all design stages due to increasing impact from energy and environmental issues.

To address the building performance in design, a new methodology was developed, called building performance informed design. Under this new methodology, performance information (for example, building energy consumption) should be taken into consideration not only after the design process but also integrated into all design stages to achieve best performance. Building performance evaluation process should be integrated with the design process by continuously providing feedback, adjusting the design as needed, and receiving revised information in order to avoid the high cost of later changes (Abaza, 2012). As a case study, a team of architects and engineers were asked to integrate building performance evaluation into the design process in an actual architectural competition. This is a good example of building performance informed design. The result showed that a low energy demand design could be achieved by integrating building energy simulation with design, while also maintaining design quality (Jørgensen et al., 2011).

Researchers have been working in several fields to develop this design methodology, including building performance evaluation technologies, performance evaluation and design integration, design decision-making support system development, and so on (Welle et al., 2011; Weng et al., 2015; Yi & Malkawi, 2008). There remain significant research issues, and some of the important ones are identified and introduced in the following section.

1.2 Research Issues and Objectives

1.2.1 Research Issues

Among all the unsolved questions in building performance informed design, three research issues are introduced below. These are the main motivations of this research.

1.2.1.1 Design Decision-Making Support

The first issue that this research focused on was the design decision-making support system. Design decision-making support systems related to integrating building performance and design process are critical to applying building performance informed design methodology in practice.

Case studies have been conducted regarding integrating building performance evaluation with design. On building detail scale, a performance-oriented design methodology was applied to building skins. A parametric optimization design approach was used to consider daylight and thermal comfort as two indicators of design quality (Turrin et al., 2012). On a bigger scale, a study on building form optimization based on building energy performance was conducted. In the study, a wide range of variability in building forms was investigated, which resulted in significant improvement of building energy performance (Weng et al., 2015). Building energy performance simulation was also combined with artificial intelligence in the design process. A simulation-based artificial neural network model was used to predict energy performance, and a genetic algorithm was used for design optimization (Magnier & Haghighat, 2010).

Given these case studies of design integrated with building performance evaluation, some researchers attempted to develop a practical design decision-making support system to employ building performance informed design methodology. A BIM-based integrated design methodology was built for thermal simulation and daylighting simulation. Several barriers of currently commercially available simulation technologies were overcome to improve integration of building performance evaluation with design (Welles t al., 2011). As another example, a platform was developed to support integration of an optimized design process with energy and environmental performance. The platform assisted collaboration of different members of a design project throughout different design stages (Michael et al., 2013).

In addition to design feedback on single case, design decision-making support systems can contribute to knowledge about the key design factors that most influence building performance. For example, a study was conducted with a design workshop, when all design decisions and identified common patterns were analyzed based on qualitative social science research methods (Bleil de Souza, 2013). Researchers also pointed out that parameter variations in building performance simulation could cause a significant difference in results, and understanding the potential of different parameters would be helpful for designers during the decision-making process. A backtracking search was performed to identify the most influential variables (Bucking et al., 2014). Recently, a sensitivity analysis of different decision-making processes was performed, for better performance robustness on energy analysis (Attia et al., 2013). All of these studies attempted to determine key design factors, which would contribute not only to one case but also to future designs.

In short, decision-making support systems integrating building energy performance with design was established. The benefits of such a design decision-making support system were also recognized. However, these studies mainly focused on building energy consumption. Design decision-making support system focusing on other aspects of building performance, in this research the natural ventilation as introduced in the next section, is the main target of this dissertation.

1.2.1.2 Natural Ventilation

Natural ventilation has been a popular research topic for decades. It benefits the built environment in several ways; however, it has been challenging to fully utilize this strategy in design.

Natural ventilation has been recognized as one of the most promising passive strategies to reduce building energy consumption by HVAC systems, which is a large part of total building energy consumption (Etheridge, 2012). It is self-evident that natural ventilation can contribute to reduction in building energy consumption directly, as a free cooling resource when the outdoor climate conditions fall in the comfort range. This benefit is especially critical in moderate climate zones. For example, a case study was conducted in Hong Kong that presented a 24% energy savings achieved by utilizing natural ventilation in public housing (Yik & Lun, 2010).

In addition, natural ventilation can benefit a built environment by improving the thermal comfort level (Nicol, 2012). Early in 1992, a field study of thermal comfort in both air-conditioned and naturally ventilated offices was performed using a questionnaire and measurements of the thermal environment. The observation was that occupants in naturally ventilated offices had a higher tolerance of temperature than those accustomed to an air-conditioned environment (Busch, 1992). Based on this conclusion, the air-conditioning hours could be reduced, leading to significant reduction of building cooling energy consumption. This benefit was recognized more widely in recent years as part of active thermal comfort theory (ASHRAE, 2013).

These two benefits of natural ventilation can help reduce building energy consumption and improve the building thermal environment. In addition to these two benefits, researcher also observed productivity improvement in a naturally ventilated environment. The impact of natural ventilation was significant on focus and cognition

(Yudelson, 2006).

Although all these benefits of natural ventilation are understood, how to apply this strategy in design in the modern architecture context is still unclear (Mumovic et al., 2009; Santamouris et al., 1998). There are several problems to be solved in achieving high performance naturally ventilated buildings. These include, for example, wind condition unpredictability, high costs for computing time and detailed natural ventilation analysis, and difficulties with understanding analysis results and translating them into design advice.

Case studies about integrating natural ventilation evaluation with design were also found in literature. Researchers worked on different scales of design to promote natural ventilation. On building detail scale, a case study was conducted for optimization of the openings for natural ventilation, with Fast Fluid Dynamics (FFD) and genetic algorithm (Attar et al., 2014). In other studies, design roof vents and dimensions of openings were optimized with evolutionary algorithm (Hasni et al., 2006; Stephen et al., 2011). On room scale, an indoor configuration optimization methodology was presented, with genetic algorithm and computational fluid dynamic (CFD) simulation. Indoor CFD simulation was employed to provide detailed information about indoor airflow and the thermal environment. A genetic algorithm was used to generate and optimize design variations (Kim et al., 2007). On building scale, the design optimization process for a natural ventilation improvement in high-rise residential buildings was recorded and validated by file measurements. The study described clearly three levels for step-by-step optimization of natural ventilation performance, which included community level, floor plan level, and room level (Zhou et al., 2014). Similar studies were conducted on other climate and urban conditions (Abdelrahman et al., 2017; Guo et al., 2015). Researchers also attempted to combine natural ventilation evaluation with building energy performance evaluation. A study on integration of building performance evaluation and building form optimization was conducted, taking natural ventilation into consideration. The study employed CFD simulation and energy simulation to provide accurate building performance feedback for design. An optimal building form generated by genetic algorithm was presented, based on building performance evaluation (Yi & Malkawi, 2008).

All these studies illustrate the great potential of building performance informed design methodology focusing on building natural ventilation. However, comparing to studies on design decision-making support focusing on building energy consumption, the missing part of natural ventilation research is a practical decision-making support system focusing on integrating natural ventilation evaluation with design. Therefore, among all aspects of building performance, natural ventilation is the focus of this research due to the potential for improving built environment, and the challenges still outstanding in effectively incorporating natural ventilation into design.

1.2.1.3 Early Design Stage

The last focus of this research is early design stage. In 1976, Paulson concluded that level of influence regarding costs related to construction would decrease along with project time (Paulson, 1976). Accordingly it is important to design smart in the early stage, when the opportunity to make cost-effective changes remains. The same principle applies to building performance as well. This suggests that building performance information should be introduced in the early design stage to achieve the best performance and reduce later design modification costs (Abaza, 2012).

However, obtaining building performance information in the early design stage is difficult (Negendahl, 2015). A critical reason is the lack of available detailed information about design at this stage. Taking building energy simulation as an example, existing software requires detailed input that may remain uncertain in the early stage of design such as occupancy and operation. To overcome this problem, one possible solution is to simplify the calculation model by identifying the most critical inputs. With this idea, researchers conducted a detailed building energy performance simulation and then simplified the simulation progressively, recording the influence of each simplification step. In this way the most significant parameters in terms of accuracy were identified and a proper simplified building energy calculation method was determined for the early design stage (Picco et al., 2014). Another piece of building performance information that is hard to evaluate in the early design stage is the lengthy computing time, especially when the number of design alternatives is large, as in most cases. A regression methodology was employed to predict building energy performance, with an artificial neural network model. The predicted results, based on the back-propagation neural network model, showed great agreement with simulated results while the computing time was significantly reduced (Yao, 2010).

These attempts to introduce building performance information in the early design stage emphasize the importance of this issue. Since this stage may have varying requirements and provide limited information, current building performance simulation technologies cannot be applied directly. The solutions for evaluating early-stage natural ventilation performance are not yet fully understood.

1.2.2 Research Objectives and Aim

The research proposal addresses all three research issues: a decision-making support system in early design stage for high performance naturally ventilated building would be necessary to help designers to make smarter decisions.

Assisting design with focus on natural ventilation is not a new area of study. It is difficult to give design advice with regard to natural ventilation in the early stage because natural ventilation performance is influenced by several different factors. There are some simple guidelines for natural ventilation suggested at the early design stage. For example, ASHRAE (the American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 62.1, Ventilation for Acceptable Indoor Air, has recommendations for cross-ventilation (ASHRAE, 2013). "Naturally ventilated spaces should be within 8m (25 ft.) of operable windows; Openable area should be a minimum of 4% of the floor area; Interior rooms: the unobstructed opening to the adjoining room shall be at least 8% of the interior room, but not less than 2.33 m^2 (25 $ft.^2$)." However, in most cases these guidelines are too simple to effectively promote natural ventilation in design.

As opposed to the simple guidelines for the early design stage described above, studies have also illustrated the great potential of new technologies for integrating design with natural ventilation evaluation. For this, the most advanced technologies for natural ventilation evaluation, such as CFD, were used, together with design optimization methodologies such as the genetic algorithm (Kim et al., 2007; Yi & Malkawi, 2008; Zhou et al., 2014). With regard to the advanced technologies, there have been several tools developed for natural ventilation evaluation in the early design stage in recent years. CoolVent, developed by the Massachusetts Institute of

Technology, is an easy-to-use early design stage tool for prediction of the effects of natural ventilation on occupant comfort and energy savings. It employs a multi-zone model as well as CFD simulation to predict natural ventilation performance (Tan & Glicksman, 2005). Energy2D is an interactive, visually based multi-physics simulation program that models all three modes of heat transfer (conduction, convection, and radiation) and their coupling with particle dynamics, which can be used by designers to visualize and understand natural ventilation (Xie, 2012). UMI is a Rhino-based design environment for architects and urban planners that models the environmental performance of neighborhoods and cities with respect to operational and embodied energy use, as well as walkability and daylighting potential. It also includes a natural ventilation module for the early design stage (Reinhart et al., 2013).

While promising, these tools still do not efficiently support decision-making about natural ventilation in the early design stage. Some tools require a lot of information for calculation that is not readily available at the early design stage. Some tools are not integrated well with design modeling software, creating a critical gap between analysis and design decision-making. Current guidelines and tools for natural ventilation are either too simple or too complicated.

As a response, a good decision-making support system for the early design stage of high performance naturally ventilated buildings is still needed. It should be neither too simple nor too complicated, and should fit in the early-stage design context while fulfilling the special requirements of this stage. Most importantly, it should integrate with the design modeling environment for easy operation and effective feedback.

Based on reviews of current practice and tools for natural ventilation integration in the early design stage, two issues remain unclear. They are also the two objectives of this research, which will be introduced in more detail in the next chapters. The first one is the natural ventilation evaluation index: what index should be used for natural ventilation evaluation in the early design stage? The second is the natural ventilation evaluation calculation method for early-stage design, considering the precision criterion was special for design decision-making in this stage and the available design information was limited.

As a summary, the aim of this research is to develop a decision-making support system for the early design stage of high performance naturally ventilated buildings, with the two main foci being the natural ventilation evaluation index and the calculation procedure.

1.3 Research Methodologies

1.3.1 Research Framework

This research began with a literature review of the background: building performance informed design. Three research issues were identified based on review of the current research. Then one research proposal was chosen: developing a decision-making support system for the early design stage of high performance naturally ventilated buildings.

Further analysis of the research proposal subdivided the task into two considerations. The first is the evaluation index for natural ventilation performance in the early design stage, and the second, how to calculate the evaluation index and integrate it with design. These two parts comprise the main contributions of this research.

As the last part of this research, a case study was conducted to illustrate how the design decision-making support system informed design in the early stage. The limitations of this research and recommendations for future studies were also summarized.

1.3.2 Natural Ventilation Evaluation Index

The first research task was to define the target of natural ventilation evaluation, that is, what index should be used to evaluate natural ventilation in the early design stage. The research began by reviewing current practice of natural ventilation evaluation as described in the literature and seen in practice. Drawbacks of current practice due to the limitation of available design information at this stage were analyzed. The special precision criterion for natural ventilation evaluation at this stage were also considered. As a result, a natural ventilation evaluation index specifically for the early design stage called the Design-Based Natural Ventilation Potential was proposed.

The research methodologies for this part were mainly literature review and reasoning.

1.3.3 Natural Ventilation Evaluation Calculations

The next task was developing the practical calculation procedure for the proposed natural ventilation evaluation index. Again, the research began with reviews of current practice in both research and application. Common calculations of natural ventilation evaluation were summarized and the two-step strategy using outdoor wind environment simulation and indoor natural ventilation calculation was chosen for the early design stage.

Therefore, the study consisted of two parts, outdoor wind environment simulation and indoor natural ventilation calculation. For the outdoor wind environment simulation, an automatic process of CFD simulation was proposed to provide annual wind pressure information on facades, taking into consideration the influence of the urban environment. For the indoor natural ventilation calculation, developing a simplified calculation method was proposed as the solution to achieving quick natural ventilation evaluation for different design alternatives. To develop the simplified calculation method, similarity analysis (which would be explained in the Chapter 3) was first conducted, and then CFD simulation was employed to conduct numerical experiments. Results were regressed and validated. Cross-ventilation was used as an illustrative example of development of the calculation method. In the end, a practical calculation procedure, using the automatic outdoor simulation and simplified indoor calculation for evaluating the Design-Based Natural Ventilation Potential, was presented.

The research methodologies for this part of the research study were literature review, numerical experiments, and model development.

1.3.4 Natural Ventilation Evaluation Case Study

The last part of the research was to apply the natural ventilation evaluation index and calculation to an actual design case. The case study optimized the geometry of a single tower in a modern urban context, based on natural ventilation evaluation in the early design stage. The proposed natural ventilation evaluation index and calculation were embedded into the design modeling software Rhinoceros Grasshopper (Rhinoceros, typically abbreviated Rhino, is a commercial 3D computer graphics and computer-aided design application software. Grasshopper is a graphical algorithm editor integrated with Rhino) using scripts developed by the author (McNeel, 2008, 2010). With the scripts, the Design-Based Natural Ventilation Potential of the target tower was calculated and a genetic algorithm was employed to optimize the tower's geometric parameters.

The research methodology consisted of the case study.

1.4 Thesis Structure

The structure of this dissertation is as shown in Figure 1.1.

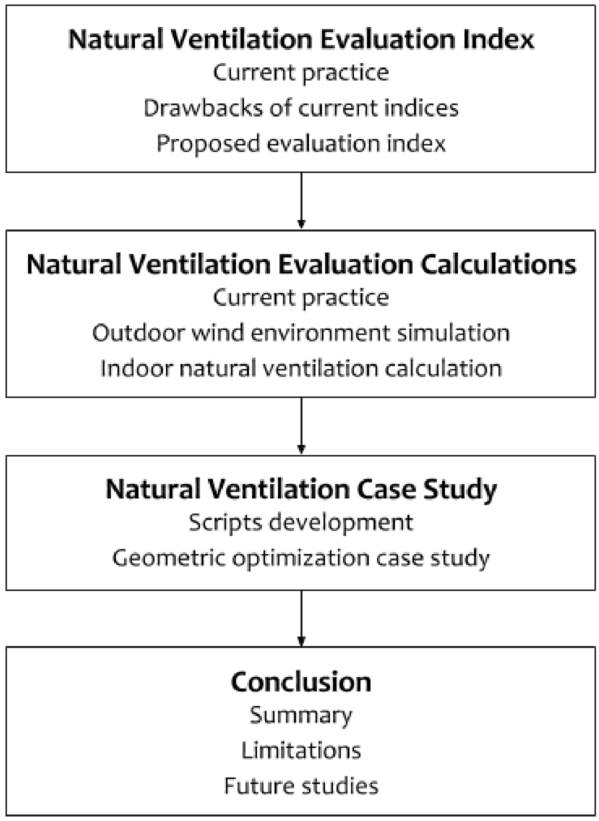

Figure 1.1 Dissertation structure

Chapter 2 Natural Ventilation Evaluation Index

2.1 Introduction

This chapter focuses on the first objective of this research, the natural ventilation evaluation index. The question to be answered was what index should be used to evaluate natural ventilation in the early design stage. At this stage, very limited design information is provided and precision criterion for building performance evaluation is special. Current evaluation indices for natural ventilation may not be appropriate for early-stage design. A review of the current natural ventilation evaluation indices seen in the literature was conducted. Based on the review, a more appropriate natural ventilation evaluation index was proposed for early-stage design, called the Design-Based Natural Ventilation Potential.

2.2 Current Natural Ventilation Evaluation Indices

Unlike for building energy performance evaluation, there is no commonly accepted evaluation index for natural ventilation. In current research studies, different indices are used, including energy consumption savings, thermal comfort level, and the hourly air change rate (ACH).

Energy consumption savings is currently the most widely used index for evaluation of natural ventilation (Carrilho et al., 2002; Schulze & Eicker, 2013; Yik & Lun, 2010) A common practice is comparing the energy consumption with and without natural ventilation, taking the difference as energy consumption savings for natural ventilation. This index is critical because energy consumption savings is the main reason for using natural ventilation as illustrated in Chapter 1, and it also equals a reduction in operation costs, making it easily understandable and a good point for evaluation.

Some researchers have also used thermal comfort level as an evaluation index in recent years, since the other well-recognized benefit of natural ventilation is expansion of the thermal comfort range of temperature and humidity for the occupant (Nguyen & Reiter, 2014; Srebric et al., 2000; Stavrakakis et al., 2008, 2010). In this situation, the evaluation index is the hours that indoor thermal environment conditions fall in the thermal comfort range with natural ventilation. It is highly correlated with energy consumption savings and operation costs.

Both of the evaluation indices have the same drawback: uncertainty of thermal modeling of space in the early design stage. The calculation methods of these two evaluation indices are similar. A thermal modeling of space is required to predict indoor environment conditions. For energy consumption calculation, only indoor temperature and humidity conditions given by thermal modeling are used, while for thermal comfort evaluation more information is involved, for example surface temperature. Thermal modeling is a calculation process based on thermal balance of space, which requires a lot of detailed information including building materials, internal load, and occupancy and operation schedules (Anderson, 2014). Because of the limited design information available at the early design stage, thermal modeling at the time is usually associated with high uncertainty.

To avoid the uncertainty issue caused by thermal modeling, some researchers use the hourly air change rate (ACH) as the evaluation index for natural ventilation (Haw et al., 2012; Teppner et al., 2014) In this way only the amount of fresh air is calculated by CFD simulation or multi-zone airflow calculation, and thermal modeling of the space is not employed. It is easy to understand that the higher amounts of fresh air indicate better natural ventilation. However, it is unclear in most cases what defines a good air change rate. As a result, this index is not easily understood or straightforward as an evaluation point.

All the indices introduced above hold the same concept, using natural ventilation performance as the target of evaluation. One problem can be readily identified: evaluating natural ventilation performance requires a lot of detailed information about the design. Thermal modeling requires inputs that include building materials, internal load, and even occupancy and operation schedules. Calculating air change rate is easier but still requires opening pressure information, dimensions of openings, and indoor configuration. Most of this information is only available at a very late stage in the design process, or even after construction. Therefore, evaluating actual performance of natural ventilation in most cases makes some assumptions about detail information, which may lead to uncertainty about the results. A diagram of the building performance evaluation indices is shown in Figure 2.1.

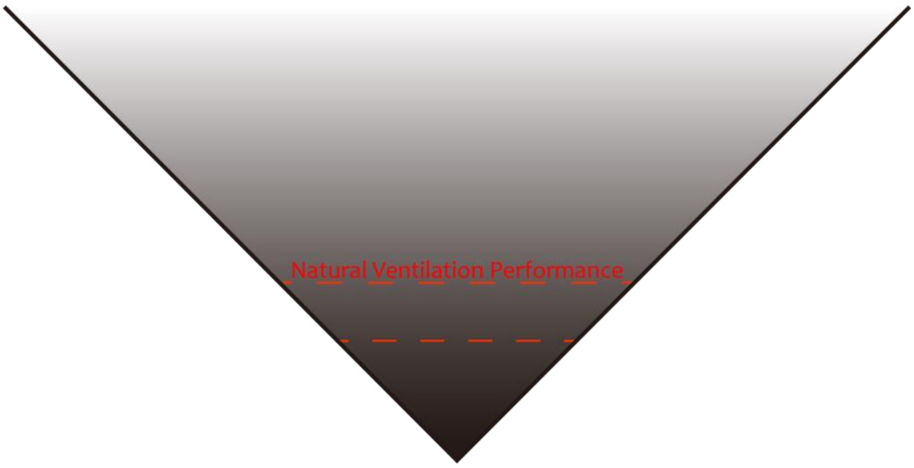

Figure 2.1 Natural ventilation performance evaluation

To tackle this problem, an alternative concept of natural ventilation evaluation should be used at early design stage. Given the limited design information available, one promising approach is to evaluate the natural ventilation potential instead of actual performance. A simple natural ventilation potential can be defined as the hours that climate conditions fulfill thermal comfort requirement (Chen et al., 2017). Case studies about natural ventilation potential have been conducted in recent years (Patil

& Kaushik, 2015; Yang et al., 2005). Researchers also tried to map the potential of natural ventilation across the country as a design reference. (Hiyama & Glicksman, 2015; Yao et al., 2009) On a broader scale, the relationship between natural ventilation potential and climate globally was explored (Causone, 2015). Because the natural ventilation potential is calculated based on climate data only, the uncertainty of the result is more known than natural ventilation performance calculation. It is easy to understand that the natural ventilation potential is an upper limit of the natural ventilation performance, as shown in Figure 2.2. This index could direct design for higher performance in early stage.

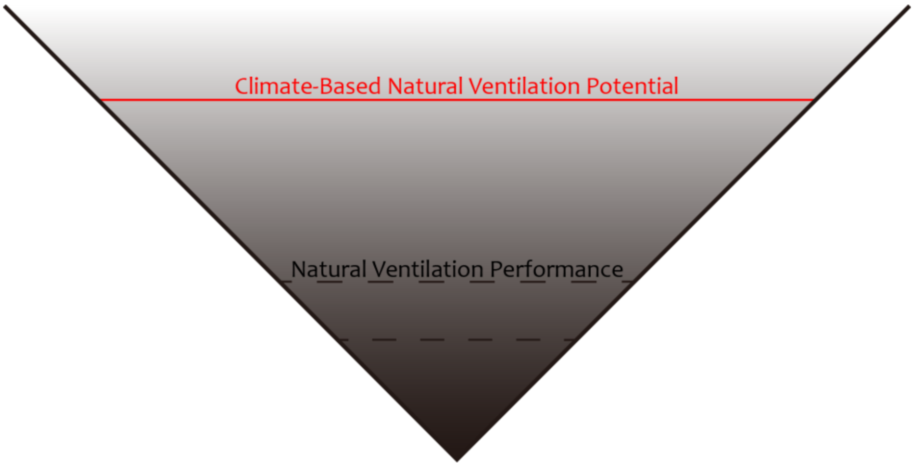

Figure 2.2 Climate-based natural ventilation potential

This idea of natural ventilation potential evaluation is very promising in the early design stage because it avoids the uncertainty of thermal modeling and also provides a good direction for design. However, there is not much design information involved in current natural ventilation potential research. There has been research about improving natural ventilation potential evaluation by taking the thermal comfort model into account (Causone, 2015). Another interesting study was conducted, defining a natural ventilation potential evaluation index called the target air change rate, which was built on natural ventilation potential evaluation together with simplified thermal modeling of space (Hiyama & Glicksman, 2015). These researches illustrated a great direction for improvement of natural ventilation potential evaluation by considering more design information.

In this research, a more appropriate evaluation index for the early design stage was proposed, to evaluate the natural ventilation potential by considering climate information as well as available design information at this stage. In this way the index should provide designers with a more accurate evaluation of natural ventilation potential. The proposed index was called the Design-Based Natural Ventilation Potential. An illustration of the proposed index with current evaluation indices is shown in Figure 2.3.

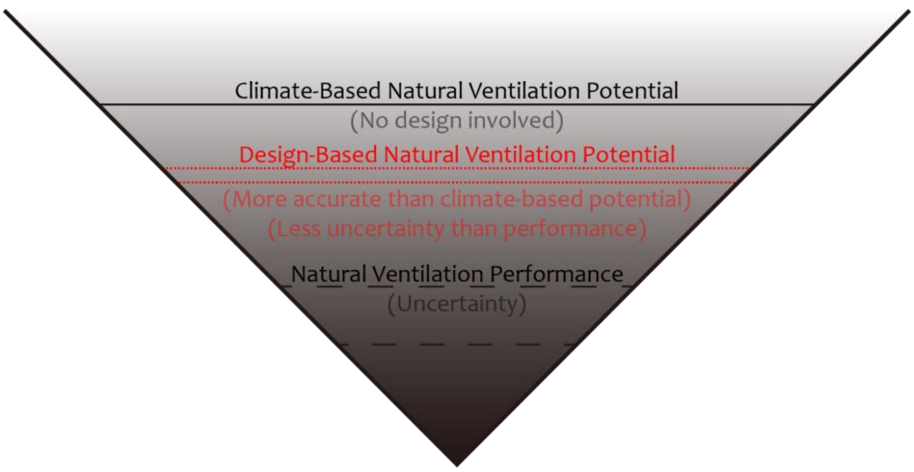

Figure 2.3 Design-Based Natural Ventilation Potential

A comparison of the proposed Design-Based Natural Ventilation Potential with natural ventilation performance indices and climate-based natural ventilation potential is found in Table 2.1.

Table 2.1 Comparison of natural ventilation evaluation indices

Evaluation Indices	**Descriptions**	**Drawbacks or Advantages**	**Reference**
Natural ventilation performance indices	Common practice	Associated to thermal modeling High uncertainty	Carrilho et al., 2002; Haw et al., 2012; Nguyen and Reiter, 2014; Schulze & Eicker, 2013; Srebric et al., 2000; Stavrakakis et al., 2008, 2010; Teppner et al., 2014; Yik & Lun, 2010
Climate-based natural ventilation potential	Latest research	Based on climate data No design involved	Causone, 2015; Chen et al., 2017; Hiyama & Glicksman, 2015; Patil & Kaushik, 2015; Yang et al., 2005; Yao et al., 2009
Design-Based Natural Ventilation Potential	Proposed index	Design information included Less uncertainty factors	

In summary, the natural ventilation evaluating indices used in current practice are not proper evaluation indices for the early design stage because of the uncertainty involved in thermal modeling. Researchers propose the use of natural ventilation potential instead of performance for evaluation in early-stage design. However, current research studies based natural ventilation potential evaluation on climate data only. This research proposes an improvement on natural ventilation potential evaluation by considering design information that is available at the early design stage. More details of the proposed evaluation index are introduced in the next section.

2.3 Design-Based Natural Ventilation Potential

2.3.1 Definition

The Design-Based Natural Ventilation Potential is defined as the hours that the space can be well naturally ventilated with the design at this early stage over the course of the whole year. It is designated as an integer between 0 and 8760. The scope is limited to the early design stage in this study but can be expanded to other design stages in further research. Besides climate conditions, the urban context as well as other known design detail information is taken into account, such as building geometry, windows, and function.

Defining the evaluation index is straightforward, however the main question that needs to be answered is what good naturally ventilated space is. Among the many reasons for designing ventilation, the two main purposes are indoor air quality and thermal environment (Awbi, 2013). The next two parts will introduce the requirements of both of these aspects based on reviews of current design practice and how the requirements should be adapted for natural ventilation in the early design stage.

2.3.2 Indoor Air Quality

For decades, indoor air quality (IAQ) requirement for ventilation were built for laboratory experiments. IAQ requirement is directly related to pollution that concerns people, for example, CO_2 levels (Awbi, 2013). The amount of fresh air needed to reduce the concentration of pollution in space is calculated based on limit values of pollution given by laboratory experiments. The minimum fresh air volume is also known as minimum ventilation rate (ASHRAE, 2013b). The majority of today's design standards and regulations are still built on this approach. Guidelines and standards related to IAQ have been developed by governments as well as international organizations. A list of examples is shown in Table 2.2.

Table 2.2 Guidelines and standards for indoor air quality

ASHRAE Standard	ASHRAE 62.1-2013	Ventilation for acceptable indoor air quality
	ASHRAE 62.2-2013	Ventilation and acceptable indoor air quality in low-rise residential buildings
European Standard	EN 15251-2007	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting, and acoustics
ISO Standard	ISO 4225: 1994	Air quality, general aspects, vocabulary
	ISO 4226: 2007	Air quality, general aspects, units of measurement
	ISO 16813: 2006	Building environment design, indoor environment, general principles
	ISO 16814: 2008	Building environment design, indoor air quality, methods of expressing the quality of indoor air for human occupancy
	ISO 8756: 1994	Air quality; handling of temperature, pressure, and humidity data
	ISO 16000-16: 2008	Indoor air Part 16: detection and enumeration of molds, sampling by filtration
	ISO 7708:1995	Air quality, particle size fraction definitions for health-related sampling

Taking the United States as an example, requirements and guidance for indoor air quality and safety were provided in newly approved standards, ASHRAE Standard 62.1-2013, Ventilation for Acceptable Indoor Air Quality, and ASHRAE Standard 62.2-2013, Ventilation for Acceptable Indoor Air Quality in Low-Rise Residential

Buildings. These standards provided the minimum requirements necessary to achieve acceptable indoor air quality, meaning that indoor air will not likely pose a significant health hazard and will not be irritating or have unacceptable odors (ASHRAE, 2013b). For example, the minimum ventilation rate in ASHRAE Standard 62.1–2013 for office space is 2.5 L/s per person plus 0.3 L/sm^2 floor area. Other standards have similar requirements for the minimum ventilation rate.

Besides the minimum ventilation rate, some researchers recommended evaluating the effect of ventilation on IAQ. “Ventilation effectiveness” or “ventilation efficiency” refers to the ability to remove internally produced pollutants (Awbi, 2013). Another concept for ventilation effectiveness evaluation, called “age of air,” is the length of time the fresh air remains in the ventilated space (Etheridge, 2012; Xing et al., 2001). These ventilation effectiveness indices were used to evaluate the distribution of fresh air. They were used more commonly for mechanical ventilation systems.

However, this concept was used in research in most cases. It may be difficult to adapt for practice in the early design stage. There is currently no standard established for ventilation distribution evaluation describing what “well-distributed" ventilation is. Also, ventilation distribution is highly influenced by floor layout and even furniture position, which remain unknown in the early design stage. This leads to high uncertainty of ventilation distribution evaluation results. Because of that, ventilation distribution evaluation may not be necessary in early design stage. Therefore, requirements of ventilation distribution are not included in this research.

In conclusion, due to the uncertainty of the other metrics mentioned in this section, the indoor air quality requirement for natural ventilation used in the early design stage is the minimum ventilation rate.

2.3.3 Thermal Environment

Natural ventilation is increasingly used as part of a strategy to improve thermal environment. It is also important to pay attention to characterization of thermal environment evaluation in standards and regulations. Some guidelines and standards that may be of interest to thermal environment researchers are enumerated in Table 2.3.

Table 2.3 Guidelines and standards for thermal comfort

ASHRAE Standard	ASHRAE 55-2013	Thermal environmental conditions for human occupancy
European Standard	EN 15251-2007	Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and, acoustics
ISO Standard	ISO 11399:1995	Ergonomics of the thermal environment, principles and application of relevant international standards
	ISO 7730:2005	Ergonomics of the thermal environment, analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria
	ISO 9920:2007	Ergonomics of the thermal environment, estimation of thermal insulation and water vapor resistance of a clothing ensemble
	ISO 8996:2004	Ergonomics of the thermal environment, determination of metabolic rate
	ISO 7726:1998	Ergonomics of the thermal environment - instruments for measuring physical quantities
	ISO 10551:1995	Ergonomics of the thermal environment, assessment of the influence of the thermal environment using subjective judgment scales

For characterizing thermal environment conditions, indices of thermal comfort have been derived. These were mainly based on laboratory research. The most common indices are predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD): these predict the mean response of a large group of people according to the International Organization for Standardization (ISO)/ American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The thermal sensation scale for PMV is as follows: +3 = hot; +2 = warm; +1 = slightly warm; 0 = neutral; −1 = slightly cool; −2 = cool; −3 = cold (ASHRAE, 2013a).

The predicted mean vote (PMV) and predicted percentage of dissatisfied (PPD) indices were developed by Fanger and described in ISO 7730 (Fanger, 1972; ISO, 2005). Furthermore, the general measuring methodology is described in the ISO 7726 (ISO, 1998). ASHRAE 55 is equivalent to the contents described in the ISO standards (ASHRAE, 2013a). ASHRAE 55 and ISO 7730 are the only standards that define local thermal comfort in an indoor environment. Besides of PMV and PPD, other thermal comfort indices include effective temperature (ET*) and standard effective temperature (SET) (ASHRAE, 2013a).

All the thermal comfort indices use air temperature and relative humidity in the calculation. Besides these two factors, metabolic rate, clothing insulation, mean radiant temperature, and air velocity are normally included in the thermal comfort model. Some models also consider the influence of culture and activity patterns. For thermal comfort evaluation in the early design stage, thermal modeling is employed in most cases to predict air temperature, relative humidity, and mean radiant temperature, while all other parameters are assumed as typical values according to function of the space.

It is important to draw attention to the fact that the derived indices are all based on laboratory testing. Thermal comfort models were first developed for air-conditioned space (Fanger, 1972). Equations were given for evaluating thermal comfort level in steady-state conditions. Concerns have been expressed about the relation between the stated needs in laboratory conditions and needs in the real world, where steady-state conditions do not exist. In parallel with the laboratory studies, there has been a whole range of thermal comfort field studies (Barbadilla-Martín et al., 2017; Damiati et al., 2016). The changing comfort temperatures found in various field studies led to the idea of viewing thermal comfort as a self-regulating system. This way of regarding thermal comfort has become generally known as the adaptive thermal comfort model (Nicol et al., 2012). This approach is receiving much interest in recent years. At present, the following conclusion can be drawn from the various studies: people accept a much more diverse set of thermal environments than those in laboratory-based studies (Daghigh et al., 2009).

There were many researchers who believed that this concept might lead to new comfort criteria, where different targets could be set for different operation modes (Nicol et al., 2012). A proposal for these new criteria was developed, which made a distinction between centralized HVAC and naturally ventilated buildings. This new concept was employed in the updated ASHRAE standard 55 (ASHRAE, 2013a). According to the new thermal comfort model, the air velocity is critical in evaluating naturally ventilated space. A study on natural ventilation and thermal comfort was conducted, creating a chart for the relationship of operative temperature and minimal air velocity, shown as Figure 2.4 (Christhina et al., 2011). This study concluded that the minimal air velocity requirement changes according to the operative temperature. This thermal model is taken as the reference for thermal comfort evaluation in the research described in this dissertation.

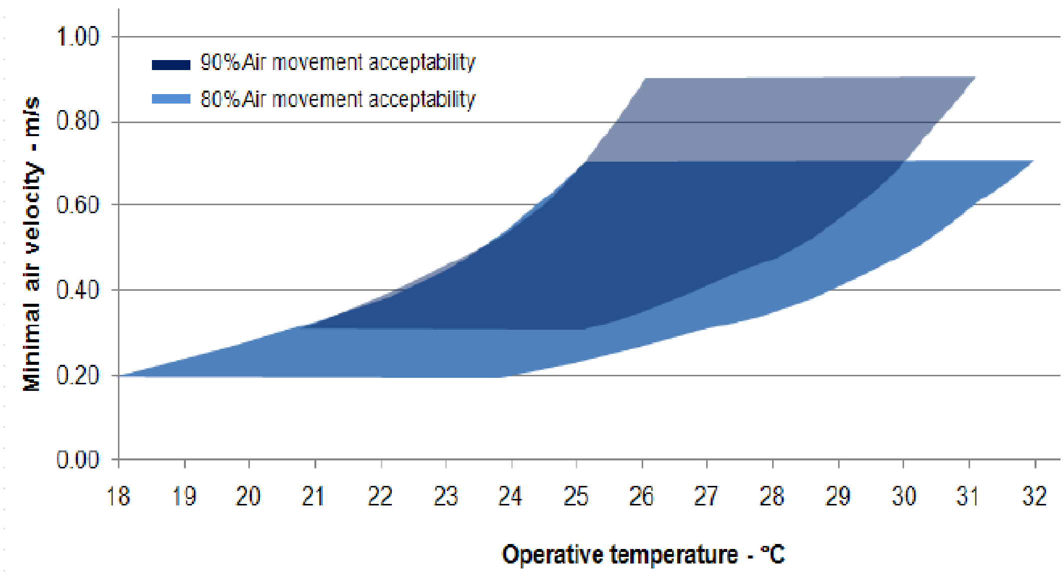

Figure 2.4 Minimal air velocity requirement within the occupied zone

In addition to thermal comfort calculation, another concern for thermal comfort evaluation is the comfort level distribution in the space. This is critical, but unfortunately there is no standard established yet. Furthermore, the detail distribution evaluation of the thermal comfort level remains unnecessary in the early design stage because of the as yet unclear floor layout and furniture placement. In the research described here, the percentage of floor area that fulfills the thermal comfort requirement is proposed as the index to evaluate thermal comfort level distribution, named the ventilated ratio.

In conclusion, the thermal comfort requirements for natural ventilation in the early design stage are built based on the latest adaptive thermal comfort model, which requires minimal air velocity for different operative temperatures. The space should also meet the ventilated ratio requirement, defined as is a certain percentage of floor area fulfilling the thermal comfort requirement.

2.4 Summary

The evaluation index for natural ventilation plays a critical role in the early design stage. In current practice indices for natural ventilation performance, for example, energy consumption savings, are widely used. However, these indices are not appropriate for early-stage design because of uncertainty issues related to the limitation of available design information at this stage. According to the latest research, evaluating natural ventilation potential instead of natural ventilation performance provides better design decision-making support at the early stage. A new evaluation index called the Design-Based Natural Ventilation Potential has been proposed in this research for natural ventilation evaluation in early-stage design.

The Design-Based Natural Ventilation Potential was defined as the hours that the space could be naturally well-ventilated in the course of one year. It took available early-stage design information into consideration, as well as climate conditions, which provided more accurate evaluation than the climate-based natural ventilation potential used in recent research.

The definition of naturally well-ventilated space consisted of two aspects, indoor air quality and thermal environment. For indoor air quality, the requirement for natural ventilation referred to the minimum ventilation rate. For thermal environment, the requirement for natural ventilation was called the ventilated ratio, defined as the percentage of floor area fulfilling the minimal air velocity for different operative temperatures based on the thermal comfort model.

Chapter 3 Natural Ventilation Evaluation Calculations

3.1 Introduction

After defining the objective of this research, the next question was how to calculate the Design-Based Natural Ventilation Potential in the early design stage. A review of current research of natural ventilation illustrates that there are two main steps to calculate, the outdoor wind environment simulation and the indoor natural ventilation calculation (Etheridge, 2015).

Indoor natural ventilation calculation is a key part of all ventilation studies. The indoor air motion is the target of the calculation. All critical parameters required for natural ventilation evaluation, such as air velocity and ventilation rate, are provided by indoor air motion calculation. There are seven types of research models for natural ventilation studies, five of which are calculation models: analytical, empirical, multi-zone network, zonal, and computational fluid dynamic (CFD) (Chen et al, 2009). CFD is considered as the calculation model providing the most detailed information about ventilation and the most sophisticated to have been widely used in recent years (Chen et al., 2010). The other widely used calculation models are known as zonal and multi-zone network models. For zonal model, a much larger number of zones is used comparing to multi-zone network model (but much fewer than the number of cells used for CFD calculation), and approximate forms of the conservation equations are used to calculate the velocity and temperature fields (Etheridge, 2015). These mathematical models are used to calculate indoor air motion and temperature variation, but with much less detail than is used with CFD for faster evaluation (Chen, 2009).

For all the indoor natural ventilation calculation methods, pressures of openings are taken as boundary conditions. As a common practice, the pressures are provided by a pressure coefficient database (ASHRAE, 2009). The pressure coefficient database by ASHRAE was built based on measurement of a single box building in a wind tunnel experiment, without any surrounding buildings. On the other hand, the influence of urban context on facade pressure has been receiving interest in recent years. Early in 1998, Green and Etheridge tested the influence of the urban environment on natural ventilation with a wind tunnel experiment (Green & Etheridge, 1998). Recently researchers conducted comprehensive reviews of the impact of urban blocks on ventilation as well as solar access and thermal performance (Sanaieian et al., 2014). More specifically, a review of recent studies on the outdoor environment using CFD was provided (Blocken et al., 2011). CFD is becoming more popular in natural ventilation studies because it includes the effect of urban context on facade pressure.

Due to the rapid increase in computer capacity and the development of CFD program, the capacity of CFD simulation has improved to the point that both outdoor wind environment and indoor natural ventilation can be simulated at the same time now (Mohd Farid et al., 2013). This method is considered more accurate because it includes the detailed geometry of openings, but as a consequence it is more expensive in terms of computing time and power. In the early design stage, this method is too slow for evaluating a lot of design alternatives. Balancing calculation time and precision in the early design stage, the two-step calculation method is better for this research.

As a conclusion, development of natural ventilation evaluation for the early design stage consists of two steps, outdoor wind environment simulation and the indoor natural ventilation calculation. First, the outdoor wind environment will be simulated by CFD to obtain the pressure on the building facade, taking into account the influence of urban context. Then the pressure on openings will be used as boundary conditions for the indoor natural ventilation calculation. This chapter will introduce how calculations are adapted for early-stage design based on this two-step calculation method.

3.2 Natural Ventilation Evaluation Calculations

3.2.1 Outdoor Wind Environment Simulation

3.2.1.1 Outdoor CFD Simulation

To calculate the indoor natural ventilation, a detailed distribution of pressure on the building facade is required. The wind pressure coefficient database provided by ASHRAE gives facade pressure by simple calculation (ASHRAE, 2009). However, the pressure database was derived from a wind tunnel experiment on a single box building without any urban context. A previous study conducted by the author compared the database and CFD simulation results, indicating that the pressure coefficient database could be misleading when evaluating natural ventilation for a building in an urban context (Wang et al., 2012). The influence of urban context is well recognized by other researchers as well, and CFD is recommended for natural ventilation studies (Blocken et al., 2011; Green & Etheridge, 1998; Sanaieian et al., 2014) Therefore, CFD simulation of the outdoor wind environment is necessary for a detailed pressure distribution on a building facade in an urban context.

Several studies about the reliability of CFD simulation results have been conducted. The Architectural Institute of Japan (AIJ) carried out a series of studies on CFD simulation of the outdoor wind environment. The wind velocity of CFD simulation results were compared with wind tunnel experiment data, as well as turbulence strength (indicated by turbulent kinetic energy and turbulent energy dissipation rate), for a single high-rise building with various *k-ε* models. The study showed that, with the appropriate settings, the CFD simulation results and wind tunnel experiment data were in agreement (Mochida et al., 2002). Following this study, cross-comparisons of CFD simulation results with wind tunnel experiments data for a high-rise building in an urban context were conducted. Though the cases in the study were quite complex, relatively high correlations were achieved with special attention to CFD simulation settings (Tominaga et al., 2004). Based on the all the research, the Architectural Institute of Japan (AIJ) developed a guideline for outdoor wind environment CFD simulation (Tominaga et al., 2008).

3.2.1.2 Computing Time

With rapid development of both computer software and hardware, the computing time for CFD simulation has significantly decreased in recent years. However, to perform a detailed and careful analysis of natural ventilation potential, hourly simulation for the year was necessary. In this case the computing time for CFD became an issue. An acceleration of the simulation speed was critical. The author conducted a study on interpolating CFD simulation results to achieve a shorter computing time for annual simulation (Wang & Malkawi, 2014). The research expanded the concept of the pressure coefficient of the building to an urban environment and validated that the wind velocity of the inflow did not influence the pressure coefficient on the building facade even in an urban context. As a result, the building facade pressure coefficient of one particular wind direction can be calculated with one CFD simulation. For other cases with the same wind direction, the pressure on building facade can be achieved based on the pressure coefficient with simple calculation. With this conclusion, the urban pressure coefficient database could be determined by running only several base cases with different wind directions by CFD. Then the hourly pressure distribution on the facade could be interpolated from the pressure coefficient database. In this way the CFD computing time for annual outdoor wind environment simulation could be significantly reduced, as Figure 3.1 illustrates. For each urban environment, only eight cases were calculated for this research.

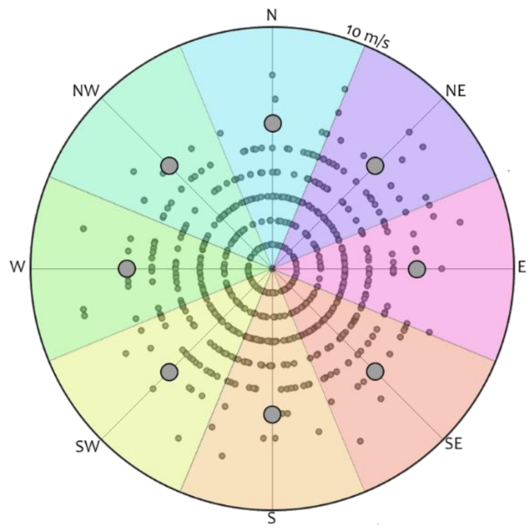

Figure 3.1 Reducing CFD computing time for annual wind environment simulation

3.2.1.3 Automatic Calculation

An automatic pressure coefficient database calculation is employed for outdoor wind environment simulation in this research. A plugin in Rhino and Grasshopper developed by the author is used to achieve the goal (Wang & Malkawi, 2014). The detail settings used in the plugin is introduced below.

The commercial CFD simulation software used was Ansys Fluent (Ansys, 2013). Detail boundary conditions and simulation settings for all the CFD simulation cases followed the CFD simulation guideline provided by AIJ (Tominaga et al., 2008) The grid number was around 50,000 in an adequately sized domain, due to the educational license limit of Ansys Fluent. Grid-independent studies were conducted.

The inflow boundary condition had a vertical velocity profile, as well as a vertical distribution of turbulent energy, both of which were given by power laws equations as follows:

$$U(z) = U_r \left(\frac{z}{z_r} \right)^{\alpha} \tag{3.1}$$

$$I(z) = I_r \left(\frac{z}{z_r} \right)^{-\alpha - 0.05} \tag{3.2}$$

where U is the wind velocity, z is the height, I is the turbulent energy, α is the terrain coefficient.

For the lateral and upper surfaces of computational domain and the downstream boundary, the normal velocity component and normal gradients of tangential velocity components were set to zero. A logarithmic law with roughness parameters was used to set solid surface boundary conditions.

Steady simulation with the SIMPLE solution algorithm and the first order upwind differencing scheme were used. The turbulence model was a standard *k*-*ε* model.

With these settings, a plugin for Rhino and Grasshopper was developed to automatically calculate the pressure coefficient database in an urban environment (Wang & Malkawi, 2014). The results can be visualized in Rhino, shown in Figure 3.2. In this research, the pressures on building facade are fed back into Grasshopper for further analysis.

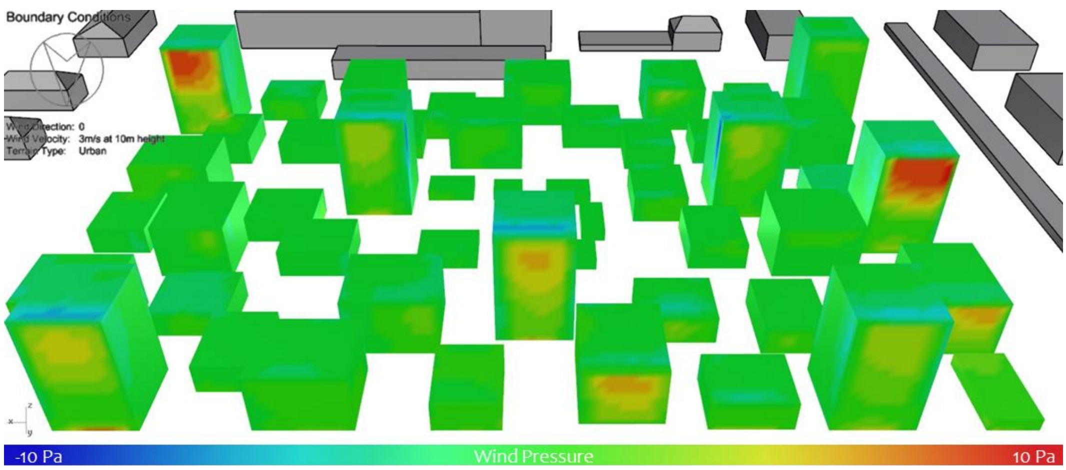

Figure 3.2 Visualizing CFD simulated pressure on facade in Rhino

3.2.2 Indoor Natural Ventilation Calculation

The next step was the indoor natural ventilation calculation. As summarized at the beginning of this chapter, there are several well-established methods for indoor natural ventilation calculation. For this research, the target parameters for indoor natural ventilation calculation were the ventilation rate and the percentage of ventilated area that fulfilled certain air velocity limits, named the ventilated ratio. The ventilation rate of the space could be calculated easily using existing indoor natural ventilation calculation methods, given the pressure on the openings and the dimensions of the openings (Chen et al., 2010). On the other hand, CFD simulation was suggested to calculate the ventilated ratio. So, calculating the natural ventilation potential was very straightforward. The difficulty was identifying a best-case scenario for ventilation rate and ventilated ratio.

However, finding the best case scenario for ventilated ratio was very challenging. The calculation method for ventilated ratio, which is CFD simulation, requires detailed design information such as floor shape and dimensions of openings. This information is not available at the early design stage in most cases. For this unknown design information, it is common to have several possibilities for each individual item in the early design stage. In addition, CFD simulation takes hours for one case. As a result, the total calculation time becomes unaffordable. It is impossible to cover all possibilities for determining the best-case natural ventilation scenario by running CFD simulation.

Therefore, a simplified calculation method that evaluates natural ventilation potential in seconds is necessary at this stage. In this research, the ventilated ratio is the only parameter needed for CFD simulation. The precision requirement for the early design stage is also relatively low. So instead of running CFD cases to find out the best-case scenario, this research proposed developing correlating equations of design and natural ventilation potential to achieve fast indoor natural ventilation calculation. The simple calculation method was built on a similarity analysis, which is the process of deducing the dimensionless numbers for correlating equations regression, called similarity criteria (Gyenge, 2005; Szirtes, 2006; Soboleva, 2013; Weisberg, 2013). The correlating equations to calculate the ventilated ratio were established by regression, based on numerical experiment results obtained by CFD simulations. The equations correlated the ventilated ratio with the pressure differences of openings, the floor shape, the dimensions of openings and other parameters.

However, developing such a simple calculation method involved an extensive amount of numerical experiments. This research subdivided the task into parts according to different natural ventilation types, including cross-ventilation, single-side ventilation and buoyancy-driven ventilation. From these, cross-ventilation was chosen for this research. Cross-ventilation is widely used for natural ventilation but is very difficult to evaluate in the early design stage due to its complexity. In addition, cross-ventilation is highly related to urban context and building geometry, the latter of which is mainly determined in the early design stage and difficult to change later. Among all types of natural ventilation, cross-ventilation potential evaluation is most critical in the early design stage. As an illustration of the process, this research focused on development of a simplified calculation method for cross-ventilation. More specifically, the cross-ventilation was defined as ventilation with only one inlet and one outlet on the same floor.

The process consisted of four parts: similarity analysis, numerical experiments, equations regression, and validation.

3.2.2.1 Similarity Analysis

Similarity analysis is the process of deducing the similarity criteria, as the dimensionless numbers for correlating equations regression (Gyenge, 2005; Soboleva, 2013; Szirtes, 2006; Weisberg, 2013). The indoor air motion parameter, in this research the ventilated ratio, may be influenced by many factors, including building geometry, pressure on openings, location and dimensions of openings. Correlating equations between the influencing factors and the target parameter, achieved by regression of numerical experiment results, can provide quick calculation in seconds (Gyenge, 2005).

Each factor has several options of value in the early design stage. As a result, it is very difficult to cover all possibilities. Therefore, similarity analysis is critical to narrow down the possibilities. Based on similarity theory, the motion of fluid, in this research the air, is consider similar while the similarity criteria are the same (Soboleva, 2013; Weisberg, 2013). That is to say, two cases with the same similarity criteria are considered repeated that only need to be calculated once for numerical experiment.

For the same type of natural ventilation, for instance, cross-ventilation with one inlet and one outlet, the flow pattern is similar. This makes it possible to correlate the target air parameter with the other factors in a general way using a dimensional analysis.

Dimensional similarity analysis is deducing the similarity criteria that describe the air motion, for numerical experiments and correlating equations regression in the next two sections. It comprises the following steps (Szirtes, 2006): (1) a list containing all the related parameters is compiled, with their respective SI units; (2)

each dimensional quantity on the list is divided by its SI units, generating quantity-unit groups; (3) considering the total number of independent SI units (N_{SI}) involved in the model, a number of N_{SI} SI-unit groups Γ_I are selected, so that all SI units encountered to be represented in the N_{SI} groups; (4) each of the SI-unit groups is assigned a value of 1 and designated as a primary group; (5) the rest of the SI-unit groups on the list are converted into an initial set of dimensionless numbers Π_i, by substituting the units using the N_{SI} primary groups; and (6) the initial set of dimensionless numbers Π_i is further transformed by algebraic manipulation in order to obtain dimensionless numbers with clear physical meaning, called similarity criteria. A list of example parameters and SI-unit groups is shown as Table 3.1. In this research, MLT (Mass, Length, Time) dimension system was used, meaning 3 SI-unit groups are selected. A list of example similarity criteria is shown as Table 3.2. Table 3.1 and Table 3.2 illustrate the dimensional similarity analysis process.

Table 3.1 Example parameters and SI groups for similarity analysis

Variable	**Description**	**Unit**	**Dimension**	**SI Group / Dimension Analysis**
ρ	Air density	kg/m^3	ML^{-3}	Γ_1
ν	Air kinetic viscosity	m^2/s	L^2T^{-1}	Γ_2
H	Floor height	m	L	Γ_3
g	Gravity	m/s^2	LT^{-2}	$\Gamma_2^2\Gamma_3^{-3}$
ΔP	Pressure difference on openings	kg/ ms^2	$ML^{-1}T^{-2}$	$\Gamma_1\Gamma_2^2\Gamma_3^{-2}$

A_f	Total floor area	m^2	L^2	Γ_3^2

Table 3.2 Example similarity criteria

Dimensionless Number No.	Similarity Criteria	Physical Significance
Π_1	$\frac{H^3 g}{\nu^2}$	Represents the influence of gravity on air
Π_2	$\frac{\Delta P}{\rho g H}$	Represents the influence of pressure difference on openings
Π_3	$\frac{A_f}{H^2}$	Represents the influence of total floor area

The next part describes the dimensional similarity analysis of this research in detail. As previously mentioned, this research focused on cross-ventilation with only one inlet and one outlet. Some assumptions were made for the following analysis. One was that the all walls of the space were adiabatic. The other was that there was no internal heat source in the space, so an energy equation was not considered in this dimensional similarity analysis. In addition, because the target of this research was natural ventilation potential, this research focused on the best-case cross-ventilation scenario, which meant that the openings were fully open and there was no internal layout causing flow resistance.

The first step of similarity analysis was listing all variables related to indoor natural ventilation calculation. There were five general aspects: geometry, openings, boundary condition, constants, and target.

The geometry was the most difficult part of this research since there were too many possibilities. In this research, primary shapes were chosen as basic shapes, considered as most representative two-dimensional design (Wong, 1972). The three basic floor shapes included a rectangle, a triangle, and a circle, shown in Figure 3.3. A right triangle was used for the triangle shape, as it is most common in architectural practice. Other geometries could be added in future research and will be discussed in the Chapter 5.

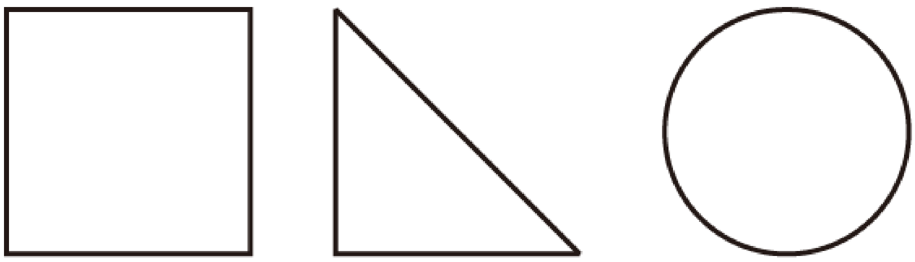

Figure 3.3 Basic geometries for cross-ventilation study

Shapes are defined and described by parameters intended to be visually compelling and formally sound and productive (Stiny, 1975). They vary, depending on the objective. For example, a parameter named perimeter efficiency was employed to describe shapes in the research on geometry in architecture (Blackwell, 1984). Inspired by Blackwell, floor height, total floor area, and total wall length were chosen to describe the shapes, illustrated in Figure 3.4.

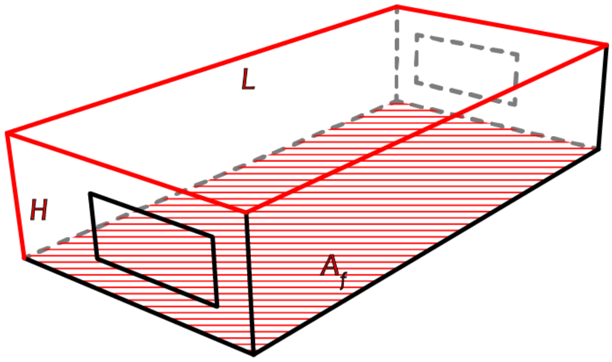

Figure 3.4 Variables describing shapes

The variables describing location and dimensions of openings included area, height, and elevation from the floor for both the inlet and outlet openings, assuming a rectangular shape for the openings. Describing the locations of both openings on the floor was complex. However, describing the relative position of the two openings was much simpler. Taking the center of the inlet opening as the coordinate origin, the position of the outlet opening could be described by three parameters, relative position *x*, relative position *y*, and relative normal angle *α*, illustrated in Figure 3.5. Variables describing openings is shown in Figure 3.6.

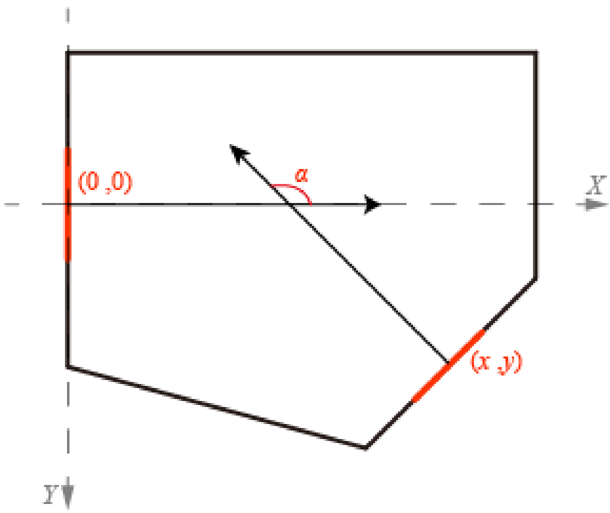

Figure 3.5 Relative position and normal angle of outlet

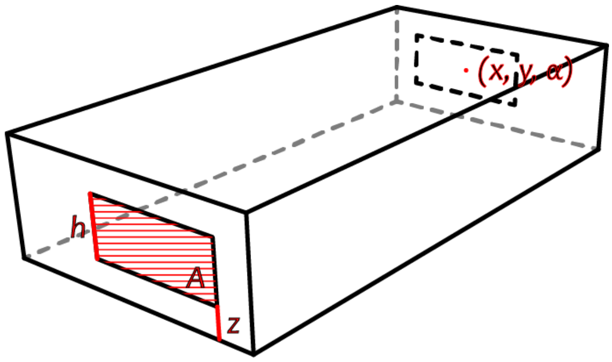

Figure 3.6 Variables describing openings

For boundary condition of the indoor ventilation cases, the only variable needed for calculation was the pressure difference between the two openings. Variables describing boundary condition is shown in Figure 3.7.

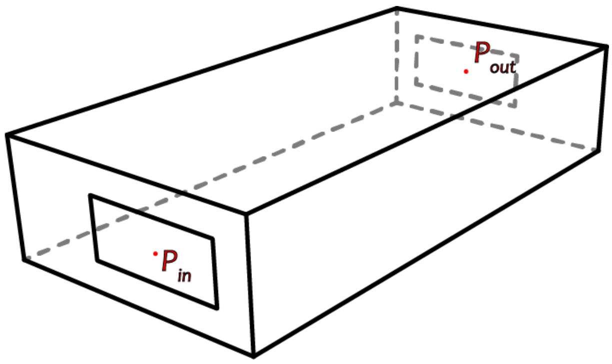

Figure 3.7 Variables describing boundary condition

There were also some constants related to air flow used in this research, including gravity, air density, and kinetic viscosity of air.

As defined in Chapter 2, the target was the ventilated ratio of area that fulfilled certain air velocity limits. Two sections of the space with different elevations from floor level were selected, a 1.2 m height and a 1.6 m height, representing human head level while sitting and standing. Variables describing target is shown in Figure 3.8.

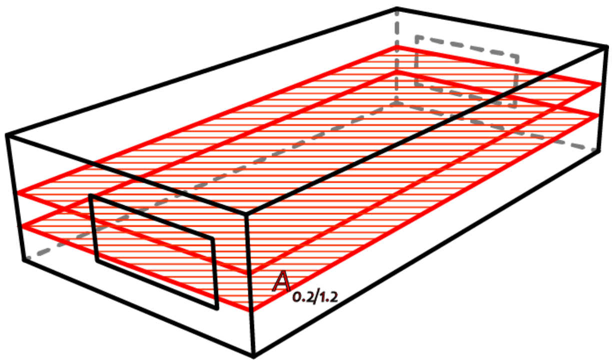

Figure 3.8 Variables describing target

Tables 3.1 and 3.2 summarize the selected variables and constants with their SI units for this research.

Table 3.3 Input variables and constants for similarity analysis

Variable	**Description**	**Unit**	**Type**
ρ	Air density	kg/m^3	Constant
ν	Air kinetic viscosity	m^2/s	Constant
g	Gravity	m/s^2	Constant
ΔP	Pressure difference on openings	kg/ ms^2	Parameter
H	Floor height	m	Parameter

A_i	Inlet area	m^2	Parameter
A_o	Outlet area	m^2	Parameter
z_i	Inlet elevation from floor level	m	Parameter
z_o	Outlet elevation from floor level	m	Parameter
w_i	Inlet width	m	Parameter
w_o	Outlet width	m	Parameter
x	Outlet relative position x	m	Parameter
y	Outlet relative position y	m	Parameter
α	Outlet normal relative angle	π	Parameter
A_f	Total floor area	m^2	Parameter
L	Total wall length	m	Parameter

Table 3.4 Target variables for similarity analysis

Variable	Description	Unit	Type
$A_{0.2/1.2}$	Area with air velocity above 0.2m/s at 1.2m height	m^2	Target
$A_{0.3/1.2}$	Area with air velocity above 0.3m/s at 1.2m height	m^2	Target
$A_{0.4/1.2}$	Area with air velocity above 0.4m/s at 1.2m height	m^2	Target
$A_{0.5/1.2}$	Area with air velocity above 0.5m/s at 1.2m height	m^2	Target
$A_{0.6/1.2}$	Area with air velocity above 0.6m/s at 1.2m height	m^2	Target
$A_{0.2/1.6}$	Area with air velocity above 0.2m/s at 1.6m height	m^2	Target
$A_{0.3/1.6}$	Area with air velocity above 0.3m/s at 1.6m height	m^2	Target
$A_{0.4/1.6}$	Area with air velocity above 0.4m/s at 1.6m height	m^2	Target
$A_{0.5/1.6}$	Area with air velocity above 0.5m/s at 1.6m height	m^2	Target
$A_{0.6/1.6}$	Area with air velocity above 0.6m/s at 1.6m height	m^2	Target

After listing all related parameters, 3 SI-unit groups were selected. ρ, H, g were designated as primary groups. The rest were converted into an initial set of dimensionless numbers Π_i. A total of 23 dimensionless numbers could be deduced using dimensional similarity analysis, 13 as inputs and 10 as targets. A conclusion of similarity criteria is shown in Tables 3.3 and Table 3.4.

Table 3.5 Input similarity criteria

No.	Similarity Criterion	Physical Significance
Π_1	$\frac{H^3 g}{\nu^2}$	Represents the influence of gravity on air
Π_2	$\frac{\Delta P}{\rho g H}$	Represents the influence of pressure difference on openings
Π_3	$\frac{A_f}{H^2}$	Represents the influence of total floor area
Π_4	$\frac{L^2}{A_f}$	Represents the influence of total wall length
Π_5	$\frac{x^2}{A_f}$	Represents the influence of outlet relative position x
Π_6	$\frac{y}{x}$	Represents the influence of outlet relative position y
Π_7	α	Represents the influence of outlet relative normal angle
Π_8	$\frac{A_i}{A_f}$	Represents the influence of inlet area
Π_9	$\frac{z_i}{H}$	Represents the influence of inlet elevation from floor level
Π_{10}	$\frac{w_i}{H}$	Represents the influence of inlet width
Π_{11}	$\frac{A_o}{A_f}$	Represents the influence of outlet area
Π_{12}	$\frac{z_o}{H}$	Represents the influence of outlet elevation from floor level
Π_{13}	$\frac{w_o}{H}$	Represents the influence of outlet width

Table 3.6 Target similarity criteria

No.	Similarity Criteria	Physical Significance
y_1	$\frac{A_{0.2/1.2}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.2m/s at 1.2m height
y_2	$\frac{A_{0.3/1.2}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.3m/s at 1.2m height
y_3	$\frac{A_{0.4/1.2}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.4m/s at 1.2m height
y_4	$\frac{A_{0.5/1.2}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.5m/s at 1.2m height
y_5	$\frac{A_{0.6/1.2}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.6m/s at 1.2m height
y_6	$\frac{A_{0.2/1.6}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.2m/s at 1.6m height
y_7	$\frac{A_{0.3/1.6}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.3m/s at 1.6m height
y_8	$\frac{A_{0.4/1.6}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.4m/s at 1.6m height
y_9	$\frac{A_{0.5/1.6}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.5m/s at 1.6m height
y_{10}	$\frac{A_{0.6/1.6}}{A_f}$	Represents the ventilated ratio of area with air velocity above 0.6m/s at 1.6m height

3.2.2.2 Numerical Experiments

The next preparation of regression is building a case database of numerical experiment. To achieve this, geometric templates are built first and for each template, different values are assigned to each design parameters. A list of all cases is compiled and CFD simulation is used to calculate each case. In the end, the distribution of input similarity criteria for the case database is analyzed.

To begin with, case templates were built based on geometries and openings position. Due to the symmetry of the shapes, all the shape and opening positions configurations could be listed, as shown in Figure 3.9.

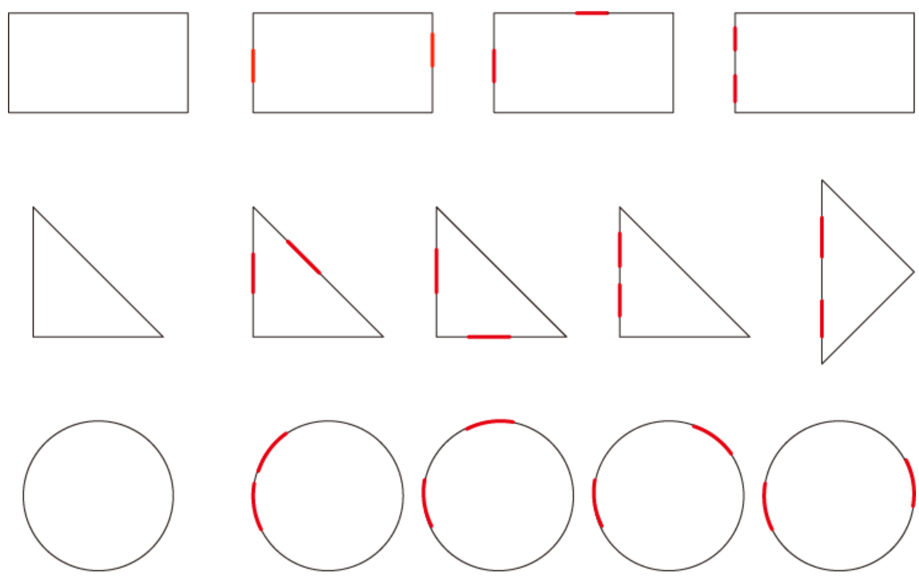

Figure 3.9 All shape and opening positions configurations

For each parameter, there were several architectural design value options in the early design stage, so a wide range of cases was covered. At this time, the opening distance from ceiling *h* was introduced. Then the opening area *A* could be calculated from opening elevation *z*, opening distance from ceiling *h*, and opening width *w*. The limitation $z + h < H$ (floor height) was applied. Parameters describing the total floor area and total wall length varied based on the shape. For the triangle, one right-side-edge length a_T was used. For the rectangle, two side-edge lengths a_R and b_R were used. For the circle, radius r was used. In this research, the relative angle of the outlet normal was limited to eight options.

A list of all value options of the design parameters for numerical experiments is shown in Table 3.5.

Table 3.7 Value options of design parameters and constants

Variables	Description	Unit	Value options	Count
ρ	Air density	kg/m^3	Constant, 1.205	1
ν	Air kinetic viscosity	m^2/s	Constant, 15.11 x 10^{-6}	1
g	Gravity	m/s^2	Constant, 9.8	1
ΔP	Pressure difference on openings	$kg/\ ms^2$	(0, 50)	NA
H	Floor height	m	2.5, 2.7, 2.9, 3.1, 3.3, 3.5	6
h_i	Inlet distance from ceiling	m^2	0.1, 0.4, 0.7, 1, 1.3, 1.6, 1.9, 2.2, 2.5, 2.8, 3.1, 3.4 [1]	12
h_o	Outlet distance from ceiling	m^2	0.1, 0.4, 0.7, 1, 1.3, 1.6, 1.9, 2.2, 2.5, 2.8, 3.1, 3.4 [1]	12
z_i	Inlet elevation from floor level	m	0.1, 0.4, 0.7, 1, 1.3, 1.6, 1.9, 2.2, 2.5, 2.8, 3.1, 3.4 [1]	12

Table 3.7 Value options of design parameters and constants (continues)

Variables	Description	Unit	Value options	Count
z_o	Outlet elevation from floor level	m	0.1, 0.4, 0.7, 1, 1.3, 1.6, 1.9, 2.2, 2.5, 2.8, 3.1, 3.4 [1]	12
w_i	Inlet width	m	0.5, 0.9, 1.3, 1.7, 2.1, 2.5, 2.9, 3.3, 3.7, 4.1, 4.5, 4.9 [2]	12
w_o	Outlet width	m	0.5, 0.9, 1.3, 1.7, 2.1, 2.5, 2.9, 3.3, 3.7, 4.1, 4.5, 4.9 [2]	12
a_T	Triangle side edge length	m	(1,10)	NA
a_R	Rectangle side edge length	m	(1,10)	NA
b_R	Rectangle side edge length	m	(1,10)	NA
r	Circle radius	m	(1,10)	NA
x	Outlet relative position x	m	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1 (×L) [3]	10
y	Outlet relative position y	m	0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1 (×L) [3]	10
α	Outlet relative normal angle	π	0.25, 0.5, 0.75, 1 (×π)	4

[1] Limited by floor height

[2] Limited by wall length

[3] L represents the side edge length or radius depending on shape of the case, also limited by opening position

The total case number for all combinations of the value options is over 30 billion. A lot of cases are considered similar with the same similarity criteria. Based on similarity theory, it is not necessary to cover all possibilities, but it is critical to have a good distribution of values for each similarity criterion. For each numerical case, a value was randomly selected from the options for each parameter. A similar number of cases was conducted for each different shape. In total approximately 2800 cases were calculated. The distribution of similarity criteria will be validated in the end of this section.

CFD simulation was employed to calculate the cases and find the numerical experiments results. They were then used for the equations regression in the next step. The commercial CFD simulation software used was Ansys Fluent (Ansys, 2013). The grid number was around 50,000. Grid-independent studies were conducted. The turbulence model was the standard k-ε model. Both the inlet and outlet had pressure profiles set as boundary conditions, while in addition the inlet has a standard turbulence profile. A logarithmic law with roughness parameters was used for setting the solid surface boundary conditions. Steady simulation with a SIMPLE solution algorithm and a first order upwind differencing scheme were used (Sørensen & Nielsen, 2003; Tominaga et al., 2008).

The ventilated ratios of area with air velocity above different limits were the outputs for each case. All the similarity criteria were calculated for each case. Around 30 cases with extreme similarity criteria were filtered out in this research. In the end, the numerical experiment database consists of 2795 cases in total. A list example of 10 cases with all inputs and outputs is included as Appendix A to Appendix D.

According to similarity theory, it is not necessary for the database to cover all possibilities, but the values of each input similarity criterion should distribute evenly in its range (Gyenge, 2005; Szirtes, 2006). Taking input similarity criterion Π_1 and Π_2 as examples, the distribution of values is shown as Figure 3.10 and Figure 3.11.

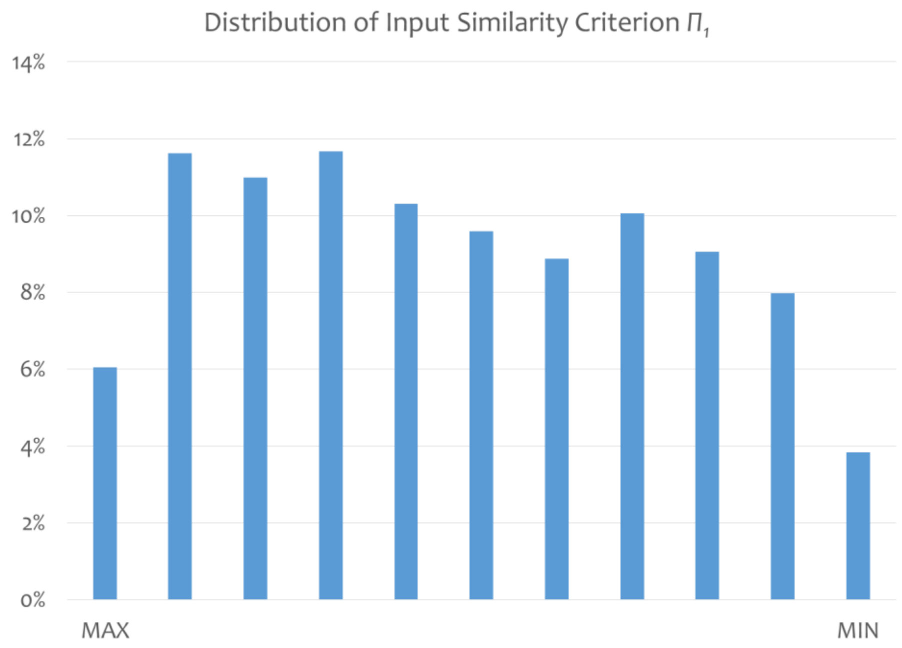

Figure 3.10 Distribution of values for input similarity criterion Π_1

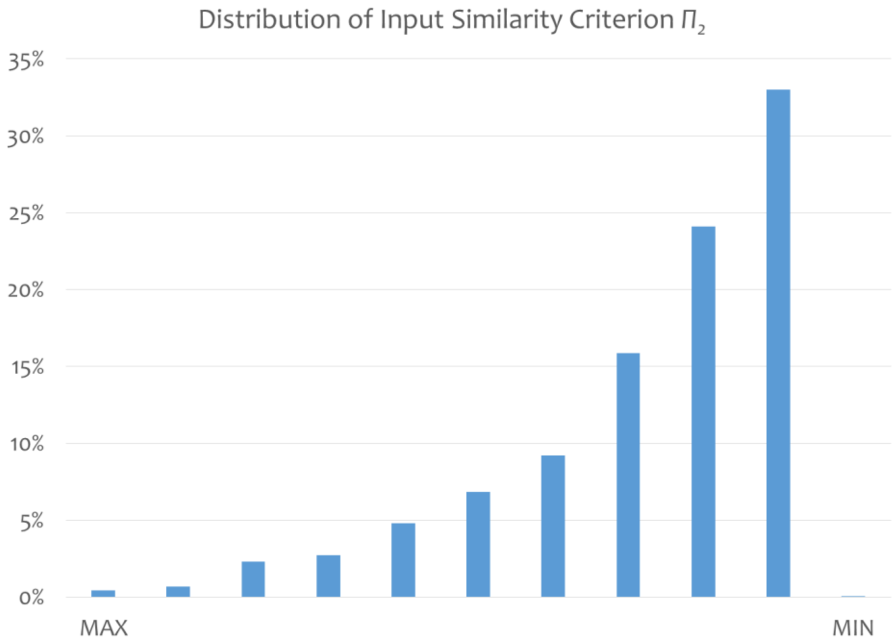

Figure 3.11 Distribution of values for input similarity criterion Π_2

As mentioned in section 3.2.2.1, input similarity criterion Π_1 ($\frac{H^3 g}{\nu^2}$) represents the influence of gravity on air, the distribution of its values is close to even in the range. Input similarity criterion Π_2 ($\frac{\Delta P}{\rho g H}$) **r**epresents the influence of pressure difference on openings. There are more cases with low Π_2 values in the database. This is because cross-ventilation potential is more sensitive to lower pressure difference according to some test cases. Distribution of other input similarity criteria values can be found in Appendix E. The distribution can be improved in future research, which will be discussed in detail in Chapter 5.

Lastly, the ranges of the input similarity criteria values are shown in Table 3.8, indicating that cross-ventilated spaces with the 13 input similarity criteria in these ranges could apply this simplified calculation method.

Table 3.8 Range of similarity criteria for numerical experiments

No.	Similarity Criteria	Range of Values
Π_1	$\frac{H^3 g}{\nu^2}$	(6.7 x 10^{11}, 18.4 x 10^{11})
Π_2	$\frac{\Delta P}{\rho g H}$	(0.003, 1.547)
Π_3	$\frac{A_f}{H^2}$	(2.965, 31.371)
Π_4	$\frac{L^2}{A_f}$	(12.566, 34.755)
Π_5	$\frac{x^2}{A_f}$	(0.007, 2.164)
Π_6	$\frac{y}{x}$	(-2.414, 8)
Π_7	α	(0.785, 3.142)
Π_8	$\frac{A_i}{A_f}$	(0.001, 0.267)
Π_9	$\frac{z_i}{H}$	(0.029, 0.8)
Π_{10}	$\frac{w_i}{H}$	(0.286, 1.96)
Π_{11}	$\frac{A_o}{A_f}$	(0.001, 0.229)
Π_{12}	$\frac{z_o}{H}$	(0.029, 0.769)
Π_{13}	$\frac{w_o}{H}$	(0.294, 1.96)

3.2.2.3 Equations Regression

Regression of the correlation equations of the 13 input similarity criteria (Π_1 – Π_{13}) and the 10 target similarity criteria ($y_1 - y_{10}$) are the main tasks of this simplified calculation method development. The equations are shown as follow.

$$\frac{A_{0.2/1.2}}{A_f} = f_1\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.3)$$

$$\frac{A_{0.3/1.2}}{A_f} = f_2\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.4)$$

$$\frac{A_{0.4/1.2}}{A_f} = f_3\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.5)$$

$$\frac{A_{0.5/1.2}}{A_f} = f_4\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.6)$$

$$\frac{A_{0.6/1.2}}{A_f} = f_5\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.7)$$

$$\frac{A_{0.2/1.6}}{A_f} = f_6\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.8)$$

$$\frac{A_{0.3/1.6}}{A_f} = f_7\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.9)$$

$$\frac{A_{0.4/1.6}}{A_f} = f_8\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.10)$$

$$\frac{A_{0.5/1.6}}{A_f} = f_9\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.11)$$

$$\frac{A_{0.6/1.6}}{A_f} = f_{10}\left(\frac{H^3 g}{v^2}, \frac{\Delta P}{\rho g H}, \frac{A_f}{H^2}, \frac{L^2}{A_f}, \frac{x^2}{A_f}, \frac{y}{x}, \alpha, \frac{A_i}{A_f}, \frac{z_i}{H}, \frac{w_i}{H}, \frac{A_o}{A_f}, \frac{z_o}{H}, \frac{w_o}{H}\right) \quad (3.12)$$

There are different types of regression models (Fahrmeir et al., 2013). The most widely used models are linear regression models, including simple linear regression model and multiple linear regression, and nonlinear regression models (Fahrmeir et al., 2013; Seber & Wild, 1989). In recent years, artificial neural network is recognized as a powerful tool to solve regression problems (Zhang, 2010). All models can accomplish the regression task of this research with different precision of regression results and effort to embed the models in current design platform Rhino Grasshopper. The model performance is evaluated by coefficient of determination R^2 and residual standard deviation s, shown as following equations.

$$R^2 = 1 - \frac{\sum_{i=1}^{N_{Train}} \left(y_i - f_i\right)^2}{\sum_{i=1}^{N_{Train}} \left(y_i - \overline{y}\right)^2} \tag{3.13}$$

$$s = \sqrt{\frac{\sum_{i=1}^{N_{Train}} \left(y_i - \overline{y}\right)^2}{N_{Train} - 1}} \tag{3.14}$$

This regression model evaluation method describes how the model fits the training data. In addition to these evaluation indices, the model should have the capacity to predict the result of test data, meaning any case not included in the training data. In this research, ninety percent of the cases were randomly chosen as training data while the other ten percent were used as test data. The regression models' performance is evaluated based on these two aspects.

MATLAB was used to test the different regression models with the data that resulted from the 2795 cases (Higham & Higham, 2005). After testing the different regression models and considering the model performance as well as the availability in design platform, multiple linear regression with the quadratic model, also known as second order linear regression model, was employed. In addition to conventional multiple linear regression method, stepwise regression method was also tested but did not improve the performance much (Armstrong & Hilton, 2011; Higham & Higham, 2005).

For the multiple linear regression process, the target similarity criteria y_1 and y_6 were defined as primary target similarity criteria, and were regressed first. The calculated results of these two primary target similarity criteria were then used as inputs for the regression of the other target similarity criteria, defined as secondary target similarity criteria. This is because the secondary target similarity criteria clearly had certain correlations with the primary target similarity criteria. For example, y_2 is the ventilated ratio of area with air velocity above 0.3m/s at 1.2m height, which will be related to y_1, as the ventilated ratio for air velocity above 0.2m/s at the same height. This regression strategy improved the multiple linear regression model.

The detailed regression results are shown in the Appendix F. The coefficient of determination R^2 and residual standard deviation s are shown as Table 3.9.

Table 3.9 Standard residual deviations of multiple linear regression

Similarity Criteria	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}
R^2	0.709	0.975	0.943	0.920	0.903	0.706	0.974	0.942	0.919	0.903
s	13.8%	4.6%	7.0%	8.2%	8.7%	13.8%	4.6%	7.0%	8.1%	8.6%

3.2.2.4 Validation

Around 280 cases were randomly picked from numerical experiments to verify the simplified calculation method. If the results calculated by using the above regression equations agreed with the results provided by CFD simulation, the simplified calculation method was considered to have worked well.

Taking the target similarity criterion y_1 as an example, the calculated results and simulated results of all 280 validation cases is plotted in Figure 3.12 and a distribution of the difference is shown in Figure 3.13.

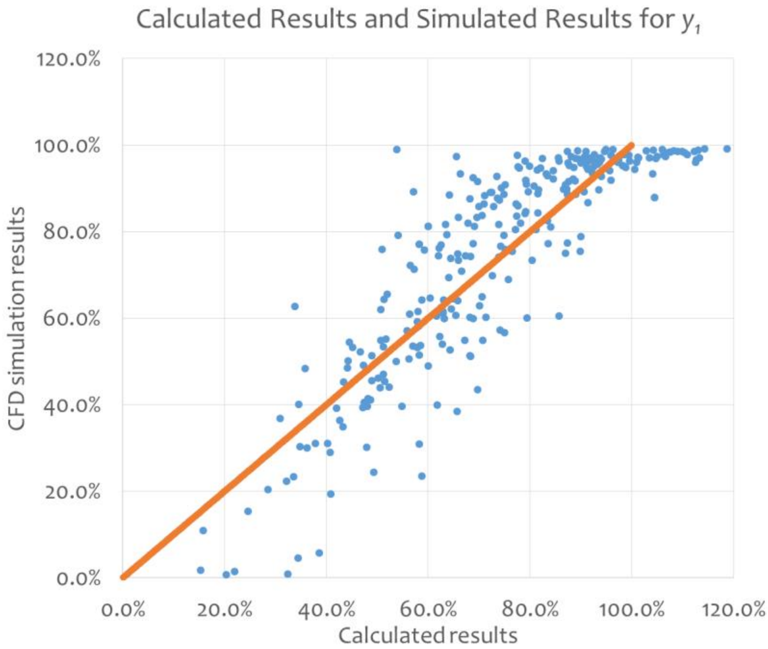

Figure 3.12 Calculated results and simulated results of all test cases for y_1

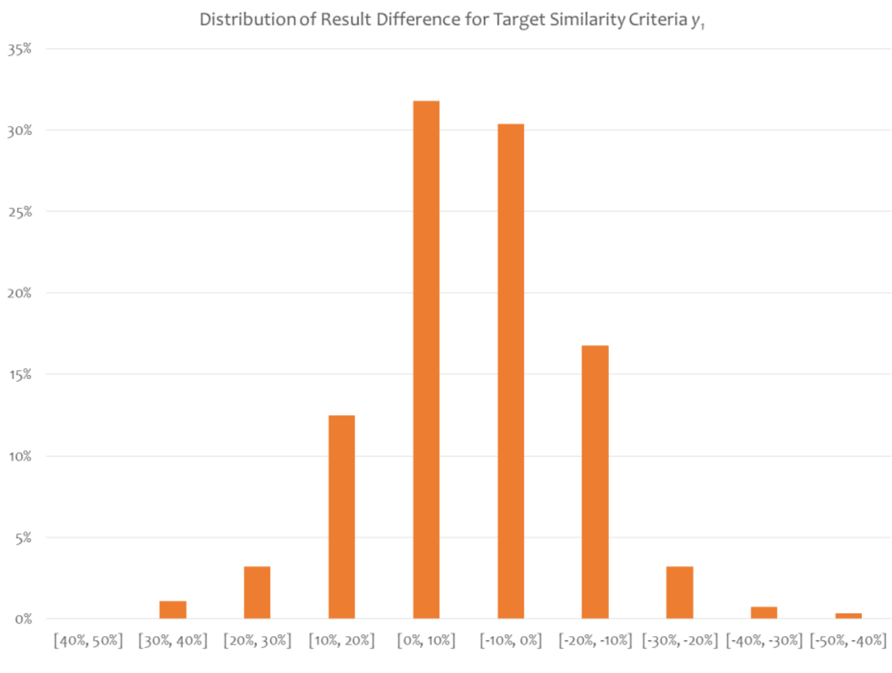

Figure 3.13 Distribution of difference of calculations and simulations for y_1

Shown as Figure 3.12 and Figure 3.13, 62.1% of the test cases had a difference between calculated results and simulated results below 10%, while 91.4% of the test cases had a difference between calculated results and simulated results below 20%. The average absolute difference of the equations-calculated results and the CFD-simulated results is 9.6%.

According to following equation, the coefficient of determination R^2 of target similarity criterion y_1 for the test cases is 0.6725.

$$R^2 = 1 - \frac{\sum_{i=1}^{N_{Test}} \left(y_i - f_i\right)^2}{\sum_{i=1}^{N_{Test}} \left(y_i - \overline{y}\right)^2} \tag{3.15}$$

Validation of other similarity criteria can be found in Appendix G. The comparison of the equations-calculated results and the CFD-simulated results for 10 target similarity criteria are shown in Table 3.10.

Table 3.10 Comparison of calculated results and simulated results

Target Similarity Criterion	**Average Absolute Difference**	**Coefficient of Determination R^2**	**Absolute Difference Lower than 10%**	**Absolute Difference Lower than 20%**
y_1	9.6%	0.672	62.1% of cases	91.4% of cases
y_2	11.0%	0.721	58.6% of cases	83.6% of cases
y_3	11.2%	0.756	58.2% of cases	82.5% of cases
y_4	10.6%	0.785	60.7% of cases	85.7% of cases
y_5	9.9%	0.796	62.5% of cases	85.7% of cases
y_6	9.5%	0.665	62.1% of cases	90.7% of cases
y_7	10.8%	0.716	56.8% of cases	82.9% of cases
y_8	10.8%	0.752	59.3% of cases	83.6% of cases
y_9	10.1%	0.779	61.4% of cases	86.8% of cases
y_{10}	9.5%	0.791	67.5% of cases	87.5% of cases
Average	10.3%	0.672	60.9% of cases	86.0% of cases

With an average absolute difference of 11.5%, the results calculated by the regression equations were considered agreed well with those simulated by CFD for the 10 target similarity criteria. This precision was acceptable for the early design stage, considering the simplified calculation method only took several seconds for a result, while CFD would take hours for each case.

3.2.2.5 Summary

In conclusion, for indoor natural ventilation calculation, two target parameters identified for natural ventilation potential were ventilation rate and ventilated ratio. While ventilation rate could be calculated quickly by existing methods (Etheridge, 2012), ventilated ratio would take hours by CFD simulation for one case (Chen et al., 2010), making it difficult to identify the best-case scenario. Therefore, a simplified calculation method for the ventilated ratio was necessary.

Cross-ventilation was used to illustrate the process of developing the simplified calculation method. A similarity analysis was conducted first, and then numerical experiments were performed by CFD simulation. Based on the numerical experiments results, multiple linear regression was employed to establish the correlation equations between the target similarity criteria and the input similarity criteria. The simplified calculation method was validated by comparing results given by regression equations and by CFD simulated results.

With the regression equations, the ventilated ratio could be calculated without running CFD simulation while achieving similar precision, in this way saving a lot of computing power and time.

3.2.3 Evaluation Procedure

After defining the index for natural ventilation evaluation in the early design stage and developing the calculation methods for both outdoor wind environment simulation and indoor natural ventilation, a practical evaluation outline for Design-Based Natural Ventilation Potential was established, shown as Figure 3.8. The detailed calculation procedure is presented below.

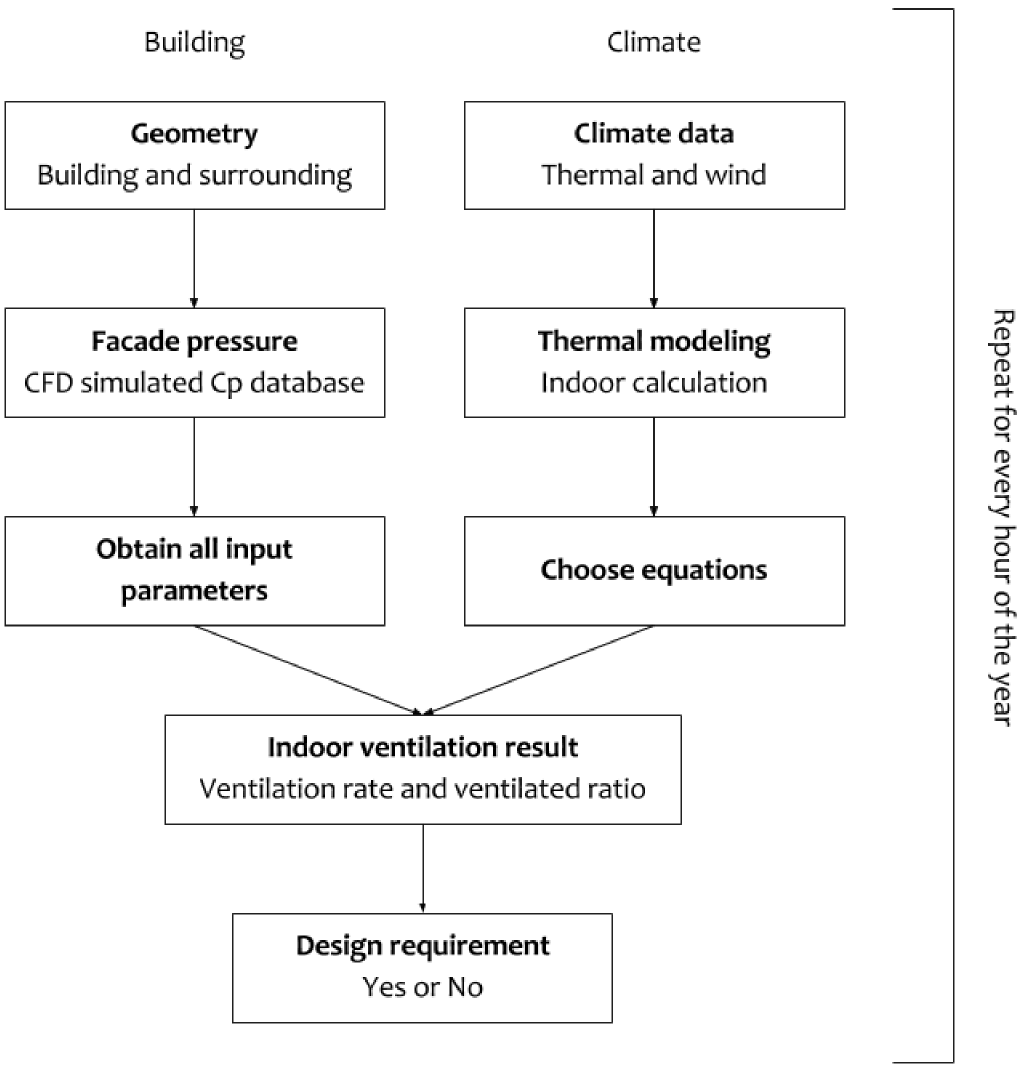

Figure 3.14 Evaluation of Design-Based Natural Ventilation Potential

Firstly, two aspects of input information were required for the calculation, the building and the climate. For the building, target building geometry and urban context were necessary. The outdoor wind environment simulation was conducted to obtain the pressure coefficient database, by running CFD cases automatically. For each hour, the pressure on the facade was calculated based on the pressure coefficient database, while other input parameters were collected, such as floor shape, opening positions, etc. At the same time, the climate information was abstracted from weather data, including temperature, humidity, wind direction, and velocity. A thermal modeling of the space was calculated to predict the operative temperature of the space. Given the operative temperature, a certain air velocity limit was identified for thermal comfort purposes. Two equations were chosen according to the air velocity limit. The ventilated ratios at two section heights were calculated. At the same time, the ventilation rate was calculated by the analytical model. All the results were compared to design requirements of the space. Then a conclusion was made about whether the space had natural ventilation potential for the hour or not. The process was repeated for every hour of the year. In this way, the Design-Based Natural Ventilation Potential was calculated, which could inform designers about natural ventilation in the early design stage with a relatively short calculation time.

3.3 Summary

This chapter focused on calculation of the Design-Based Natural Ventilation

Potential in the early design stage. A review and summary of current studies of natural ventilation illustrated that two-step calculation would work better for this research. The calculation methods consisted of outdoor wind environment simulation and indoor natural ventilation calculation. For the outdoor wind environment simulation, an automatic process to calculate the pressure coefficient database in an urban context was proposed. For the indoor natural ventilation calculation, a simplified calculation was developed by similarity analysis and regression from numerical experiments. Cross-ventilation was used as an example to illustrate the process of developing the simplified calculation method. In the end, a practical procedure to calculate Design-Based Natural Ventilation Potential was created based on the two parts.

As a result, a practical calculation method of Design-Based Natural Ventilation Potential evaluation was developed, which can provide designers feedback on natural ventilation in the early design stage, with a relatively short calculation time.

Chapter 4 Natural Ventilation Evaluation Case Study

4.1 Introduction

The previous chapters of this research have illustrated the importance of a decision-making support system in the early design stage for natural ventilation. Chapter 2 defined the natural ventilation evaluation index to be used, named the Design-Based Natural Ventilation Potential. Chapter 3 developed the method to calculate natural ventilation potential with outdoor wind environment simulation and indoor natural ventilation calculation. The purpose of the decision-making support system is to assist designers in the early stage and enable a better informed design process that takes natural ventilation into consideration.

This chapter presents a case study of natural ventilation evaluation in the early stage and how the evaluation process can suggest design. A building form optimization was performed by genetic algorithm, which will be described in Section 4.2.3. The optimization was built on the Design-Based Natural Ventilation Potential calculated. As a result, the optimized building form had significant improvement in natural ventilation potential with relatively small changes to the original box shape. This case study illustrates the possibility and potential of the decision-making system in the early design stage.

4.2 Natural Ventilation Evaluation Case Study

Among all the design problems in the early design stage, building form is one of the most critical design decisions made by designers (March, 1976; Raffaelli & Antonini, 2016). It is very common for designers to decide on the building form in the early stage, and many other decisions in later stages are made according to that form. It becomes very expensive to change the building form later, in terms of time and effort. On the other hand, the building form is one of the most important factors influencing natural ventilation potential in an urban context, especially in the case of cross-ventilation (Blocken et al., 2011; Zhou et al., 2014). As a consequence, natural ventilation evaluation in the early stage is very necessary to advising on building form design.

This research included a building form optimization case study, based on the natural ventilation potential evaluation index proposed in Chapter 2 and the evaluation methodology developed in Chapter 3. To accomplish the case study, scripts were developed in Rhino Grasshopper to carry out the Design-Based Natural Ventilation Potential evaluation, feeding natural ventilation information back to design. Meanwhile, a genetic algorithm component Galapagos in Rhino Grasshopper, as will be described in Section 4.2.3, was used to optimize the building form for optimal natural ventilation potential (Rutten, 2013). A high-rise tower design with a simplified urban context was the optimization target, to maximize the natural ventilation evaluation result. With the scripts developed, the target building form was optimized automatically and a significant improvement of natural ventilation potential was achieved with several small changes in design.

4.2.1 Building Design

This case study focused on a high-rise tower design with a simplified urban context. The original shape of the target building was a box shape. The target building with surrounding buildings is shown as Figure 4.1.

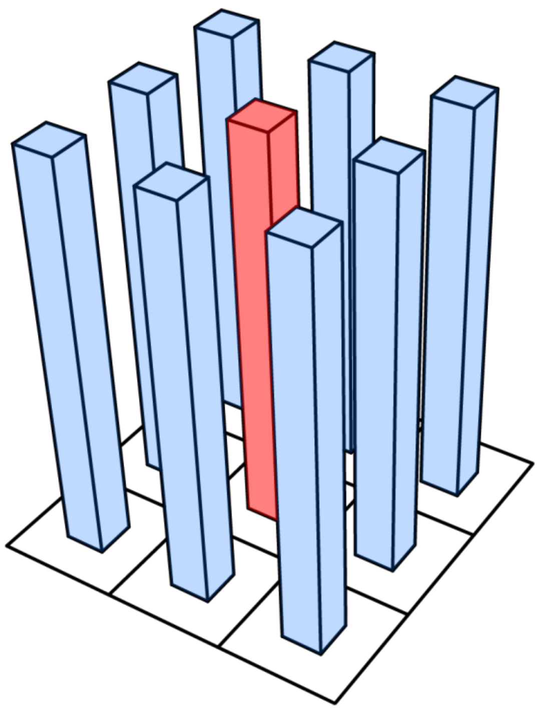

Figure 4.1 Target building with original box shape and urban context

The building form was the optimization target. In this case study, there were several fixed design conditions as well as several design variables describing the building form. Fixed design conditions include: site, urban context, floor-to-area ratio, floor height, and window-to-wall ratio. Design variables include: floor width, floor depth, floor number, corner radius, orientation, twist angle, tilt angle, and tile angle. Detail of each aspect is described below.

Fixed design conditions:

1) Site

The case study had a square grid site with a size of 30 by 30 meters, which was considered representative for a high-density urban environment, shown as Figure 4.2. The site size was limited by the meshing capacity of the CFD software. The location of the site was Boston, Massachusetts (US).

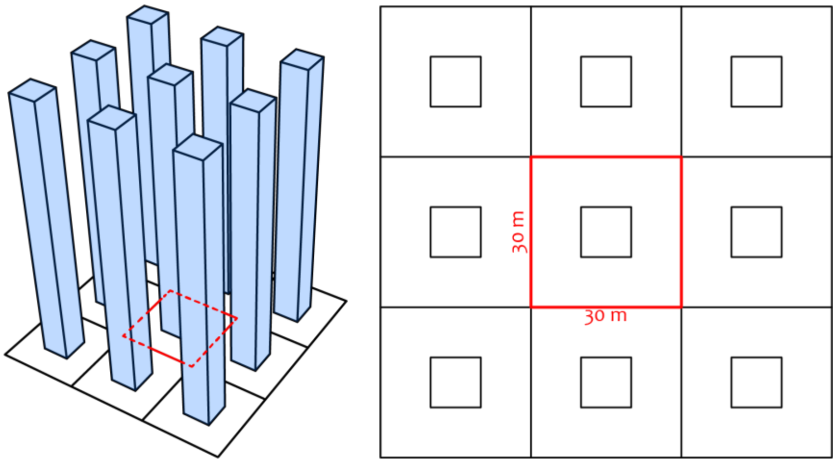

Figure 4.2 Fixed design conditions - site

2) Urban context

The surrounding buildings were simplified to represent a high-density urban context. Each building had a square floor shape with a size of 10 by 10 meters, located in the middle of the site grid. Each building had 30 floors with a floor height of 3.5 meters, giving a total height of 105 meters, as shown in Figure 4.3.

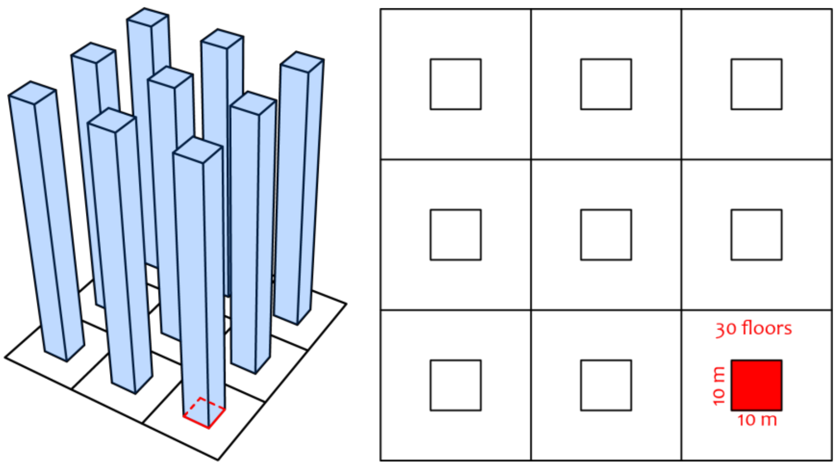

Figure 4.3 Fixed design conditions – urban context

3) Floor-to-area ratio (FAR)

Setting a floor-to-area ratio (FAR) target is common in the early design stage. The floor-to-area ratio for the surrounding buildings was 3.33, shown as Figure 4.4. The same FAR was set as the target for the investigated building. However, the actual FAR of the investigated building would shift slightly around the target FAR.

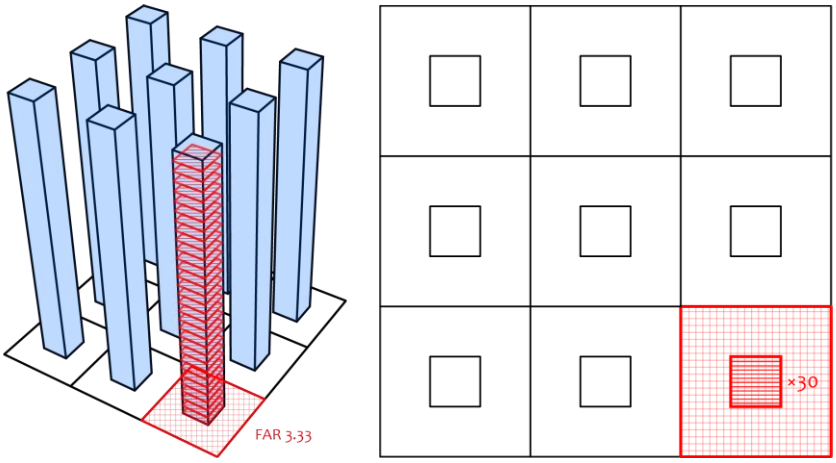

Figure 4.4 Fixed design conditions – floor-to-area ratio

4) Floor height

The floor height was set as 3.5 meters for both the investigated building and surrounding buildings, as shown in Figure 4.5.

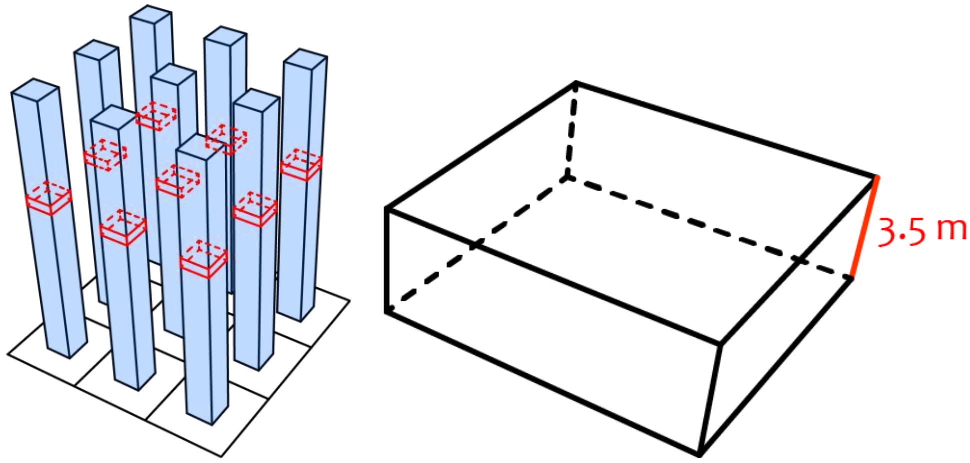

Figure 4.5 Fixed design conditions – floor height

5) Window area

There were four windows designed for each floor, one in the middle of each facade. Each window had a height of 2 meters, with a 1 meter elevation from floor level. The window to wall ratio (WWR) was set at 40%, based on which the window width was calculated, shown as Figure 4.6.

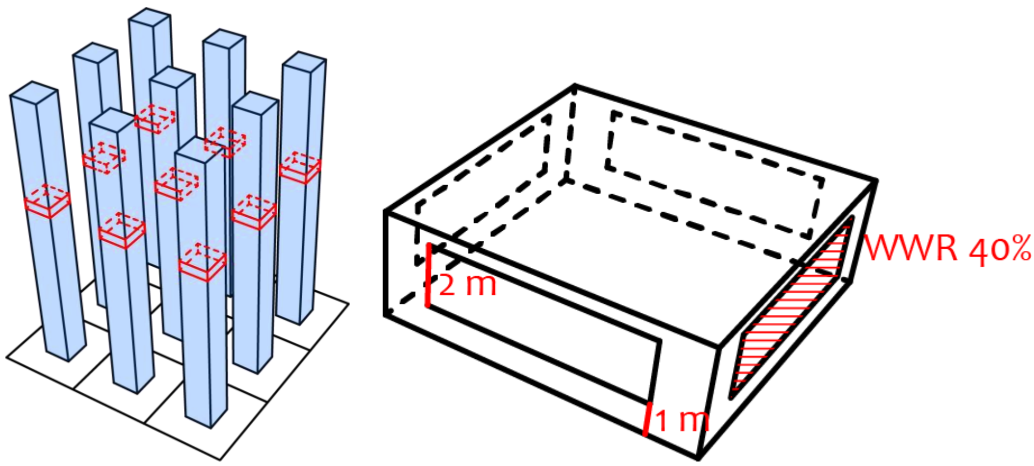

Figure 4.6 Fixed design conditions – window area

Design variables describing the target building form:

1) Floor width

The floor width was set as a variable between 0 and 30 meters, shown as Figure 4.7.

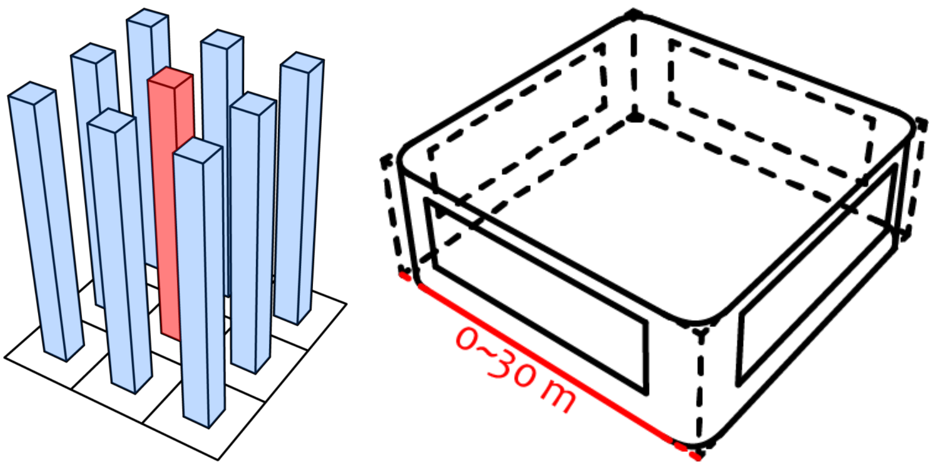

Figure 4.7 Design variables – floor width

2) Floor depth

The floor depth was set as a variable between 0 and 30 meters as well, shown as Figure 4.8.

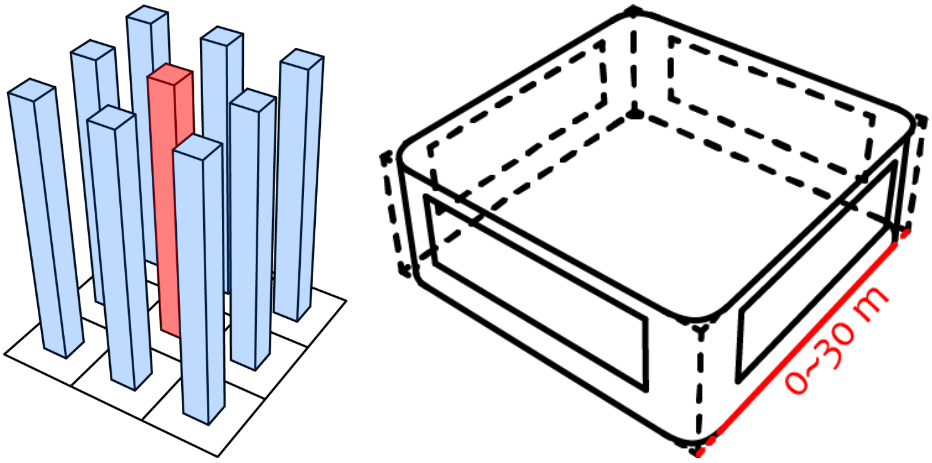

Figure 4.8 Design variables – floor depth

3) Corner radius

The corner radius described the size of a round corner for the floor shape, which was set as a variable between 0 and 30 meters, shown as Figure 4.9. At the same time, it was limited by the lengths of the floor width and the floor depth.

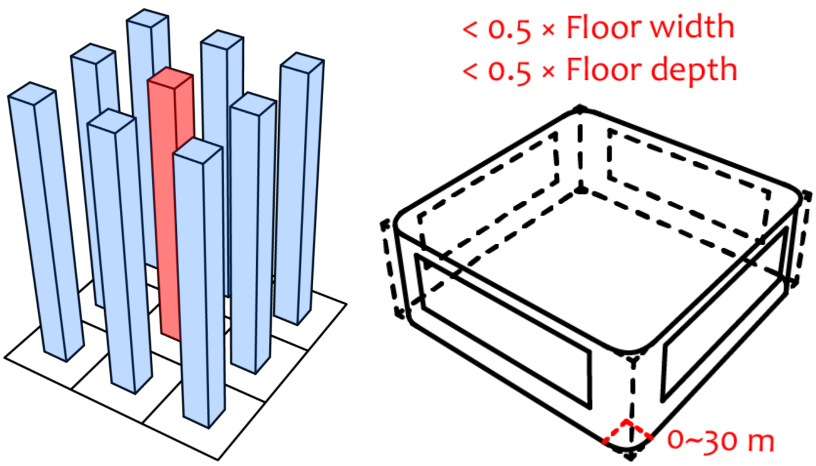

Figure 4.9 Design variables – corner radius

4) Floor number

Based on floor width, floor depth, and corner radius, the floor area was calculated. With the target FAR 3.33, the target building height could be calculated. Total floor number was then decided by dividing the target building height by the fixed floor height of 3.5 meters. The floor number was rounded to the nearest integer. In this way, the floor number was calculated from other variables.

5) Orientation

The orientation of the building was set as a variable between -180 and 180 degrees from the north, shown as Figure 4.10.

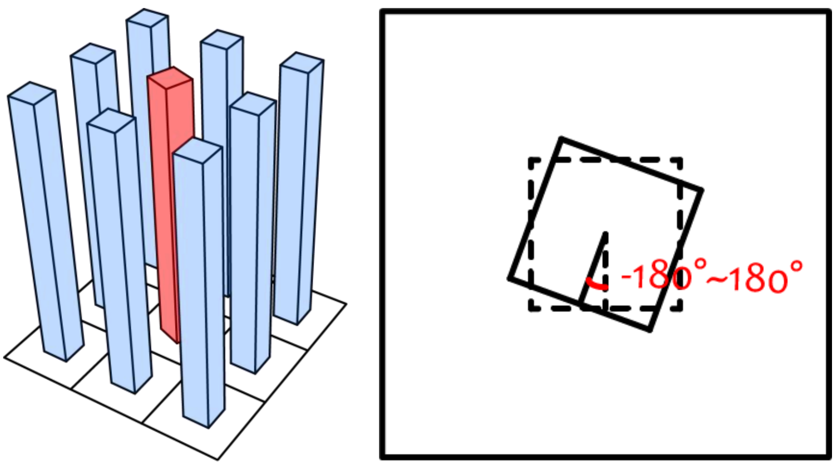

Figure 4.10 Design variables – orientation

6) Twist angle

The twist angle of the building was set as a variable between −180 and 180 degrees, measuring the angle between orientation of the roof and ground floor, shown as Figure 4.11. Then the twist angle of each floor was calculated by dividing the twist angle of the building with the floor number.

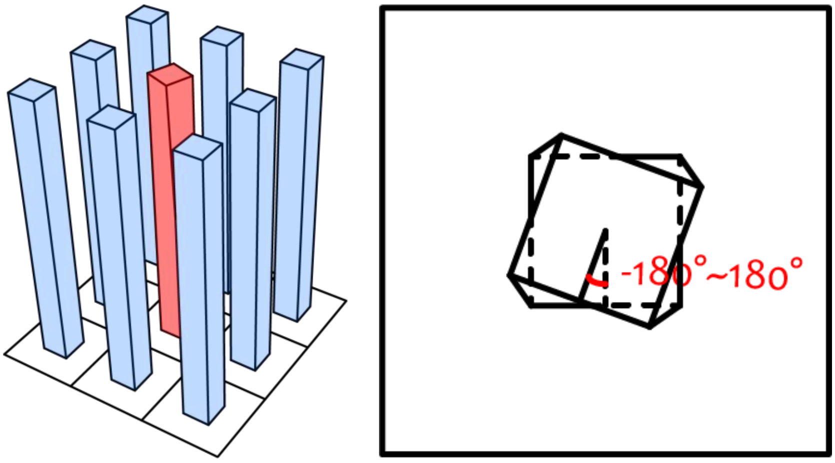

Figure 4.11 Design variables – Twist angle

7) Tilt angle

The tile angle of the building was set as a variable between 0 and 10 degrees, shown as Figure 4.12.

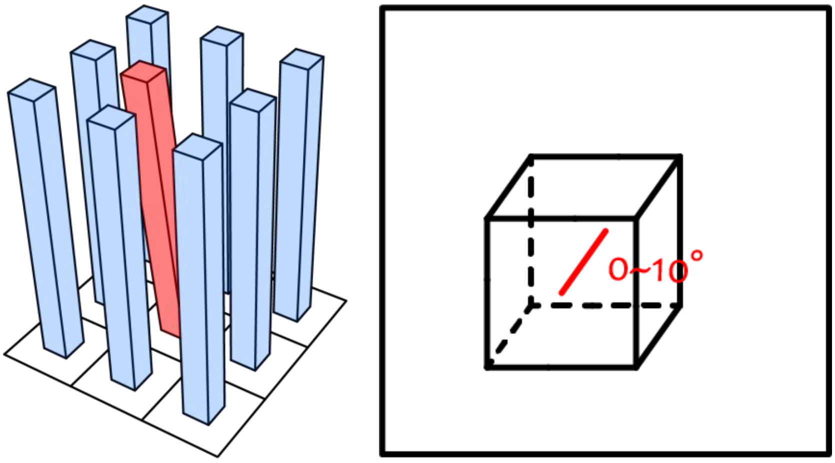

Figure 4.12 Design variables – tile angle

8) Tile direction

The tile direction of the building was set as a variable between -180 and 180 degrees from the north, shown as Figure 4.13.

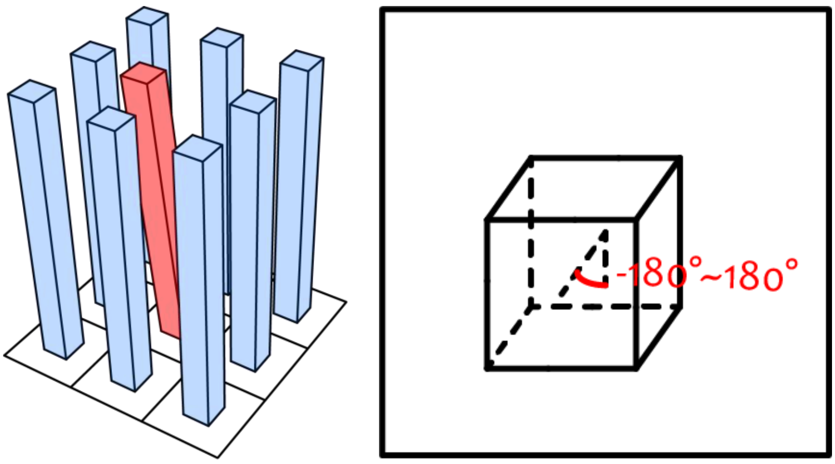

Figure 4.13 Design variables – tile direction

In summary, this design was described by five fixed design conditions and eight design variables about the target building. Because the floor number is calculated based on three other design variables, there are seven design parameters to be investigated. With these conditions, the investigated building and surrounding buildings were modelled in Rhino Grasshopper. The seven design parameters would be optimized for the best natural ventilation potential.

4.2.2 Calculation Assumptions

The Design-Based Natural Ventilation Potential calculation was carried out in this case study with scripts in Rhino Grasshopper. The general calculation procedure was described in Chapter 3. A few additional information about the calculation particularly for this case study is introduced below. .

1) Openings

The pressure coefficient database of the building was given by outdoor CFD simulation. For each floor, there were four windows, and only two of them would be open for each indoor case. In total, there were six indoor cases for each floor, shown as Figure 4.14. The pressure coefficient of each opening was calculated at the central point of each window, offset 1 meter from facade. The one with higher pressure was set as the inlet and the other with a lower pressure was the outlet. All cases were evaluated and the best case was selected to represent the natural ventilation potential of this floor. This is assuming the building will be operated smartly according to wind condition, which is possible after construction.

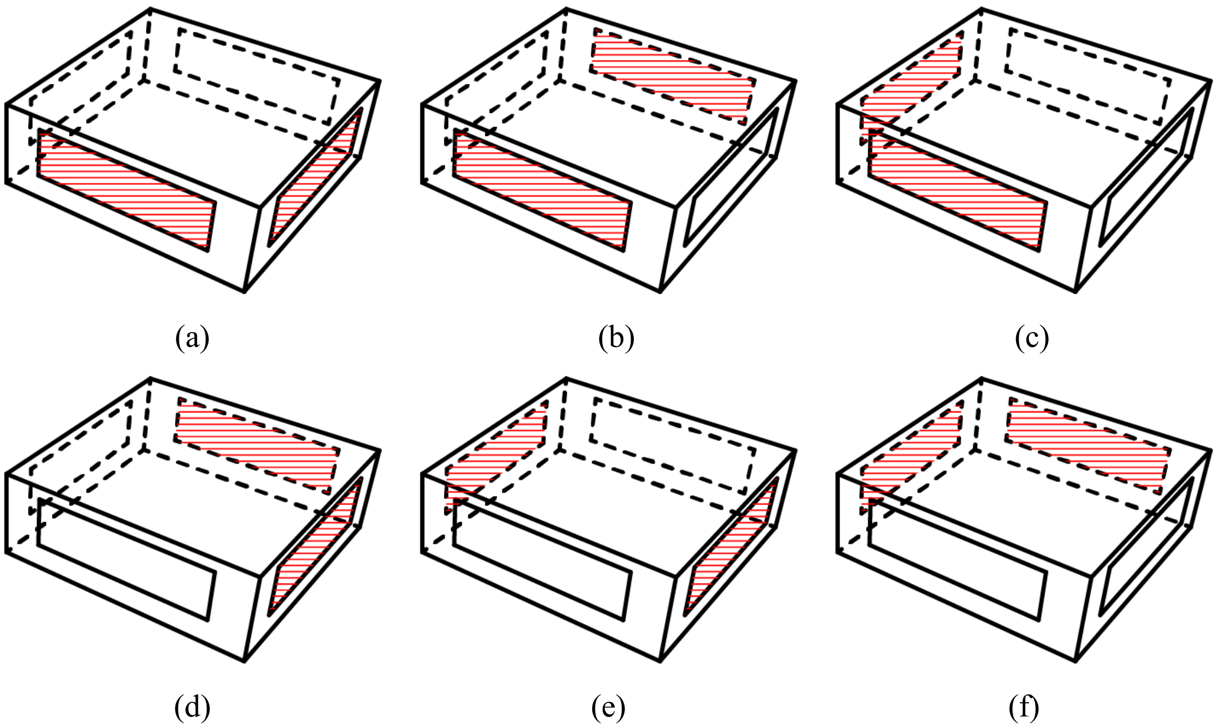

Figure 4.14 Indoor cases for each floor

2) Thermal modeling

The thermal modeling of the space was required for the natural ventilation evaluation. In this study, it is simplified by calculating a static state thermal balance of the space. The internal load of the space was set based on a reference building given by the U.S. Department of Energy (DOE), using the small office building type (National Renewable Energy Laboratory, 2011). The occupancy and the schedule of the space were also taken from the reference building. A table of all internal load settings is shown as Table 4.1.

Table 4.1 Thermal model settings based on reference small office space

Thermal Modeling	**Setting**
Occupancy load	70 W/person
Occupancy density	18.58 m^2/person
Plug load	10.76 W/m^2
Lighting load	10.76 W/m^2
Schedule	6am to 9pm on weekdays

The ventilation rate was calculated by following equation, given the pressures on openings and opening dimensions (Awbi, 2003).

$$Q = AC_d\sqrt{\frac{2\Delta P}{\rho}} \tag{4.1}$$

where Q was the ventilation rate, A was the opening area, C_d was the discharge coefficient of opening, ΔP was the pressure difference between outdoors and indoors, and ρ was the density of air.

The weather data for this case study was taken from Boston. With the calculated ventilated rate and outdoor climate information, the thermal balance of the space could be solved, providing the indoor air temperature. An assumption was made that the internal surface temperature would be the same as the indoor air temperature. Then the radiant temperature would be the same as well. In the end the operative temperature could be calculated be averaging the radiant temperature and air temperature.

With this assumption, the calculated operative temperature was higher than the actual temperature. This was because the actual internal surface temperature was higher than indoor air temperature in most of the time according to the operation schedule. As a result of lower operative temperature, the required air velocity was lower, which led to overestimation of the natural ventilation potential. However, in this study, the feedback of natural ventilation potential evaluation on design is an improvement direction instead of precise value. As long as all the cases keep this same assumption on the operative temperature, the evaluation methodology proposed can advise on design on natural ventilation potential.

This simplified thermal modeling of the space provided operative temperature calculation in seconds. It was more affordable in terms of time and integration effort comparing to detailed thermal modeling by energy simulation tools. This can definitely be improved in future research, as will be discussed in Chapter 5.

3) Natural ventilation potential thresholds

The Design-Based Natural Ventilation Potential index consists of two targets, ventilation rate and ventilated ratio. As introduced in Chapter 2, the ventilation rate refers from design standards and regulations, while the ventilated ratio varies according to function of the space. For this case study, the threshold of ventilation rate was taken from ASHRAE 62.1-2013 for an office space, as 0.3 L/s per m^2 of floor area and 2.5 L/s per person. The other threshold for ventilated ratio was set as 70%, meaning that 70% of the floor area should fulfill the thermal comfort requirement with natural ventilation.

4) Building natural ventilation potential

The Design-Based Natural Ventilation Potential calculation gave a result of the annual natural ventilation potential for each floor. In this case study, the natural ventilation potential of the building was calculated by averaging the natural ventilation potential of all the floors.

4.2.3 Natural Ventilation Potential

With all these calculation assumptions illustrated in section 4.2.2, the Design-Based Natural Ventilation Potential evaluation was carried out by scripts in Rhino

Grasshopper. The calculation procedure is illustrated below, as shown in Figure 4.15.

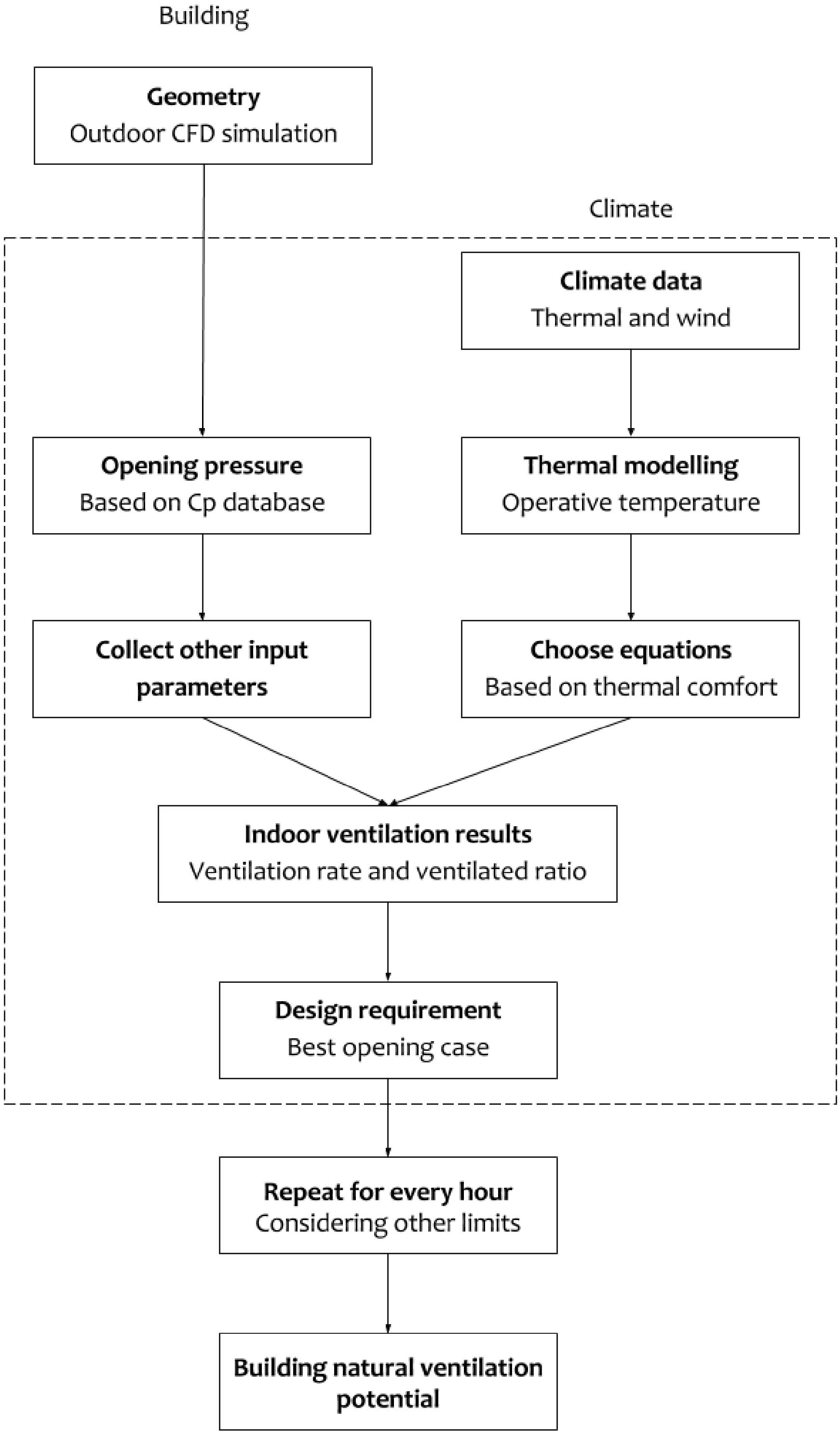

Figure 4.15 Evaluation of Design-Based Natural Ventilation Potential – case study

For the outdoor part, the wind environment CFD simulation was first conducted automatically by calling Ansys Fluent using scripts. All CFD simulation settings were described in Chapter 3. Then the pressure coefficient (C_p) database for the facade was calculated. This step only ran once for the same geometry.

For each hour, the pressure of each opening was calculated based on the CFD simulation pressure coefficient database. After that, other input parameters of the building were collected for later calculation. At the same time, the climate information was abstracted from weather data on Boston, including temperature, relative humidity, wind direction, and velocity. A simplified thermal modeling of the space was employed to predict the operative temperature of the space. According to the operative temperature, a certain air velocity limit was identified for thermal comfort purposes. Two calculation equations were chosen. With the equations and input parameters, the ventilated ratios at two section heights were calculated. Meanwhile, the ventilation rate was given by the thermal modeling.

All the results were compared to the design thresholds for natural ventilation potential evaluation. For each floor, six cases of opening configurations, as introduced in section 4.2.2, were calculated and the best one was chosen to represent the natural ventilation potential. Then a conclusion was made about whether the floor had natural ventilation potential or not. The process was repeated for every hour of the year to obtain the annual natural ventilation potential of the floor.

In the end, the evaluation method can also include other hourly information as additional limits, such as building operation schedule, air pollution, etc. In the end, the building annual natural ventilation potential was calculated by averaging the results of all floors.

With a relatively quick calculation procedure, the Design-Based Natural Ventilation Potential of the investigated building was evaluated. This result was used for the genetic algorithm–based optimization of the building form in the next section.

4.2.4 Genetic Algorithm

A genetic algorithm was used to optimize the seven design parameters, with the annual Design-Based Natural Ventilation Potential of the target building as the optimization target. The genetic algorithm employed was Galapagos, which was a genetic algorithm component built in Rhino Grasshopper (Rutten, 2013). A diagram of optimization process can be found as Figure 4.16. Detailed illustrations of optimization process can be found in Appendix H. The scripts for main calculation process can be found in Appendix I. Detailed settings of Galapagos is shown as

Figure 4.17.

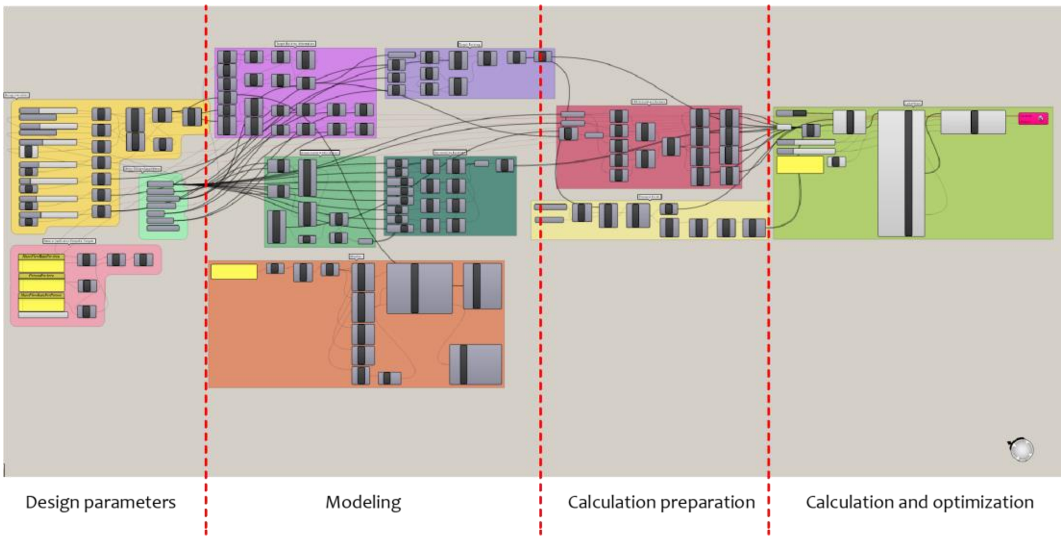

Figure 4.16 Building form optimization in Rhino Grasshopper - overall

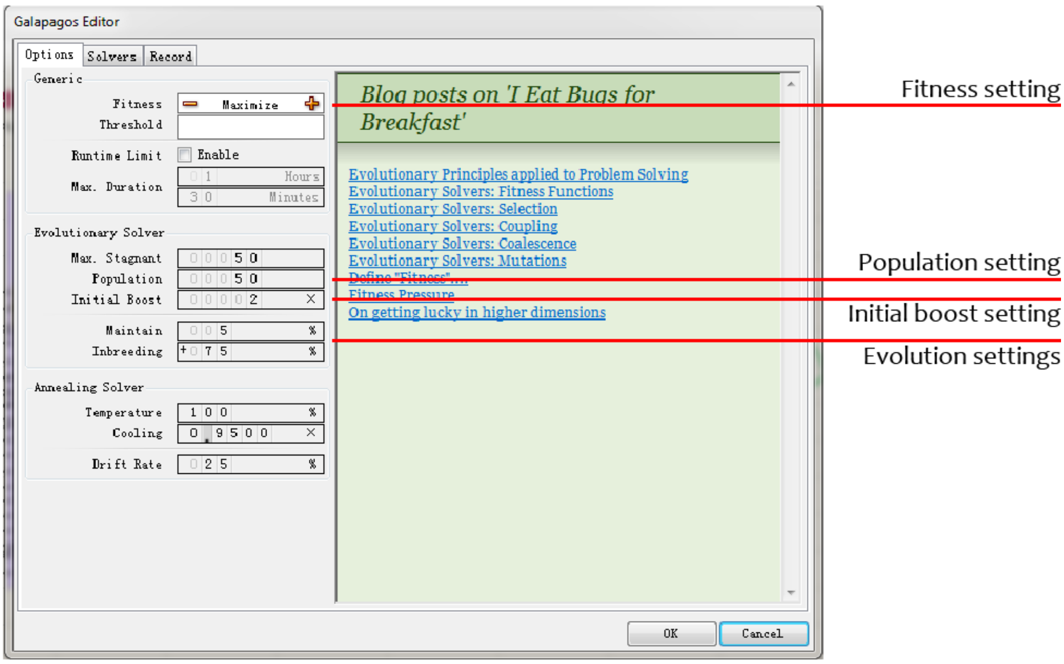

Figure 4.17 Galapagos settings

The Galapagos component took the calculated annual Design-Based Natural

Ventilation Potential of the building as the fitness, meaning the objective of the optimization, while the seven design parameters were optimization inputs. The target was set to maximize the objective. With seven inputs, the population of each generation was set as 50 and initial boost was set as two times, which means 100 individuals for the first round (Rutten, 2013). For each generation, the genetic algorithm would maintain 5% of individuals and inbreed 75% of individuals. In this case study the genetic algorithm ran eight generations before it was manually stopped. A total of 428 design options were investigated. Total optimization time was around 1.5 months. The optimization process of Galapagos is shown in Figure 4.18.

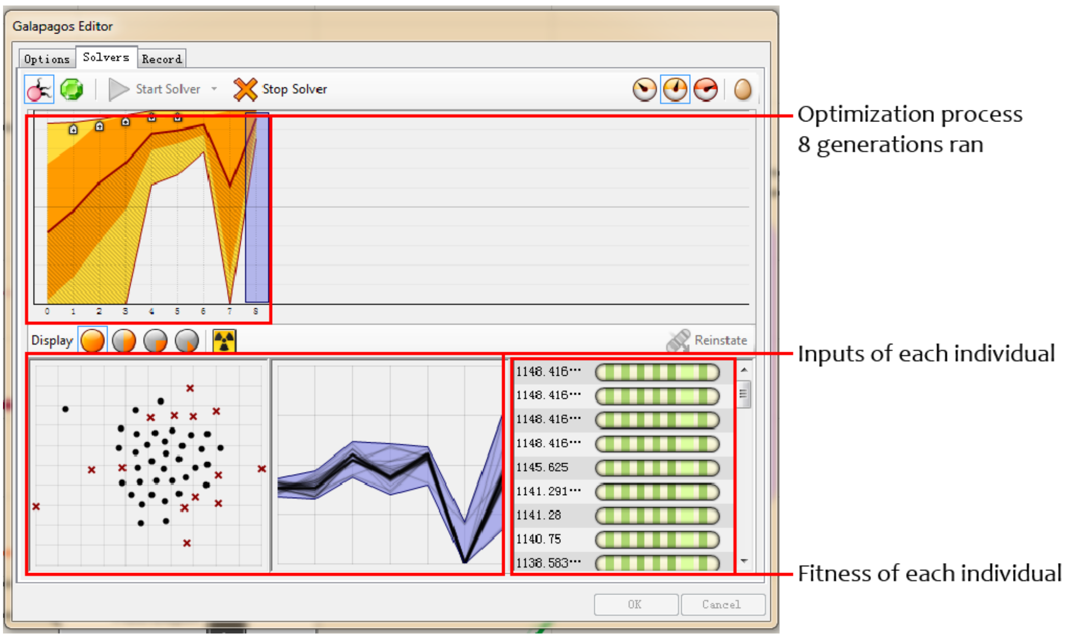

Figure 4.18 Genetic algorithm optimization with Galapagos

The annual Design-Based Natural Ventilation Potential of each design option is plotted in the order of optimization, shown in Figure 4.19. Also, the design parameter floor width of each case is shown in Figure 4.20. The plots of other design parameters can be found in Appendix J.

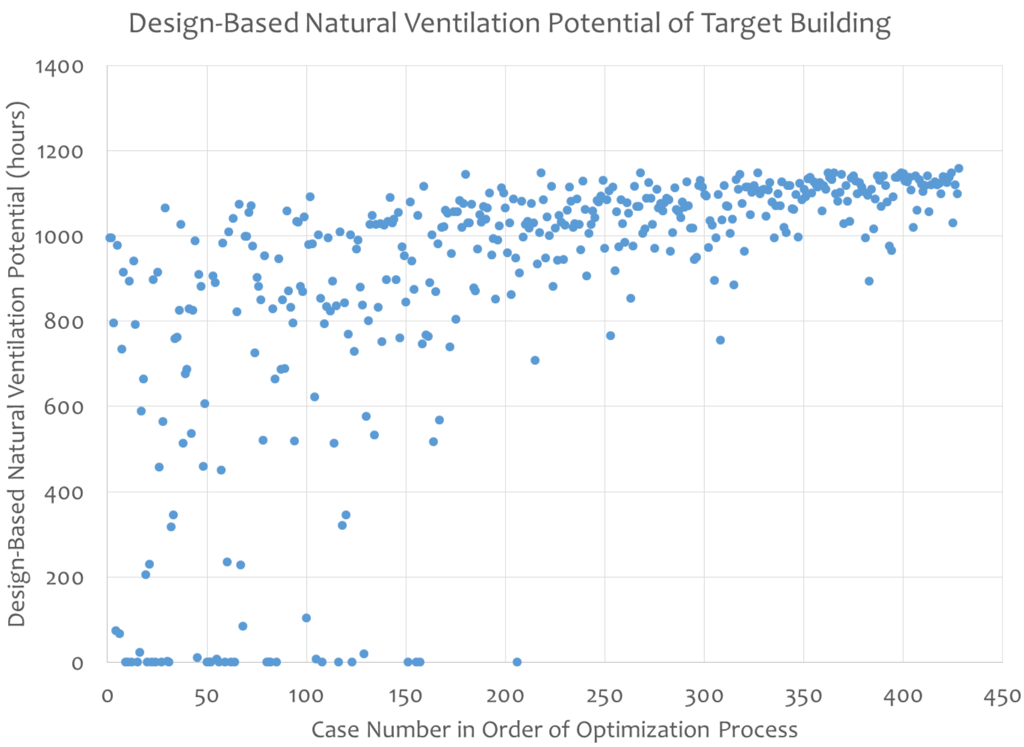

Figure 4.19 Genetic algorithm optimization process – natural ventilation potential

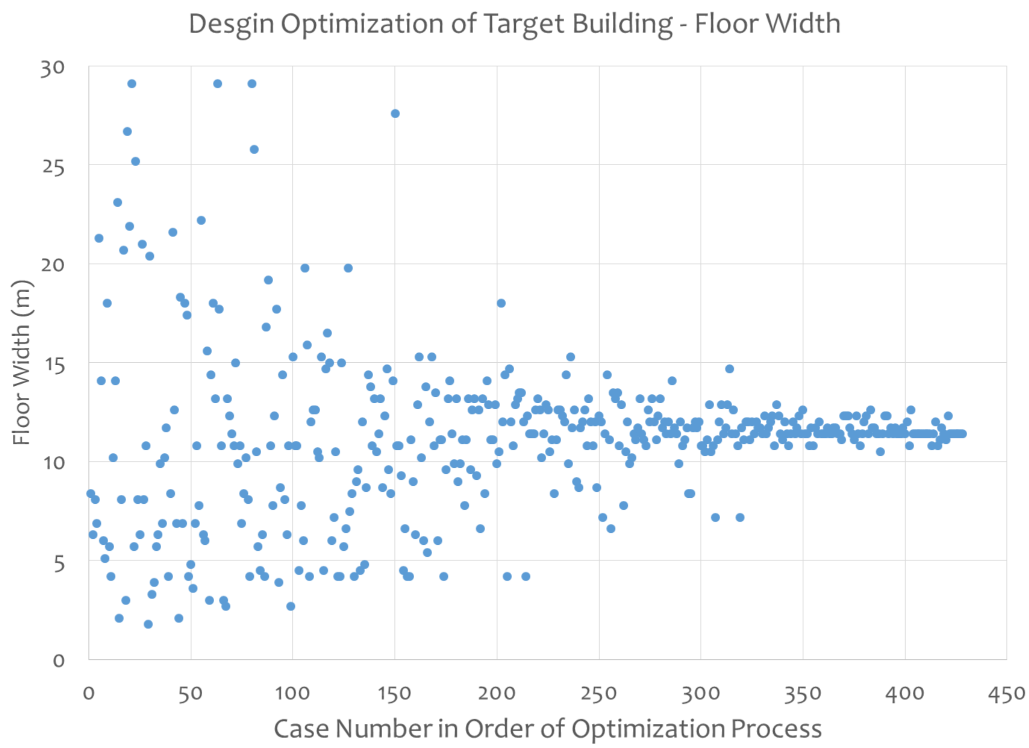

Figure 4.20 Genetic algorithm optimization process – floor width

Figure 4.19, Figure 4.20 and other figures in Appendix J showed that the target of the optimization, which was the annual Design-Based Natural Ventilation Potential, was improving along the process. The inputs were also reaching to a fix result. In conclusion, the genetic algorithm-based optimization did provide stable answers to the seven design parameters, based on natural ventilation potential evaluation.

4.2.5 Optimization Result

All 428 investigated building form options are shown as Figure 4.21. All building form options are placed in the order of the genetic algorithm optimization process and coloured by the annual Design-Based Natural Ventilation Potential of the building. From Figure 4.21 it is easy to conclude that the geometry of the investigated building and the result of the annual Design-Based Natural Ventilation Potential of the building did not change much after about half of the optimization process.

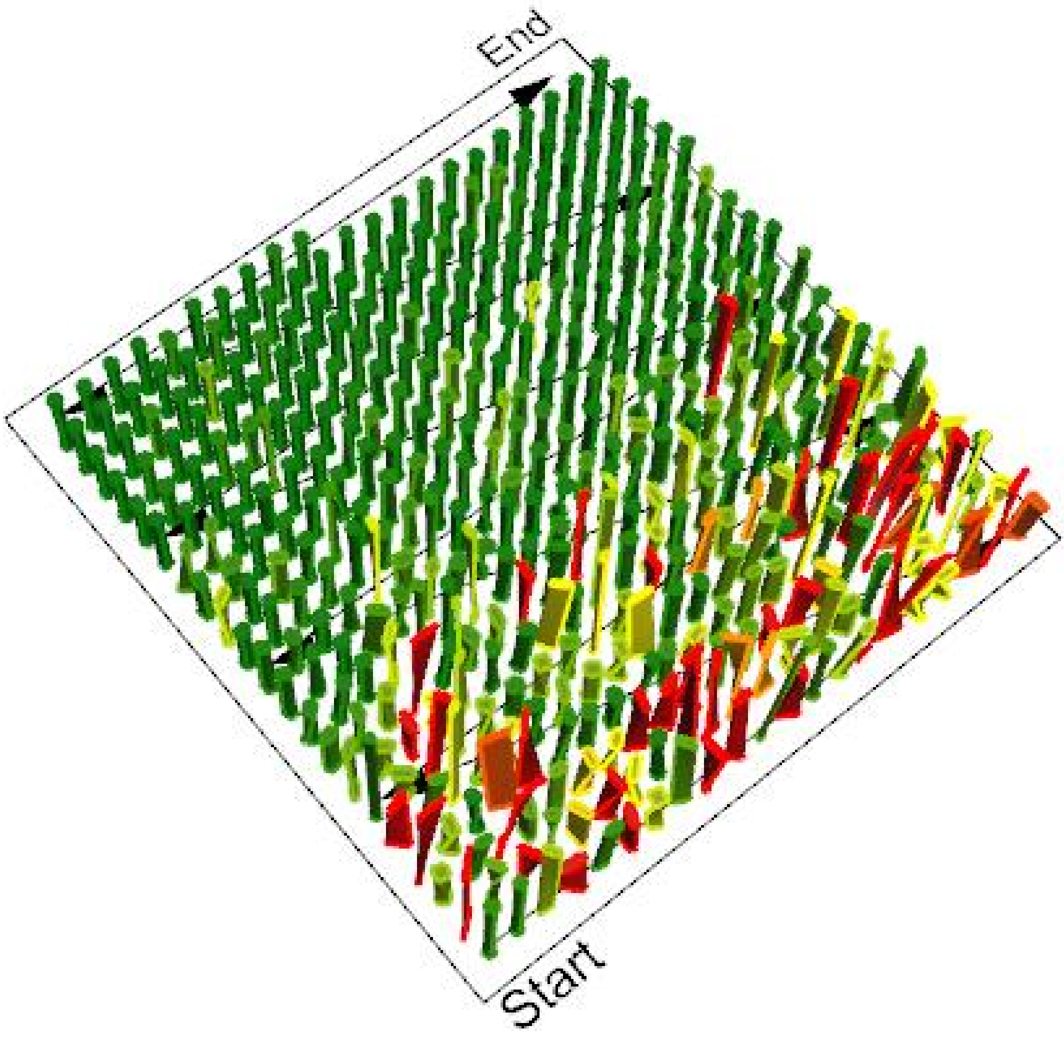

Figure 4.21 Buildings ordered by optimization process and colored by results

The optimized building form for the annual Design-Based Natural Ventilation Potential is shown in Table 4.2 and Figure 4.22, using the original box shape building for comparison.

Table 4.2 Genetic algorithm optimization result

Design variable	Value
Floor width	11.43m
Floor depth	11.40m
Corner radius	3.19m
Orientation	-21.44º
Twist angle	18.65º
Tilt angle	0º
Tilt direction	0º

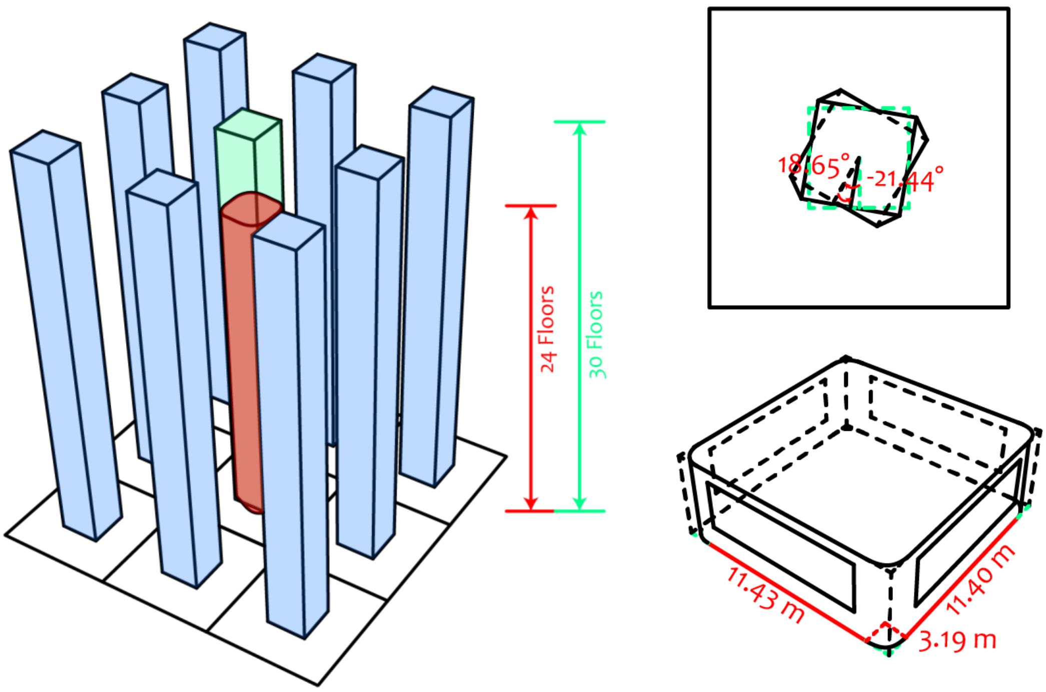

Figure 4.22 Optimized building

With the optimized building form in this urban context, the highest Design-Based

Natural Ventilation Potential is 1144 hours of the year, while the climate-based natural ventilation potential of Boston is 2745 hours (Chen, 2017). A comparison of the two natural ventilation potentials is shown in Figure 4.23. It is easy to understand that the Design-Based Natural Ventilation Potential provides a better estimation of the natural ventilation potential than the climate-based evaluation, because it considers more early-stage design information.

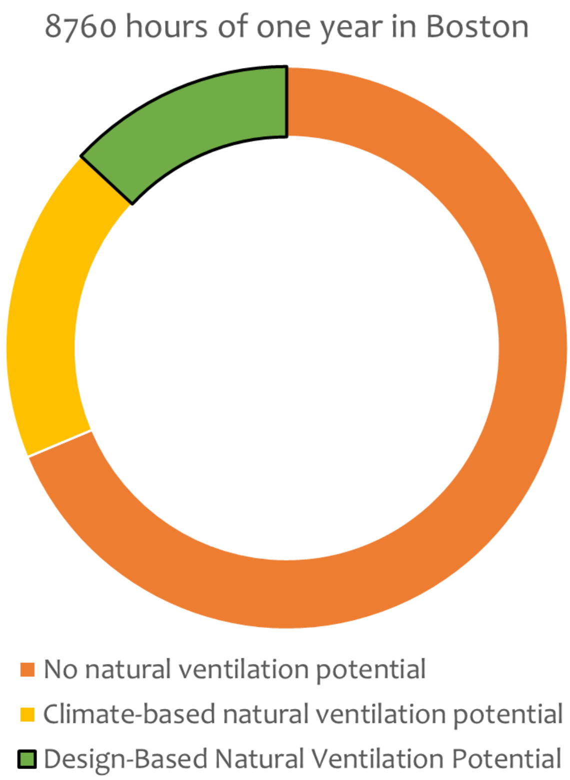

Figure 4.23 Design-Based and climate-based natural ventilation potential

4.2.6 Discussion

This case study presented a building form optimization in the early design stage built on the Design-Based Natural Ventilation Potential. With scripts developed in Rhino Grasshopper, the calculation of the Design-Based Natural Ventilation Potential was carried out automatically and integrated with building design. The genetic algorithm provided a stable optimization result of the investigated building form for the highest natural ventilation potential.

The design optimization study illustrated the possibility of providing design decision-making support for natural ventilation evaluation in the early design stage. With the calculation method developed in Chapter 3, the proposed natural ventilation evaluation index was applied in an architectural modeling environment. The calculation process was conducted automatically with a relative short computing time. This automate calculation enabled natural ventilation evaluation and design integration in early design stage. The case study proved the feasibility of this design decision-making support system. In addition, the comparison of natural ventilation potential given by this case study with other researcher's conclusion agreed well with the analyze in Chapter 2. It validated the theory of this research. Instead of providing general design suggestions on natural ventilation, this case study illustrated the procedure of analyzing natural ventilation and integrating with design, which exploded the possibility of future researches.

There are three main limitations of the case study. The first of these limitations is the natural ventilation method. In this case study, only cross-ventilation with one inlet and one outlet on the same floor was included. This was because only the simplified cross-ventilation calculation method was developed. The natural ventilation potential could be improved by utilizing other natural ventilation types, such as single-side ventilation and buoyance driven ventilation. However, this requires further studies of the simplified calculation methods for other natural ventilation types. In addition, the optimization time is a challenging issue. With the current natural ventilation evaluation method, each building form takes an average of two hours for calculation, and the whole optimization process took about 1.5 months. This is practically costly in terms of time, especially in the early design stage. This problem may be solved through parallel computing or cloud computing in the future. Last problem is the building form design. Only seven design variables of the investigated building were optimized, while in the actual design process there might be more design aspects involved, including different urban contexts, different building functions, and even multiple target buildings. More design variables may lead to longer optimization times, which adds to the second limitation.

These limitations of the case study have to be recognized. It will require further studies in the future to overcome these problems. However, this design process integrated with natural ventilation potential evaluation illustrated the great potential of design decision-making support in the early design stage, as a significant improvement in building performance informed design.

4.3 Summary

This chapter described a case study on the decision-making support system provided by natural ventilation potential evaluation in the early design stage. The proposed natural ventilation evaluation index was used and the calculations were carried out in an architectural modeling environment. A building form optimization study was conducted using a genetic algorithm based on the natural ventilation potential evaluation. An optimized building form was provided by the genetic algorithm, with several small changes in design. Even though there were some limitations of the case study and further studies are necessary to improve optimization time and scope, the case study illustrated the important potential of the design decision-making support system resulting from natural ventilation evaluation in the early design stage. With more studies on improving the calculation efficiency and expanding the application boundaries, this decision-making support system can be a critical innovation for early-stage building performance informed design.

Chapter 5 Conclusions

5.1 Review of Research Objectives

Building performance informed design has received growing attention in recent years. Building performance information should be taken into consideration at all design stages and the evaluation process should integrate with design closely. In this way, performance information can be significantly improved while the design quality stays the same.

Three research fields of building performance informed design were chosen as research issues for this study: natural ventilation, the early design stage, and design decision-making support.

The main subject chosen for this research, among all aspects of building performance, was natural ventilation. Natural ventilation has been recognized as one of the most promising passive strategies for reducing building energy consumption. In addition, natural ventilation can benefit built environments and users by improving thermal comfort level and occupant productivity. The benefits of natural ventilation are understood, but how to apply this strategy in design remains unclear.

Another research focus for building performance informed design in recent years is the early-stage design. Studies have suggested that evaluating building performance in the early design stage is critical for achieving high performance and reducing later design modification costs. Since the early-stage design may have very different requirement of precision and limited design information, the difficulties and solutions for evaluating building performance in early-stage design are not yet fully understood.

The last research topic is the design decision-making support system for building performance informed design. Case studies have been conducted integrating the design process with building performance evaluation. Some design decision-making support systems for building energy consumption have been developed and proved successful in assisting designers with making better informed design decisions. However, a practical design decision-making support system focusing on natural ventilation in the early stage is not yet available and was set as the main target for this research.

As a response, a research proposal was summarized: a design decision-making support system in the early design stage for high performance naturally ventilated buildings is needed to help designers make better informed decisions. Current design guidelines and tools for natural ventilation in the early design stage are not sufficient to accomplish this goal. With this research aim, there were two objectives identified in this dissertation, the first of which was a natural ventilation index. The other was a natural ventilation evaluation calculation procedure for the early-stage design.

In summary, the aim of this research was to develop a design decision-making support system in the early design stage for high performance naturally ventilated buildings, focusing on a natural ventilation evaluation index and evaluation procedure integrated with design.

5.2 Summary of Conclusions

To accomplish the research goal of developing a decision-making support system for high performance naturally ventilated buildings in the early design stage, literature reviews, reasoning, numerical experiments, and model development were conducted. The system developed as a result of this research consists of a natural ventilation evaluation index and a calculation procedure in the early design stage.

5.2.1 Natural Ventilation Evaluation Index

For the natural ventilation evaluation, current evaluation indices are problematic in the early design stage. Energy consumption savings, thermal comfort indices, and air change rate (ACH) are currently the most widely used indices for evaluating natural ventilation. For all these indices, the actual performance of natural ventilation is the target of evaluation. Because very limited information is available for natural ventilation performance evaluation in the early stage, these indices have unavoidable uncertainty issue.

Using natural ventilation potential instead of performance for evaluation in early-stage design is considered as a promising idea. This is because potential evaluation requires much less information and the uncertainty issue is better understood. However, current research evaluates natural ventilation potential based only on climate data without considering design conditions. As a solution, this research proposed an improved natural ventilation potential evaluation, the Design-Based Natural Ventilation Potential, by considering available design information at the early design stage.

The Design-Based Natural Ventilation Potential was defined as the hours that the space could be naturally well-ventilated throughout the year. In addition to climate conditions, the known design information at this stage was taken into account. Detailed definition comprised the two main requirements: indoor air quality and thermal environment.

For indoor air quality, natural ventilation evaluation criterion in the early design stage was the minimum ventilation rate. The ventilation rate requirement for this research was taken from ASHRAE Standard 62.1-2013. On the other hand, the effectiveness of ventilation for indoor air quality was not evaluated in this research. Although the distribution of ventilation was critical, the detailed result was not necessary for early-stage design.

For thermal environment, the latest thermal comfort model was used. According to the model, required minimal air velocity in the space varies based on the operative temperature. This was referred from researches of adaptive thermal comfort models in recent years, which were developed for naturally ventilated spaces with more focus on air velocity. The thermal comfort level distribution in the space is very critical, but detailed result was not required. Instead of detailed distribution, the percentage of floor area that fulfilled the thermal comfort requirement was proposed as the index and named the ventilated ratio. It evaluated thermal comfort level distribution for the early-stage design.

In conclusion, the definition of Design-Based Natural Ventilation Potential consisted of two aspects, indoor air quality and thermal environment. For indoor air quality, this study used the minimum ventilation rate. For thermal environment, the ventilated ratio was proposed - the percentage of floor area fulfilling the minimal air velocity requirements based on different operative temperatures.

5.2.2 Natural Ventilation Evaluation Calculations

To calculate the natural ventilation evaluation index developed, the two-steps calculation procedure was chosen according to the review of current researches on natural ventilation in design. It consisted of two main steps: outdoor wind environment simulation and indoor natural ventilation calculation.

For outdoor wind environment simulation, an automatic calculation process was proposed, with the help of scripts developed in the architectural modeling environment. The concept of pressure coefficient database was expanded into an urban environment to solve the computing time issue for annual hourly natural ventilation evaluation.

For indoor natural ventilation calculation, a simplified calculation method was developed. Because finding the best-case scenario for natural ventilation was very challenging, considering the infinite possibilities of indoor configurations, a quick calculation method was necessary to replace CFD simulation. The simplified calculation method development process consisted of four parts: similarity analysis, numerical experiments, equations regression, and validation. Cross-ventilation with one inlet and one outlet was used to illustrate the process of developing this simplified calculation method. The ventilated ratio could be calculated based on the regression equations, without running CFD simulation but achieving similar precision. In this way a lot of computing power and time were saved and indoor natural ventilation potential can be calculated.

In the end, a practical evaluation procedure for the Design-Based Natural Ventilation Potential was established, after developing the calculation methods for both outdoor wind environment simulation and indoor natural ventilation calculation. This natural ventilation potential evaluation would provide designers feedback on natural ventilation in the early design stage, with a relatively short calculation time. The main contribution of this part is the development process of the design decision-making support system. It will also be used as a research framework for similar studies in the future. The application of this system is summarized and discussed in next part.

5.2.3 Natural Ventilation Evaluation Case Study

A case study was conducted to present the use of this design decision-making support system with natural ventilation potential evaluation in the early design stage. An optimized building form was provided by the genetic algorithm, significantly improving the natural ventilation potential with relatively small changes from the original shape. Compared to the optimization result of the case study, the more important conclusion is the feasibility of the design decision-making support system. This case study illustrated the potential of the design decision-making support system and exploded the possibility of future researches on natural ventilation in the early design stage. This is a critical improvement for building performance informed design in the early design stage.

5.3 Limitations of Research

This research presented a design decision-making support system for natural ventilation in the early design stage, which was very promising for building performance informed design. The research built a complete framework for developing the design decision-making support system and took cross-ventilation as an example for the development process. However, there are some limitations of this research that require special attention before further application in design practice.

The simplified calculation method for cross-ventilation is the first restriction. During the development process of the simplified calculation method, there were several limitations set for the numerical experiments. The floor shape options were narrow and there were also limited value options for parameters such as the floor height, floor size, opening dimensions, and opening normal angle. These values have many more possibilities in design practice. Because the regression equations can only be used for cases with input similarity criteria in the range set by the numerical experiments, the limitations on the numerical experiments would influence the applicable scope of the simplified calculation method. To address this problem, more numerical experiments should be added to the development process.

The second limitation is related to natural ventilation. In this research, cross-ventilation with one inlet and one outlet was taken as the example for the simplified calculation method. Using the same development procedure, simplified calculation methods for other natural ventilation types can be built, such as cross-ventilation with multiple inlets and outlets, single-side ventilation, and buoyancy-driven ventilation. On the other hand, a more challenging concern is development of the simplified calculation method for combined natural ventilation that is, having different natural ventilation types at the same time. Having different types of natural ventilation in the same space would have very different performance results, depending on whether they work in concert or in opposition (Stavridou & Prinos, 2013). A simple solution to this problem may be summing up the effects of different natural ventilation types and considering the target as the natural ventilation potential. However, more analysis is necessary to validate this assumption.

Another critical issue of this research is the thermal modeling. As discussed at the beginning of Chapter 2, the uncertainty of thermal modeling in the early design stage is a critical problem since it increases the uncertainty of the natural ventilation evaluation results. The uncertainty issue is a result of the limited design information available in the early stage, which also makes it difficult to avoid. This has been well-recognized in recent years and there are research studies dedicated to solving the problem. For this research the thermal modeling is relatively simple. The natural ventilation evaluation can certainly be improved by employing better thermal modeling methods, for example, using energy simulation tools.

The design application is another limitation of this research. In the case study of this research, a building form with seven design variables was investigated, while in the actual design process there may be more design aspects involved. More design variables may lead to a longer optimization time, as a notable problem. With the current natural ventilation evaluation methodology, each case took an average of two hours to calculate, and the entire computing time was around a half month. The simulation time has been improved significantly when compared to conventional analysis, but is still very expensive, especially for the early design stage. The computing time limitation may be solved through parallel computing or cloud computing in the future.

Last constraint of the research is the evaluation precision. The results calculated by the simplified calculation method compared to those simulated by CFD had an average absolute difference of 11.5%. This precision was considered acceptable only for the early design stage, because the design feedback needed at the time is an improvement direction instead of precise value. However, this is definitely a limitation of the research and could be improved in future research.

Once all the limitations have been overcome, the possibility of this design decision-making support system being used for the natural ventilation in the early stage will be dramatically expanded.

5.4 Recommendations for Future Studies

In addition to studies to overcome the limitations discussed gift a, there are other studies recommended for this research, to maximize the potential of this design decision-making support system.

One possible study is to explore the boundary of the simplified calculation method for indoor natural ventilation. As described in Chapter 3, there were several limitations set for the numerical experiments during the simplified calculation method development. The floor shape options were limited to three primary geometries. More numerical experiments for other geometries will expand the applicable scope of the simplified calculation method. However, there is no guarantee that the additional numerical experiments will improve the precision of the simplified calculation method. There is a chance that the regression of the numerical experiments results will not work well. On the other hand, there are infinite possibilities for floor shape, so there is never a complete list for numerical experiments. That being said, it is questionable whether all geometries make a difference to the simplified calculation method. In other words, what is the boundary of the simplified calculation method? What geometry should be included and what is not necessary? Or there should be different categories of geometries? Answering these questions will provide a better understanding of indoor natural ventilation in the early design stage, in addition to a more precise simplified calculation method.

Another interesting study would be an application study of the design decision-making support system. The natural ventilation evaluation integrated with design can contribute knowledge about what key factors in design influence natural ventilation the most. With some parametric studies of design, the design decision-making system could answer questions about the most influential variables of natural ventilation. For example, is the urban environment playing a more important role than the building form itself, or are the window sizes the most critical numbers for natural ventilation? Conclusions about key factors of natural ventilation would benefit not only one case study but also future design, providing designers with guidelines that are easy to follow in the early stage.

The design decision-making support system for high performance naturally ventilated buildings in early design stage developed in this research exploded the possibility of future researches. The final destination of building performance informed design research is building knowledge as well as tools for designers, which will be explored in future researches.

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Appendices

Appendix A: Numerical Experiment Case List Example – Input Parameter Values

Case No.	Geometry	H	z_{in}	h_{in}	w_{in}	z_{out}	h_{out}	w_{out}	x	y	α	ΔP	L_a[1]	L_b[2]
1	Circle	3.1	0.5	0.5	3.8	0.8	0.3	4.3	7.6	-7.6	0.5	26.2	7.6	0
2	Triangle	2.9	0.4	0.4	3.3	0.4	1	3.7	11.13	12.72	0.5	39.3	15.9	0
3	Circle	2.6	0.3	0.8	3.6	0.9	0.7	4.3	11.61	-4.81	0.75	37.9	6.8	0
4	Rectangle	3.5	0.5	0.7	3.6	0.4	0.2	3.6	4.35	11.68	0.5	40.5	8.7	14.6
5	Circle	2.9	0.7	0.8	4	0.6	0.2	2.7	10.24	-4.24	0.75	40.7	6	0
6	Circle	3.4	0.4	0.1	3.7	0.4	0.3	3.6	12.2	0	1	20.8	6.1	0
7	Triangle	2.8	0.9	0.3	4.5	0.2	0.4	4.2	5.96	4.47	0.75	14.2	14.9	0
8	Triangle	3	0.5	0.4	4.6	0.2	0.8	4.2	9.92	3.72	0.5	21.4	12.4	0
9	Rectangle	3.1	0.1	0.4	3.8	0.7	0.2	4.6	2.8	1.77	1	18.5	2.8	17.7
10	Rectangle	2.9	0.3	0.6	2.9	0.3	0.1	4.8	6.3	1.54	0.5	22.9	10.5	7.7
…	…	…	…	…	…	…	…	…	…	…	…	…	…	…
2795	Circle	3.5	1.6	1	4.3	1.7	1.5	1.1	1.61	-3.89	0.25	0.4	5.5	0

[1] L_a represents side edge length for triangle and rectangle, radius for circle

[2] L_b represents other side edge length for rectangle, not applied to triangle and circle

Appendix B: Numerical Experiment Case List Example – Simulation Results

Case No.	$A_{0.2/1.2}$	$A_{0.3/1.2}$	$A_{0.4/1.2}$	$A_{0.5/1.2}$	$A_{0.6/1.2}$	$A_{0.2/1.6}$	$A_{0.3/1.6}$	$A_{0.4/1.6}$	$A_{0.5/1.6}$	$A_{0.6/1.6}$
1	177.124	168.403	156.629	144.393	131.663	176.311	168.128	151.678	137.242	121.274
2	124.225	119.939	114.321	107.677	100.802	124.408	122.850	119.089	111.670	104.800
3	143.031	141.831	139.444	133.229	122.755	143.104	141.678	138.791	130.576	117.379
4	124.954	123.847	122.132	119.779	116.319	125.063	124.101	122.508	120.294	116.963
5	111.500	110.741	109.908	107.866	103.841	111.515	110.759	109.636	106.931	103.162
6	115.153	113.233	108.374	103.587	98.625	115.232	111.258	106.442	101.873	97.033
7	105.759	102.149	93.588	76.259	66.647	105.376	99.364	86.769	75.060	67.008
8	71.763	68.973	66.458	63.623	58.659	71.990	69.126	66.248	62.828	56.649
9	45.135	42.117	35.889	31.340	29.681	44.657	40.805	34.519	29.970	28.067
10	78.492	76.727	69.828	63.238	50.491	78.496	69.629	59.298	51.207	44.883
…	…	…	…	…	…	…	…	…	…	…
2795	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000

Appendix C: Numerical Experiment Case List Example – Input Similarity Criteria

Case No.	x_1	x_2	x_3	x_4	x_5	x_6	x_7	x_8	x_9	x_{10}	x_{11}	x_{12}	x_{13}
1	1.28E+12	0.7157	18.8822	12.5664	0.3183	-1.0000	1.5708	0.0440	0.1613	1.2258	0.0474	0.2581	1.3871
2	1.05E+12	1.1476	15.0303	23.3108	0.9800	1.1429	1.5708	0.0548	0.1379	1.1379	0.0439	0.1379	1.2759
3	7.54E+11	1.2344	21.4892	12.5664	0.9276	-0.4142	2.3562	0.0372	0.1154	1.3846	0.0296	0.3462	1.6538
4	1.84E+12	0.9799	10.3690	17.0962	0.1490	2.6851	1.5708	0.0652	0.1429	1.0286	0.0822	0.1143	1.0286
5	1.05E+12	1.1885	13.4480	12.5664	0.9276	-0.4142	2.3562	0.0495	0.2414	1.3793	0.0501	0.2069	0.9310
6	1.69E+12	0.5180	10.1123	12.5664	1.2732	0.0000	3.1416	0.0918	0.1176	1.0882	0.0831	0.1176	1.0588
7	9.42E+11	0.4295	14.1588	23.3108	0.3200	0.7500	2.3562	0.0649	0.3214	1.6071	0.0832	0.0714	1.5000
8	1.16E+12	0.6041	8.5422	23.3108	1.2800	0.3750	1.5708	0.1257	0.1667	1.5333	0.1093	0.0667	1.4000
9	1.28E+12	0.5054	5.1571	33.9185	0.1582	0.6321	3.1416	0.1994	0.0323	1.2258	0.2042	0.2258	1.4839
10	1.05E+12	0.6687	9.6136	16.3879	0.4909	0.2444	1.5708	0.0717	0.1034	1.0000	0.1484	0.1034	1.6552
…	…	…	…	…	…	…	…	…	…	…	…	…	…
2795	1.84E+12	0.0097	7.7578	12.5664	0.02731	-2.4142	0.7854	0.0407	0.4571	1.2286	0.0035	0.4857	0.3143

Appendix D: Numerical Experiment Case List Example – Target Similarity Criteria

Case No.	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}
1	0.9761	0.9281	0.8632	0.7957	0.7256	0.9716	0.9265	0.8359	0.7563	0.6683
2	0.9828	0.9489	0.9044	0.8518	0.7974	0.9842	0.9719	0.9421	0.8834	0.8291
3	0.9846	0.9763	0.9599	0.9171	0.8450	0.9851	0.9753	0.9554	0.8989	0.8080
4	0.9837	0.9750	0.9615	0.9430	0.9158	0.9846	0.9770	0.9645	0.9470	0.9208
5	0.9859	0.9792	0.9718	0.9537	0.9182	0.9860	0.9793	0.9694	0.9455	0.9122
6	0.9851	0.9686	0.9271	0.8861	0.8437	0.9857	0.9517	0.9105	0.8715	0.8301
7	0.9527	0.9202	0.8431	0.6870	0.6004	0.9493	0.8951	0.7817	0.6762	0.6036
8	0.9334	0.8972	0.8644	0.8276	0.7630	0.9364	0.8991	0.8617	0.8172	0.7368
9	0.9107	0.8498	0.7241	0.6324	0.5989	0.9011	0.8233	0.6965	0.6047	0.5663
10	0.9708	0.9490	0.8637	0.7822	0.6245	0.9709	0.8612	0.7334	0.6334	0.5551
…	…	…	…	…	…	…	…	…	…	…
2795	0	0	0	0	0	0	0	0	0	0

Appendix E: Distribution of Input Similarity Criteria

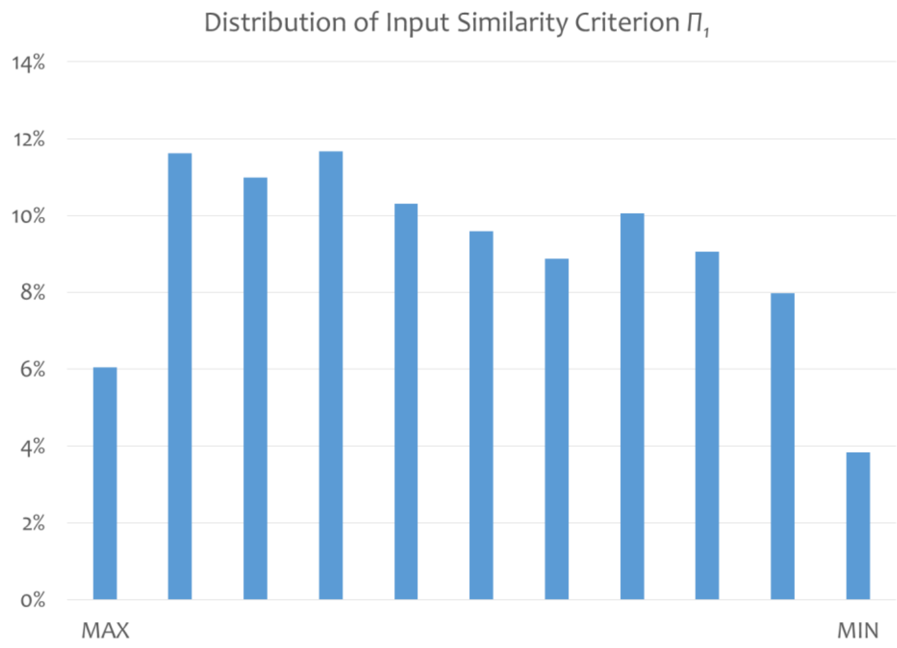

Figure E.1 Distribution of input similarity criterion Π_1

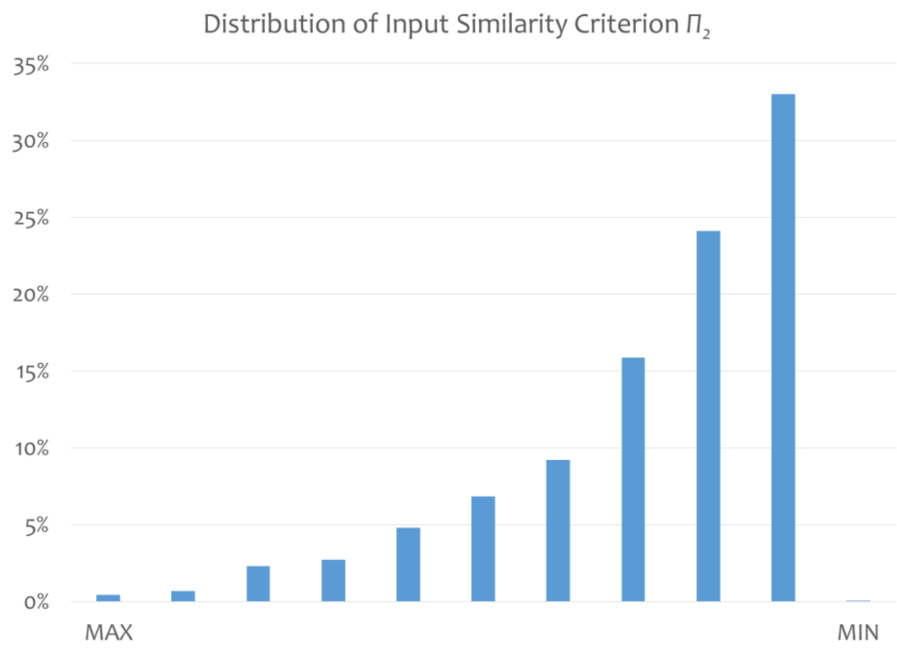

Figure E.2 Distribution of input similarity criterion Π_2

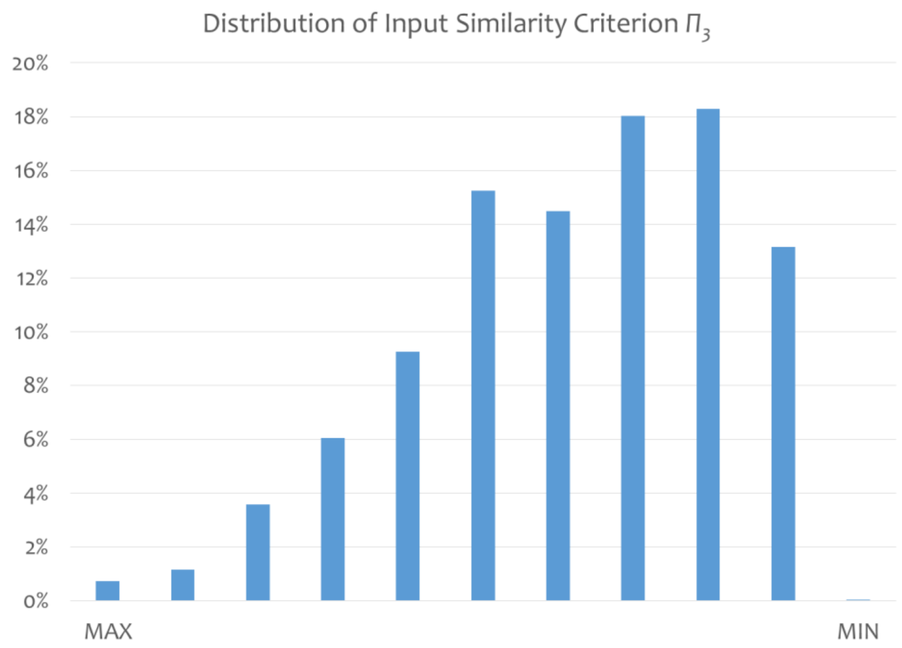

Figure E.3 Distribution of input similarity criterion Π_3

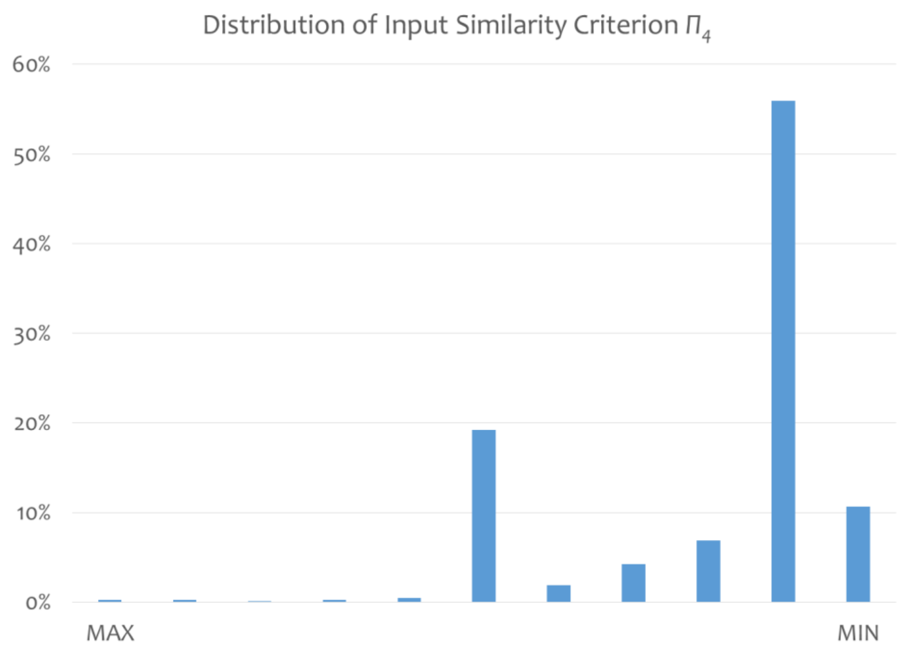

Figure E.4 Distribution of input similarity criterion Π_4

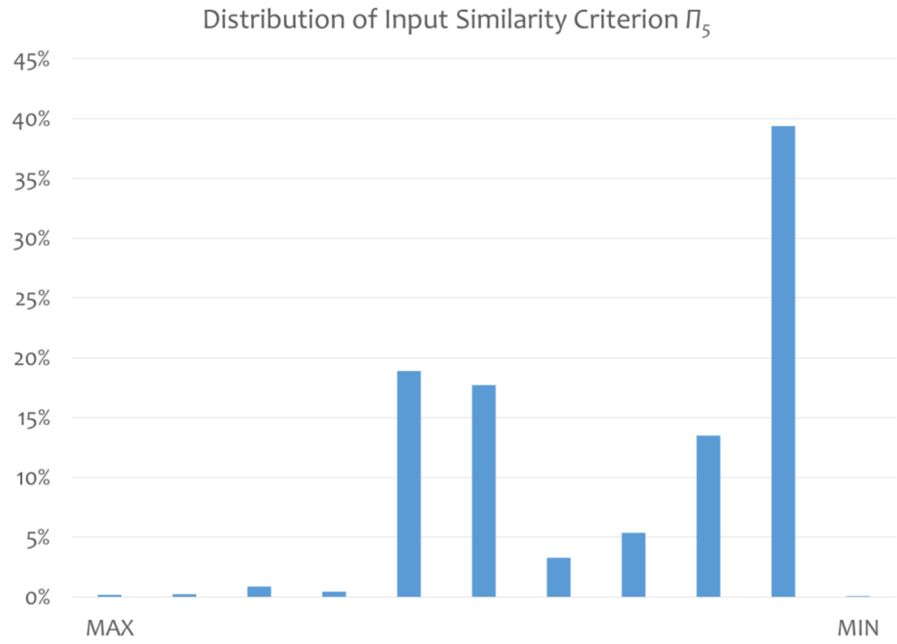

Figure E.5 Distribution of input similarity criterion Π_5

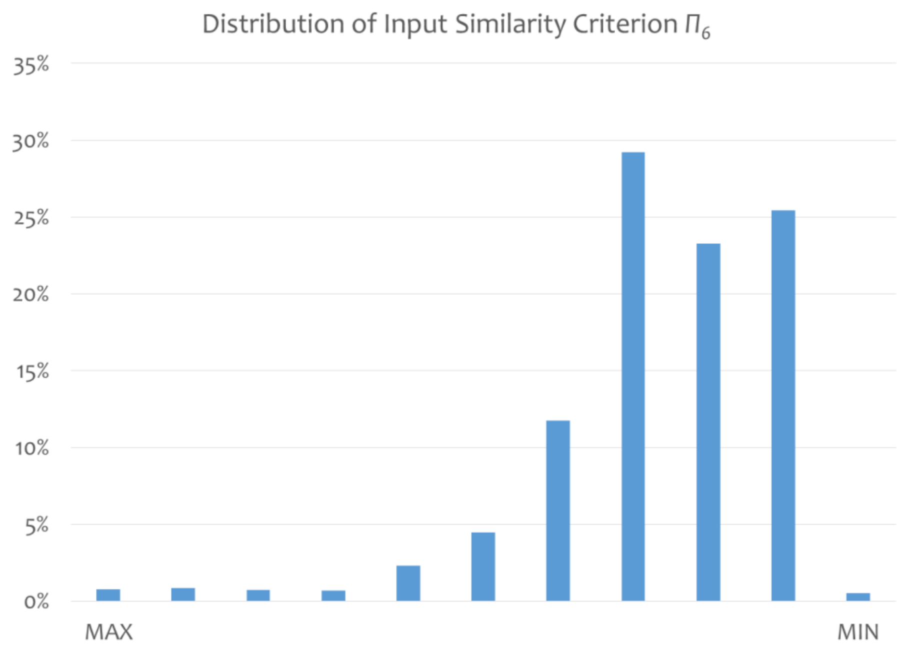

Figure E.6 Distribution of input similarity criterion Π_6

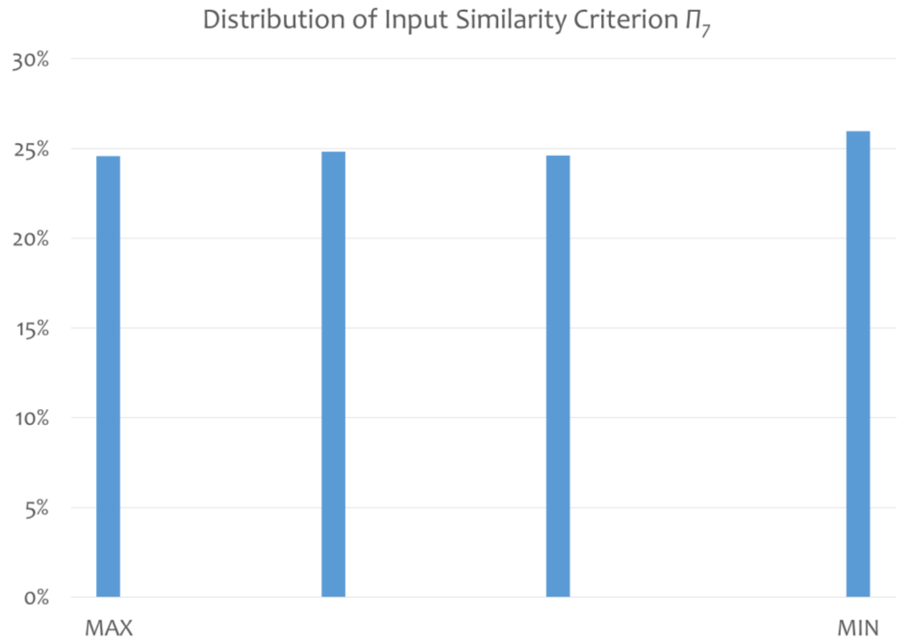

Figure E.7 Distribution of input similarity criterion *Π₇*

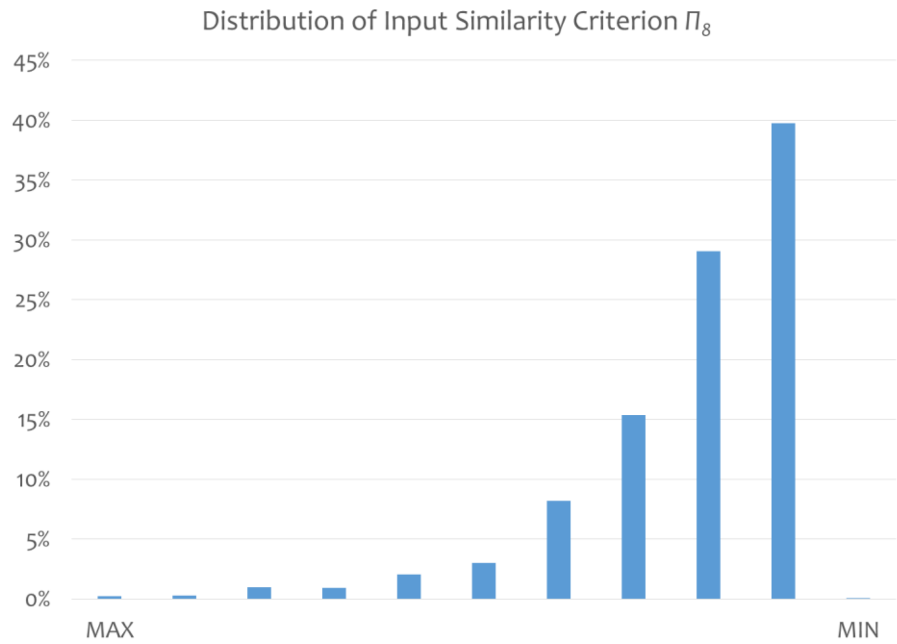

Figure E.8 Distribution of input similarity criterion Π_8

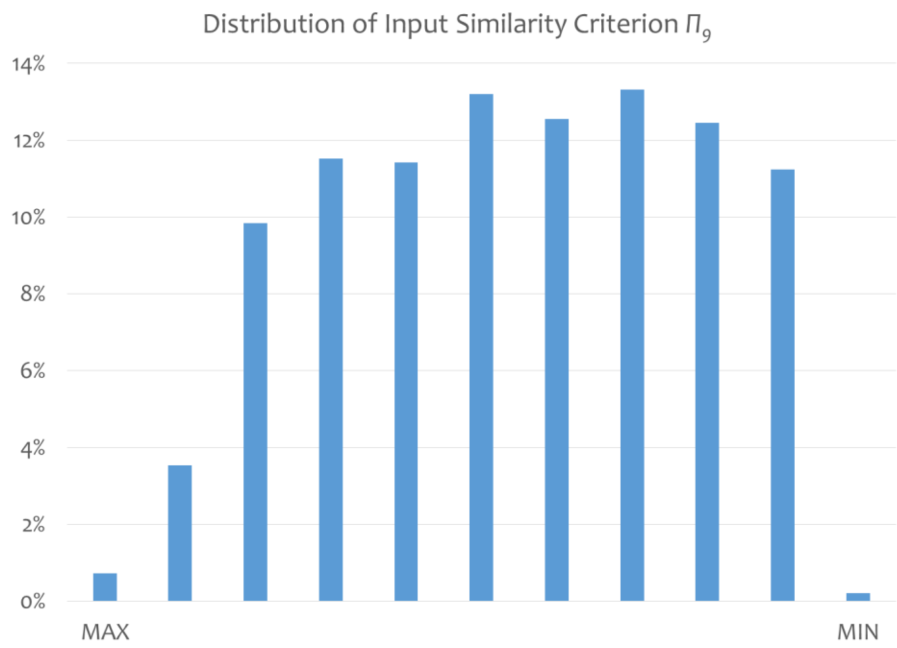

Figure E.9 Distribution of input similarity criterion Π_9

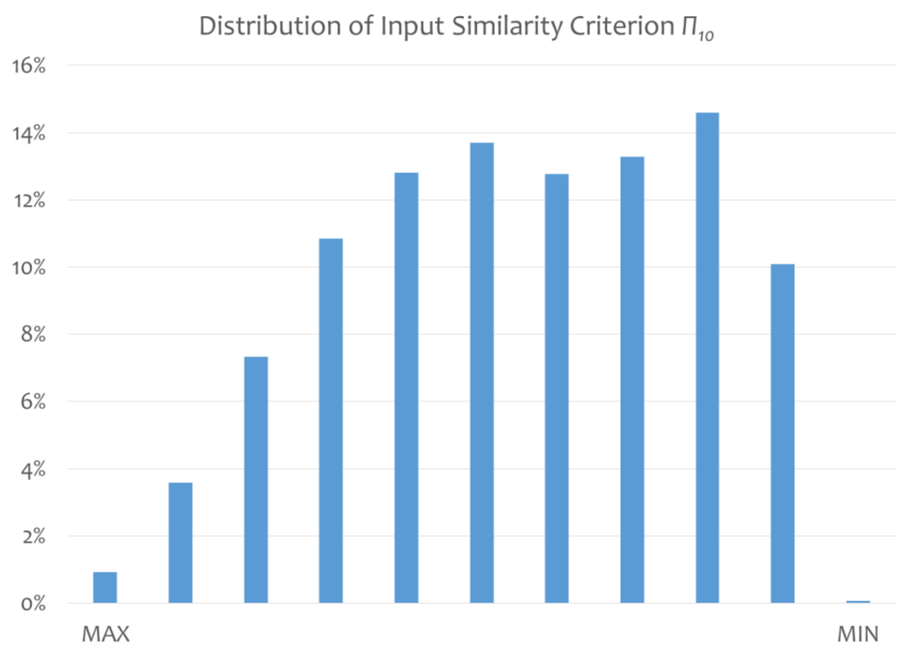

Figure E.10 Distribution of input similarity criterion Π_{10}

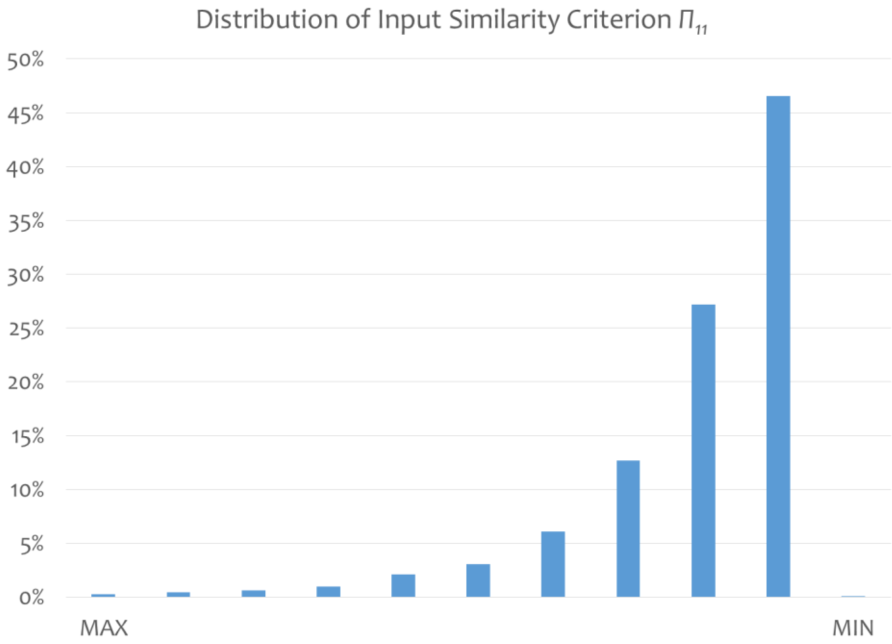

Figure E.11 Distribution of input similarity criterion Π_{11}

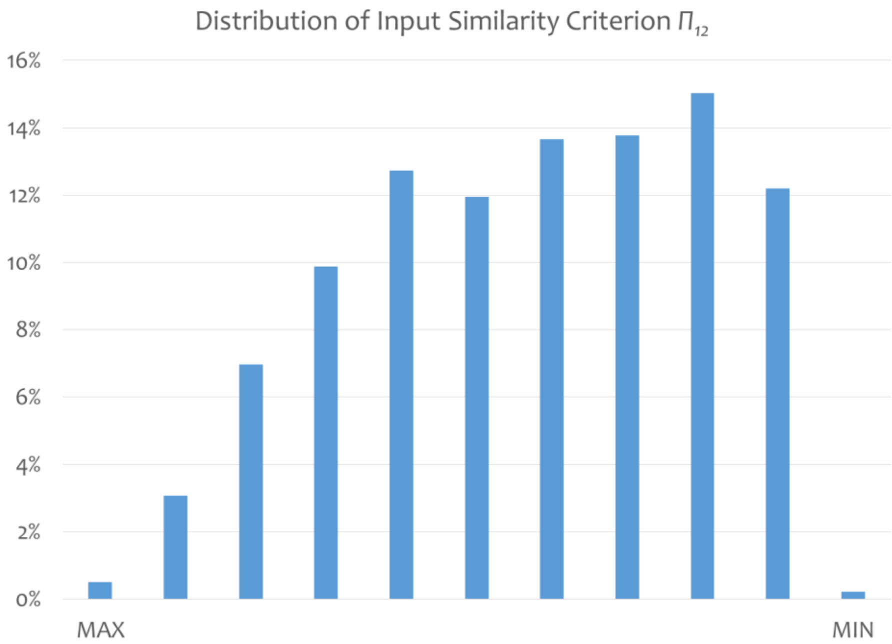

Figure E.12 Distribution of input similarity criterion Π_{12}

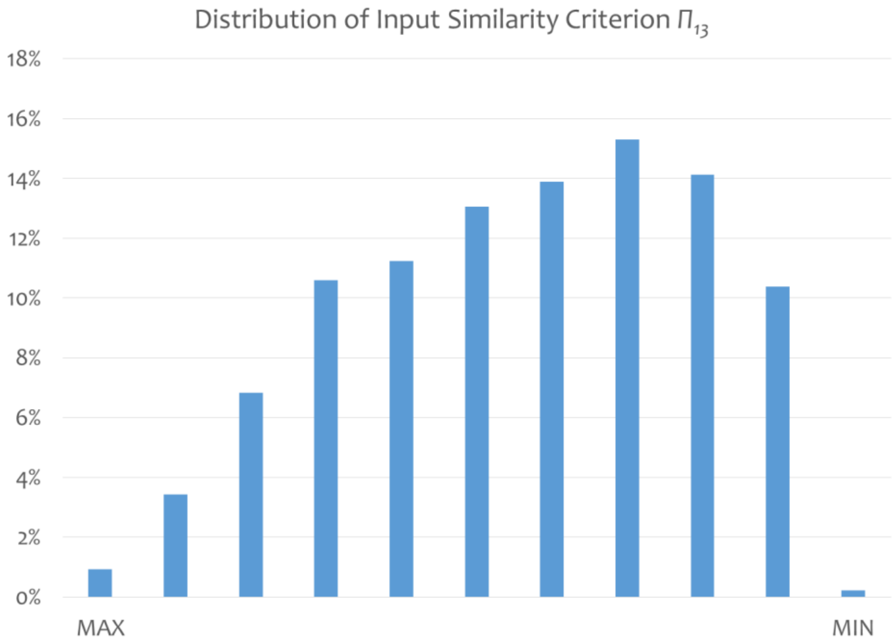

Figure E.13 Distribution of input similarity criterion Π_{13}

Appendix F: Multiple Linear Regression Statistics

Regression statistics:

Table F.1 Multiple linear regression statistics

Similarity Criteria	y_1	y_2	y_3	y_4	y_5	y_6	y_7	y_8	y_9	y_{10}
R^2	0.712	0.975	0.943	0.920	0.901	0.709	0.975	0.943	0.920	0.903
Adjusted R^2	0.699	0.973	0.940	0.915	0.896	0.696	0.973	0.940	0.915	0.898
Mean Squared Error	0.020	0.002	0.005	0.007	0.008	0.020	0.002	0.005	0.007	0.008

Table F.2 Target similarity criterion y_1 regression coefficients

Variables	Coefficients	Standard Deviation	t Value	p Value	95% Confidence Interval	
c	0.405	0.254	1.591	0.299	-0.094	0.903
x_1	1.72E-13	1.34E-13	1.278	0.090	-9.17E-14	4.35E-13
x_2	1.189	0.103	11.486	8.15E-32	0.986	1.392
x_3	-7.30E-03	0.012	-0.606	0.813	-0.031	0.016
x_4	-0.013	9.60E-03	-1.355	0.057	-0.032	5.81E-03
x_5	0.192	0.114	1.677	0.056	-0.032	0.416
x_6	0.039	0.042	0.946	0.272	-0.042	0.121
x_7	-0.035	0.064	-0.553	0.980	-0.161	0.090
x_8	-1.318	1.700	-0.775	0.382	-4.650	2.014
x_9	0.651	0.247	2.641	0.021	0.168	1.134
x_{10}	-0.061	0.126	-0.481	0.869	-0.307	0.186
x_{11}	4.662	1.529	3.049	2.11E-04	1.665	7.659
x_{12}	-0.661	0.224	-2.951	0.041	-1.100	-0.222
x_{13}	0.169	0.111	1.513	0.507	-0.050	0.387
x_1x_2	-3.29E-14	3.32E-14	-0.991	0.219	-9.80E-14	3.22E-14
x_1x_3	-6.99E-16	3.72E-15	-0.188	0.144	-7.99E-15	6.59E-15
x_1x_4	2.66E-15	2.05E-15	1.293	0.225	-1.37E-15	6.68E-15
x_1x_5	-3.22E-14	2.98E-14	-1.078	0.201	-9.06E-14	2.63E-14
x_1x_6	-2.57E-15	1.12E-14	-0.230	0.772	-2.45E-14	1.93E-14
x_1x_7	-2.63E-14	1.24E-14	-2.123	0.057	-5.06E-14	-2.03E-15

x_1x_8	-2.24E-13	5.31E-13	-0.421	0.661	-1.26E-12	8.17E-13
x_1x_9	-2.19E-15	7.73E-14	-0.028	0.840	-1.54E-13	1.49E-13
x_1x_{10}	-2.44E-15	4.12E-14	-0.059	0.926	-8.32E-14	7.84E-14
x_1x_{11}	-8.14E-13	4.70E-13	-1.733	0.006	-1.73E-12	1.07E-13
x_1x_{12}	-4.83E-14	6.77E-14	-0.713	0.262	-1.81E-13	8.45E-14
x_1x_{13}	3.91E-15	3.50E-14	0.112	0.136	-6.48E-14	7.26E-14
x_2x_3	2.72E-03	2.56E-03	1.065	0.520	-2.29E-03	7.73E-03
x_2x_4	1.42E-03	2.03E-03	0.697	0.453	-2.57E-03	5.41E-03
x_2x_5	1.50E-03	0.028	0.053	0.669	-0.053	0.056
x_2x_6	5.21E-03	0.010	0.508	0.889	-0.015	0.025
x_2x_7	0.021	0.012	1.733	0.240	-2.72E-03	0.044
x_2x_8	0.068	0.463	0.148	0.356	-0.838	0.975
x_2x_9	0.017	0.068	0.245	0.848	-0.117	0.150
x_2x_{10}	0.015	0.034	0.448	0.276	-0.051	0.082
x_2x_{11}	-2.597	0.446	-5.819	1.02E-08	-3.472	-1.723
x_2x_{12}	0.034	0.064	0.528	0.438	-0.092	0.160
x_2x_{13}	-0.048	0.030	-1.570	0.115	-0.107	0.012
x_3x_4	9.14E-05	1.70E-04	0.537	0.305	-2.42E-04	4.25E-04
x_3x_5	2.54E-03	2.55E-03	0.997	0.351	-2.46E-03	7.54E-03
x_3x_6	3.94E-04	9.16E-04	0.430	0.913	-1.40E-03	2.19E-03
x_3x_7	-5.35E-04	1.03E-03	-0.519	0.572	-2.56E-03	1.49E-03
x_3x_8	-0.316	0.069	-4.605	1.81E-05	-0.450	-0.181
x_3x_9	8.04E-03	6.73E-03	1.195	0.333	-5.15E-03	0.021
x_3x_{10}	-6.30E-03	3.24E-03	-1.942	0.036	-0.013	5.79E-05
x_3x_{11}	0.387	0.055	7.038	3.59E-14	0.279	0.495
x_3x_{12}	0.014	5.59E-03	2.454	0.015	2.76E-03	0.025
x_3x_{13}	-2.68E-03	2.64E-03	-1.018	0.070	-7.85E-03	2.48E-03
x_4x_5	-0.010	3.35E-03	-3.026	0.007	-0.017	-3.57E-03
x_4x_6	-7.66E-04	1.32E-03	-0.582	0.761	-3.34E-03	1.81E-03
x_4x_7	4.07E-03	1.48E-03	2.758	0.007	1.18E-03	6.97E-03
x_4x_8	-1.19E-03	0.029	-0.041	0.670	-0.059	0.056
x_4x_9	-0.020	4.63E-03	-4.409	1.18E-04	-0.030	-0.011
x_4x_{10}	8.02E-03	2.24E-03	3.577	0.002	3.63E-03	0.012
x_4x_{11}	0.082	0.025	3.291	5.49E-04	0.033	0.131
x_4x_{12}	-4.69E-04	4.11E-03	-0.114	0.891	-8.53E-03	7.59E-03
x_4x_{13}	9.90E-04	1.95E-03	0.507	0.329	-2.83E-03	4.81E-03
x_5x_6	0.027	0.029	0.923	0.313	-0.030	0.084
x_5x_7	0.017	0.021	0.836	0.463	-0.023	0.058
x_5x_8	0.748	0.445	1.681	0.044	-0.124	1.621
x_5x_9	-0.329	0.065	-5.036	1.93E-06	-0.457	-0.201
x_5x_{10}	0.055	0.033	1.679	0.279	-9.17E-03	0.119
x_5x_{11}	0.103	0.442	0.233	0.626	-0.764	0.969

x_5x_{12}	0.019	0.059	0.322	0.643	-0.097	0.134
x_5x_{13}	2.36E-03	0.030	0.078	0.717	-0.057	0.062
x_6x_7	4.08E-03	4.45E-03	0.918	0.462	-4.63E-03	0.013
x_6x_8	-0.231	0.182	-1.270	0.391	-0.589	0.126
x_6x_9	-0.035	0.025	-1.425	0.255	-0.084	0.013
x_6x_{10}	7.36E-03	0.012	0.635	0.997	-0.015	0.030
x_6x_{11}	-0.056	0.186	-0.301	0.245	-0.421	0.309
x_6x_{12}	0.020	0.021	0.975	0.931	-0.020	0.061
x_6x_{13}	-9.12E-03	0.011	-0.803	0.544	-0.031	0.013
x_7x_8	0.039	0.171	0.228	0.477	-0.296	0.374
x_7x_9	-3.38E-03	0.027	-0.125	0.977	-0.056	0.050
x_7x_{10}	-7.43E-03	0.014	-0.540	0.296	-0.034	0.020
x_7x_{11}	-0.117	0.152	-0.766	0.372	-0.415	0.182
x_7x_{12}	0.011	0.024	0.435	0.460	-0.037	0.058
x_7x_{13}	0.012	0.012	0.991	0.488	-0.011	0.035
x_8x_9	5.987	1.440	4.157	4.64E-06	3.164	8.810
x_8x_{10}	-2.133	0.709	-3.007	0.003	-3.524	-0.743
x_8x_{11}	-8.619	5.078	-1.697	0.037	-18.572	1.334
x_8x_{12}	-3.013	1.061	-2.839	6.57E-04	-5.093	-0.933
x_8x_{13}	1.787	0.478	3.737	2.28E-04	0.850	2.725
x_9x_{10}	-0.183	0.097	-1.890	0.063	-0.374	6.77E-03
x_9x_{11}	-2.901	0.982	-2.954	4.67E-04	-4.826	-0.976
x_9x_{12}	-0.083	0.145	-0.573	0.069	-0.368	0.202
x_9x_{13}	-0.174	0.069	-2.520	0.016	-0.309	-0.039
$x_{10}x_{11}$	1.321	0.512	2.579	0.026	0.317	2.324
$x_{10}x_{12}$	0.166	0.072	2.312	0.012	0.025	0.306
$x_{10}x_{13}$	-0.052	0.034	-1.521	0.212	-0.120	0.015
$x_{11}x_{12}$	9.658	1.101	8.772	3.58E-20	7.500	11.816
$x_{11}x_{13}$	-3.969	0.564	-7.043	2.23E-16	-5.074	-2.864
$x_{12}x_{13}$	-0.024	0.067	-0.367	0.352	-0.155	0.106
x_1^2	-2.13E-26	3.13E-26	-0.680	0.349	-8.25E-26	4.00E-26
x_2^2	-0.694	0.027	-25.448	1.51E-129	-0.748	-0.641
x_3^2	1.56E-04	1.93E-04	0.808	0.807	-2.22E-04	5.34E-04
x_4^2	-1.47E-04	2.02E-04	-0.730	0.592	-5.42E-04	2.48E-04
x_5^2	-2.28E-03	0.029	-0.079	0.896	-0.059	0.054
x_6^2	-1.56E-03	1.93E-03	-0.809	0.637	-5.35E-03	2.22E-03
x_7^2	-7.66E-03	8.10E-03	-0.946	0.159	-0.024	8.22E-03
x_8^2	10.529	4.180	2.519	0.014	2.337	18.722
x_9^2	0.115	0.143	0.805	0.092	-0.165	0.396
x_{10}^2	0.059	0.034	1.710	0.138	-8.61E-03	0.127
x_{11}^2	-7.291	3.505	-2.080	0.391	-14.162	-0.420
x_{12}^2	0.203	0.121	1.681	0.047	-0.034	0.440

x_{13}^2	0.011	0.029	0.398	0.090	-0.045	0.068

Table F.3 Target similarity criterion y_2 regression coefficients

Variables	Coefficients	Standard Deviation	t Value	p Value	95% Confidence Interval	
c	0.163	0.090	1.807	0.107	-0.014	0.340
x_1	-1.43E-13	4.56E-14	-3.129	0.002	-2.32E-13	-5.33E-14
x_2	0.122	0.042	2.930	0.003	0.040	0.204
x_3	6.50E-05	0.004	0.016	0.550	-0.008	0.008
x_4	0.002	0.003	0.579	0.360	-0.005	0.008
x_5	-0.025	0.039	-0.646	0.692	-0.101	0.051
x_6	-0.011	0.014	-0.783	0.794	-0.038	0.016
x_7	-0.041	0.022	-1.919	0.031	-0.084	8.88E-04
x_8	0.605	0.587	1.030	0.971	-0.546	1.756
x_9	0.090	0.086	1.053	0.873	-0.078	0.259
x_{10}	-0.072	0.045	-1.621	0.980	-0.159	0.015
x_{11}	0.821	0.561	1.465	0.133	-0.278	1.921
x_{12}	-0.049	0.078	-0.628	0.795	-0.203	0.105
x_{13}	0.002	0.039	0.046	0.804	-0.074	0.077
y_1	-0.490	0.436	-1.125	0.103	-1.344	0.364
y_6	0.643	0.435	1.480	0.045	-0.209	1.495
x_1x_2	1.00E-14	1.29E-14	0.777	0.649	-1.52E-14	3.53E-14
x_1x_3	3.54E-15	1.24E-15	2.854	6.13E-04	1.11E-15	5.96E-15
x_1x_4	-2.76E-16	6.90E-16	-0.400	0.989	-1.63E-15	1.08E-15
x_1x_5	7.52E-15	9.99E-15	0.752	0.815	-1.21E-14	2.71E-14
x_1x_6	2.84E-15	3.78E-15	0.750	0.984	-4.58E-15	1.03E-14
x_1x_7	3.52E-15	4.10E-15	0.860	0.245	-4.51E-15	1.16E-14
x_1x_8	1.47E-13	1.78E-13	0.829	0.088	-2.01E-13	4.96E-13
x_1x_9	9.33E-15	2.67E-14	0.349	0.241	-4.30E-14	6.16E-14
x_1x_{10}	-1.21E-14	1.37E-14	-0.880	0.100	-3.90E-14	1.48E-14
x_1x_{11}	3.87E-13	1.61E-13	2.404	0.017	7.14E-14	7.02E-13
x_1x_{12}	1.32E-14	2.32E-14	0.570	0.793	-3.22E-14	5.86E-14
x_1x_{13}	-1.55E-14	1.19E-14	-1.303	0.124	-3.88E-14	7.81E-15
x_1y_1	-2.57E-14	1.32E-13	-0.195	0.970	-2.84E-13	2.33E-13
x_1y_6	4.14E-14	1.33E-13	0.312	0.879	-2.19E-13	3.02E-13
x_2x_3	1.67E-04	9.93E-04	0.168	0.700	-0.002	0.002
x_2x_4	8.74E-04	8.06E-04	1.083	0.102	-7.07E-04	0.002
x_2x_5	-0.014	0.011	-1.259	0.035	-0.035	0.008
x_2x_6	-0.006	0.004	-1.601	0.082	-0.014	0.001
x_2x_7	0.006	0.005	1.232	0.117	-0.003	0.015
x_2x_8	0.103	0.178	0.581	0.533	-0.245	0.452

x_2x_9	0.047	0.027	1.736	0.140	-0.006	0.100
x_2x_{10}	-0.036	0.013	-2.676	0.007	-0.062	-0.010
x_2x_{11}	-0.368	0.183	-2.015	0.084	-0.726	-0.010
x_2x_{12}	-0.024	0.025	-0.940	0.274	-0.073	0.026
x_2x_{13}	0.023	0.012	1.871	0.183	-0.001	0.047
x_2y_1	-0.187	0.182	-1.024	0.155	-0.544	0.171
x_2y_6	0.272	0.181	1.503	0.055	-0.083	0.628
x_3x_4	-6.96E-05	5.80E-05	-1.201	0.281	-1.83E-04	4.40E-05
x_3x_5	0.002	8.49E-04	1.780	0.057	-1.53E-04	0.003
x_3x_6	-1.41E-04	3.06E-04	-0.461	0.571	-7.41E-04	4.59E-04
x_3x_7	-9.03E-05	3.42E-04	-0.264	0.669	-7.61E-04	5.80E-04
x_3x_8	-0.032	0.023	-1.388	0.277	-0.078	0.013
x_3x_9	-0.005	0.002	-2.130	0.142	-0.009	-3.92E-04
x_3x_{10}	0.001	0.001	1.250	0.648	-7.70E-04	0.003
x_3x_{11}	0.031	0.020	1.588	0.202	-0.007	0.070
x_3x_{12}	0.002	0.002	1.138	0.748	-0.002	0.006
x_3x_{13}	3.63E-05	8.87E-04	0.041	0.283	-0.002	0.002
x_3y_1	-0.023	0.011	-2.035	0.121	-0.045	-8.38E-04
x_3y_6	0.022	0.011	1.976	0.139	1.81E-04	0.044
x_4x_5	0.004	0.001	3.875	0.010	0.002	0.007
x_4x_6	9.22E-04	4.38E-04	2.104	0.204	6.31E-05	0.002
x_4x_7	0.001	4.92E-04	3.015	0.002	5.19E-04	0.002
x_4x_8	0.005	0.010	0.480	0.670	-0.014	0.024
x_4x_9	-0.008	0.002	-4.605	2.77E-06	-0.011	-0.004
x_4x_{10}	0.002	7.68E-04	2.336	0.017	2.89E-04	0.003
x_4x_{11}	-0.009	0.009	-1.015	0.623	-0.026	0.008
x_4x_{12}	-0.002	0.001	-1.501	0.157	-0.005	6.43E-04
x_4x_{13}	1.54E-04	6.68E-04	0.230	0.965	-0.001	0.001
x_4y_1	0.007	0.009	0.811	0.231	-0.011	0.026
x_4y_6	-0.009	0.009	-0.985	0.158	-0.027	0.009
x_5x_6	-0.063	0.010	-6.500	1.20E-07	-0.082	-0.044
x_5x_7	0.012	0.007	1.684	0.091	-0.002	0.025
x_5x_8	0.081	0.151	0.536	0.257	-0.215	0.376
x_5x_9	-0.054	0.023	-2.370	0.060	-0.099	-0.009
x_5x_{10}	0.005	0.011	0.473	0.534	-0.016	0.027
x_5x_{11}	-0.028	0.154	-0.182	0.610	-0.329	0.273
x_5x_{12}	-0.009	0.020	-0.463	0.725	-0.048	0.030
x_5x_{13}	4.16E-04	0.010	0.041	0.955	-0.020	0.021
x_5y_1	-0.096	0.106	-0.911	0.584	-0.304	0.111
x_5y_6	0.071	0.107	0.668	0.692	-0.138	0.281
x_6x_7	0.002	0.001	1.432	0.168	-7.83E-04	0.005
x_6x_8	0.015	0.062	0.243	0.336	-0.106	0.136

x_6x_9	-0.007	0.009	-0.880	0.623	-0.024	0.009
x_6x_{10}	0.001	0.004	0.301	0.285	-0.006	0.009
x_6x_{11}	-0.154	0.065	-2.366	0.005	-0.281	-0.026
x_6x_{12}	-0.001	0.007	-0.169	0.596	-0.015	0.012
x_6x_{13}	0.005	0.004	1.349	0.124	-0.002	0.013
x_6y_1	-0.019	0.035	-0.522	0.361	-0.088	0.051
x_6y_6	0.025	0.036	0.697	0.277	-0.046	0.096
x_7x_8	0.027	0.057	0.474	0.917	-0.085	0.139
x_7x_9	0.009	0.009	0.982	0.185	-0.009	0.027
x_7x_{10}	0.002	0.005	0.394	0.800	-0.007	0.011
x_7x_{11}	-0.012	0.053	-0.222	0.856	-0.116	0.092
x_7x_{12}	-0.013	0.008	-1.576	0.788	-0.029	0.003
x_7x_{13}	-1.15E-05	0.004	-0.003	0.800	-0.008	0.008
x_7y_1	-0.076	0.050	-1.515	0.085	-0.174	0.022
x_7y_6	0.053	0.050	1.057	0.194	-0.045	0.151
x_8x_9	-1.373	0.502	-2.733	0.059	-2.357	-0.388
x_8x_{10}	0.538	0.239	2.253	0.107	0.070	1.007
x_8x_{11}	2.497	1.761	1.418	0.320	-0.955	5.949
x_8x_{12}	0.172	0.358	0.480	0.766	-0.529	0.873
x_8x_{13}	-0.066	0.161	-0.407	0.901	-0.382	0.251
x_8y_1	-2.590	2.052	-1.262	0.909	-6.612	1.433
x_8y_6	2.352	2.092	1.124	1.000	-1.748	6.452
x_9x_{10}	0.095	0.034	2.793	0.016	0.028	0.161
x_9x_{11}	-0.341	0.353	-0.968	0.152	-1.032	0.350
x_9x_{12}	-0.003	0.051	-0.055	0.930	-0.102	0.097
x_9x_{13}	-0.021	0.024	-0.878	0.864	-0.068	0.026
x_9y_1	-0.533	0.298	-1.790	0.039	-1.118	0.051
x_9y_6	0.828	0.302	2.743	0.003	0.237	1.420
$x_{10}x_{11}$	-0.007	0.179	-0.038	0.916	-0.357	0.343
$x_{10}x_{12}$	0.015	0.024	0.640	0.866	-0.032	0.063
$x_{10}x_{13}$	0.011	0.012	0.971	0.586	-0.011	0.034
$x_{10}y_1$	0.194	0.146	1.329	0.227	-0.092	0.480
$x_{10}y_6$	-0.222	0.149	-1.486	0.161	-0.515	0.071
$x_{11}x_{12}$	0.342	0.381	0.900	0.560	-0.404	1.088
$x_{11}x_{13}$	-0.134	0.194	-0.689	0.937	-0.514	0.247
$x_{11}y_1$	-1.579	2.082	-0.759	0.098	-5.659	2.501
$x_{11}y_6$	1.948	2.108	0.924	0.070	-2.183	6.079
$x_{12}x_{13}$	0.031	0.023	1.365	0.120	-0.014	0.076
$x_{12}y_1$	0.403	0.255	1.579	0.554	-0.097	0.904
$x_{12}y_6$	-0.369	0.258	-1.428	0.658	-0.875	0.137
$x_{13}y_1$	0.061	0.117	0.521	0.138	-0.169	0.291
$x_{13}y_6$	-0.043	0.119	-0.366	0.163	-0.276	0.189

y_1y_6	11.863	1.188	9.987	6.72E-26	9.535	14.191
x_1^2	2.75E-26	1.04E-26	2.632	0.010	7.01E-27	4.79E-26
x_2^2	-0.106	0.012	-9.055	1.21E-20	-0.129	-0.083
x_3^2	-7.25E-05	6.44E-05	-1.127	0.618	-1.99E-04	5.36E-05
x_4^2	-9.67E-05	6.70E-05	-1.444	0.074	-2.28E-04	3.45E-05
x_5^2	-0.023	0.010	-2.444	0.009	-0.042	-0.005
x_6^2	-0.002	6.47E-04	-2.470	0.028	-0.003	-3.30E-04
x_7^2	0.003	0.003	0.952	0.402	-0.003	0.008
x_8^2	-4.852	1.392	-3.485	0.010	-7.581	-2.124
x_9^2	-0.186	0.050	-3.727	1.26E-04	-0.284	-0.088
x_{10}^2	-0.006	0.011	-0.499	0.478	-0.028	0.017
x_{11}^2	-4.323	1.247	-3.466	8.91E-05	-6.767	-1.878
x_{12}^2	-0.039	0.041	-0.955	0.349	-0.119	0.041
x_{13}^2	-0.011	0.010	-1.102	0.288	-0.030	0.008
y_1^2	-4.759	0.580	-8.199	2.52E-18	-5.896	-3.621
y_6^2	-6.472	0.630	-10.269	2.41E-27	-7.707	-5.237

Table F.4 Target similarity criterion y_3 regression coefficients

Variables	Coefficients	Standard Deviation	t Value	p Value	95% Confidence Interval	
c	0.222	0.139	1.596	0.254	-0.051	0.495
x_1	-1.70E-13	7.01E-14	-2.417	0.015	-3.07E-13	-3.21E-14
x_2	0.295	0.064	4.594	1.62E-05	0.169	0.421
x_3	-0.001	0.006	-0.210	0.571	-0.014	0.011
x_4	0.002	0.005	0.483	0.212	-0.007	0.012
x_5	-0.058	0.060	-0.962	0.949	-0.175	0.060
x_6	-0.038	0.022	-1.743	0.306	-0.080	0.005
x_7	-0.040	0.033	-1.195	0.162	-0.105	0.025
x_8	0.120	0.904	0.133	0.597	-1.652	1.891
x_9	0.151	0.132	1.144	0.528	-0.108	0.410
x_{10}	-0.035	0.069	-0.504	0.460	-0.169	0.100
x_{11}	1.272	0.863	1.474	0.084	-0.419	2.964
x_{12}	-0.133	0.121	-1.102	0.571	-0.370	0.104
x_{13}	0.014	0.059	0.236	0.931	-0.102	0.130
y_1	-1.344	0.671	-2.003	0.018	-2.659	-0.029
y_6	1.071	0.669	1.600	0.043	-0.241	2.382
x_1x_2	1.74E-14	1.98E-14	0.877	0.555	-2.15E-14	5.63E-14
x_1x_3	4.43E-15	1.91E-15	2.321	0.005	6.89E-16	8.16E-15
x_1x_4	-6.01E-16	1.06E-15	-0.566	0.649	-2.68E-15	1.48E-15
x_1x_5	1.22E-14	1.54E-14	0.793	0.778	-1.80E-14	4.23E-14
x_1x_6	4.29E-15	5.83E-15	0.736	0.861	-7.13E-15	1.57E-14

x_1x_7	5.59E-15	6.31E-15	0.886	0.268	-6.78E-15	1.79E-14
x_1x_8	1.59E-13	2.74E-13	0.580	0.231	-3.78E-13	6.95E-13
x_1x_9	1.60E-14	4.11E-14	0.390	0.413	-6.45E-14	9.65E-14
x_1x_{10}	-3.91E-14	2.11E-14	-1.853	0.026	-8.05E-14	2.27E-15
x_1x_{11}	5.20E-13	2.48E-13	2.097	0.055	3.40E-14	1.01E-12
x_1x_{12}	2.75E-14	3.56E-14	0.772	0.770	-4.23E-14	9.74E-14
x_1x_{13}	-2.11E-14	1.83E-14	-1.155	0.227	-5.70E-14	1.47E-14
x_1y_1	-2.54E-14	2.03E-13	-0.125	0.904	-4.23E-13	3.72E-13
x_1y_6	5.43E-14	2.04E-13	0.266	0.963	-3.46E-13	4.55E-13
x_2x_3	-0.001	0.002	-0.882	0.569	-0.004	0.002
x_2x_4	-4.91E-04	0.001	-0.395	0.695	-0.003	0.002
x_2x_5	-0.019	0.017	-1.151	0.113	-0.052	0.014
x_2x_6	-0.002	0.006	-0.302	0.831	-0.014	0.010
x_2x_7	0.008	0.007	1.165	0.074	-0.006	0.022
x_2x_8	-0.317	0.274	-1.158	0.275	-0.853	0.219
x_2x_9	0.081	0.042	1.940	0.077	-8.50E-04	0.162
x_2x_{10}	-0.039	0.021	-1.900	0.055	-0.080	0.001
x_2x_{11}	-0.464	0.281	-1.650	0.262	-1.015	0.087
x_2x_{12}	-0.050	0.039	-1.291	0.197	-0.126	0.026
x_2x_{13}	0.022	0.019	1.175	0.708	-0.015	0.059
x_2y_1	0.007	0.281	0.024	0.583	-0.543	0.557
x_2y_6	0.223	0.279	0.800	0.173	-0.324	0.770
x_3x_4	-1.17E-04	8.92E-05	-1.315	0.201	-2.92E-04	5.75E-05
x_3x_5	0.004	0.001	2.838	0.002	0.001	0.006
x_3x_6	1.70E-04	4.71E-04	0.360	0.699	-7.53E-04	0.001
x_3x_7	-7.87E-05	5.26E-04	-0.149	0.564	-0.001	9.53E-04
x_3x_8	-0.037	0.036	-1.024	0.292	-0.106	0.033
x_3x_9	-0.003	0.004	-0.913	0.708	-0.010	0.004
x_3x_{10}	6.13E-04	0.002	0.367	0.858	-0.003	0.004
x_3x_{11}	0.057	0.030	1.878	0.148	-0.002	0.116
x_3x_{12}	0.003	0.003	1.131	0.635	-0.002	0.009
x_3x_{13}	-5.22E-04	0.001	-0.382	0.708	-0.003	0.002
x_3y_1	-0.023	0.017	-1.358	0.349	-0.057	0.010
x_3y_6	0.023	0.017	1.339	0.378	-0.011	0.057
x_4x_5	0.006	0.002	3.641	0.009	0.003	0.010
x_4x_6	0.002	6.74E-04	2.989	0.014	6.94E-04	0.003
x_4x_7	0.002	7.58E-04	2.370	0.011	3.10E-04	0.003
x_4x_8	0.018	0.015	1.204	0.138	-0.011	0.048
x_4x_9	-0.013	0.003	-5.137	2.72E-07	-0.018	-0.008
x_4x_{10}	0.002	0.001	1.828	0.127	-1.56E-04	0.004
x_4x_{11}	-0.024	0.013	-1.826	0.156	-0.050	0.002
x_4x_{12}	-0.002	0.002	-1.079	0.153	-0.007	0.002

x_4x_{13}	-2.80E-04	0.001	-0.272	0.751	-0.002	0.002
x_4y_1	0.012	0.014	0.857	0.244	-0.016	0.040
x_4y_6	-0.015	0.014	-1.090	0.135	-0.043	0.012
x_5x_6	-0.083	0.015	-5.592	4.38E-06	-0.113	-0.054
x_5x_7	0.019	0.011	1.816	0.079	-0.002	0.040
x_5x_8	0.348	0.232	1.501	0.031	-0.107	0.803
x_5x_9	-0.102	0.035	-2.922	0.010	-0.171	-0.034
x_5x_{10}	2.87E-04	0.017	0.017	0.439	-0.033	0.033
x_5x_{11}	0.038	0.236	0.163	0.889	-0.425	0.502
x_5x_{12}	-0.008	0.031	-0.262	0.973	-0.068	0.052
x_5x_{13}	-0.011	0.016	-0.685	0.457	-0.042	0.020
x_5y_1	-0.153	0.163	-0.938	0.190	-0.472	0.166
x_5y_6	0.142	0.165	0.862	0.200	-0.181	0.464
x_6x_7	0.004	0.002	1.604	0.096	-8.13E-04	0.008
x_6x_8	0.092	0.095	0.965	0.137	-0.095	0.279
x_6x_9	-0.001	0.013	-0.092	0.968	-0.027	0.024
x_6x_{10}	-0.001	0.006	-0.226	0.248	-0.013	0.010
x_6x_{11}	-0.190	0.100	-1.897	0.030	-0.386	0.006
x_6x_{12}	-0.001	0.011	-0.136	0.944	-0.022	0.020
x_6x_{13}	0.007	0.006	1.157	0.218	-0.005	0.018
x_6y_1	-0.020	0.055	-0.363	0.306	-0.127	0.087
x_6y_6	0.028	0.056	0.505	0.246	-0.081	0.138
x_7x_8	0.031	0.088	0.351	0.818	-0.141	0.203
x_7x_9	0.005	0.014	0.330	0.477	-0.023	0.033
x_7x_{10}	0.008	0.007	1.116	0.530	-0.006	0.022
x_7x_{11}	-0.008	0.082	-0.095	0.706	-0.168	0.152
x_7x_{12}	-0.011	0.013	-0.862	0.733	-0.035	0.014
x_7x_{13}	-0.003	0.006	-0.458	0.783	-0.015	0.009
x_7y_1	-0.034	0.077	-0.442	0.370	-0.185	0.117
x_7y_6	6.48E-04	0.077	0.008	0.638	-0.150	0.152
x_8x_9	-0.755	0.773	-0.976	0.777	-2.270	0.761
x_8x_{10}	0.423	0.368	1.151	0.394	-0.298	1.144
x_8x_{11}	3.475	2.711	1.282	0.311	-1.839	8.789
x_8x_{12}	-0.041	0.551	-0.075	0.998	-1.121	1.038
x_8x_{13}	-0.059	0.249	-0.237	0.911	-0.546	0.428
x_8y_1	-1.807	3.159	-0.572	0.735	-7.999	4.385
x_8y_6	1.595	3.220	0.495	0.645	-4.717	7.906
x_9x_{10}	0.065	0.052	1.254	0.331	-0.037	0.168
x_9x_{11}	-0.528	0.543	-0.973	0.152	-1.592	0.536
x_9x_{12}	-0.071	0.078	-0.905	0.258	-0.224	0.083
x_9x_{13}	-0.040	0.037	-1.077	0.675	-0.113	0.033
x_9y_1	-0.426	0.459	-0.929	0.261	-1.325	0.473

x_9y_6	0.830	0.465	1.785	0.052	-0.081	1.741
$x_{10}x_{11}$	0.269	0.275	0.978	0.328	-0.270	0.808
$x_{10}x_{12}$	0.030	0.037	0.799	0.968	-0.043	0.103
$x_{10}x_{13}$	0.016	0.018	0.918	0.435	-0.019	0.051
$x_{10}y_1$	0.333	0.225	1.481	0.171	-0.108	0.774
$x_{10}y_6$	-0.386	0.230	-1.677	0.116	-0.836	0.065
$x_{11}x_{12}$	1.310	0.586	2.237	0.047	0.162	2.459
$x_{11}x_{13}$	-0.370	0.299	-1.241	0.423	-0.956	0.215
$x_{11}y_1$	1.749	3.204	0.546	0.595	-4.531	8.029
$x_{11}y_6$	-0.585	3.244	-0.180	0.383	-6.944	5.774
$x_{12}x_{13}$	0.051	0.035	1.450	0.215	-0.018	0.120
$x_{12}y_1$	0.345	0.393	0.877	0.946	-0.426	1.116
$x_{12}y_6$	-0.313	0.398	-0.787	0.968	-1.092	0.466
$x_{13}y_1$	-0.057	0.181	-0.315	0.660	-0.411	0.297
$x_{13}y_6$	0.101	0.183	0.551	0.811	-0.257	0.459
y_1y_6	10.752	1.828	5.881	1.28E-11	7.169	14.336
x_1^2	3.69E-26	1.61E-26	2.298	0.021	5.42E-27	6.84E-26
x_2^2	-0.232	0.018	-12.861	3.50E-37	-0.267	-0.196
x_3^2	-5.91E-05	9.91E-05	-0.597	0.921	-2.53E-04	1.35E-04
x_4^2	-8.29E-05	1.03E-04	-0.804	0.134	-2.85E-04	1.19E-04
x_5^2	-0.045	0.015	-3.059	0.001	-0.074	-0.016
x_6^2	-0.003	9.97E-04	-3.014	0.003	-0.005	-0.001
x_7^2	-0.001	0.004	-0.336	0.875	-0.010	0.007
x_8^2	-4.538	2.143	-2.117	0.081	-8.738	-0.337
x_9^2	-0.227	0.077	-2.953	0.002	-0.377	-0.076
x_{10}^2	-0.004	0.018	-0.218	0.673	-0.038	0.031
x_{11}^2	-8.633	1.920	-4.496	1.23E-06	-12.396	-4.869
x_{12}^2	-0.022	0.063	-0.344	0.864	-0.145	0.101
x_{13}^2	-0.011	0.015	-0.723	0.451	-0.040	0.018
y_1^2	-4.043	0.893	-4.525	1.33E-07	-5.794	-2.292
y_6^2	-5.925	0.970	-6.108	1.16E-12	-7.827	-4.024

Table F.5 Target similarity criterion y_4 regression coefficients

Variables	**Coefficients**	**Standard Deviation**	**t Value**	**p Value**	**95% Confidence Interval**	
c	0.202	0.163	1.237	0.472	-0.118	0.521
x_1	-1.53E-13	8.21E-14	-1.861	0.064	-3.14E-13	8.16E-15
x_2	0.443	0.075	5.891	6.61E-08	0.296	0.591
x_3	0.002	0.007	0.314	0.980	-0.012	0.017
x_4	7.71E-04	0.006	0.130	0.339	-0.011	0.012
x_5	-0.092	0.070	-1.308	0.630	-0.229	0.046

x_6	-0.062	0.025	-2.467	0.042	-0.112	-0.013
x_7	-0.031	0.039	-0.797	0.470	-0.107	0.045
x_8	0.299	1.058	0.283	0.818	-1.775	2.374
x_9	0.223	0.155	1.442	0.272	-0.080	0.527
x_{10}	-0.021	0.080	-0.263	0.483	-0.178	0.136
x_{11}	1.523	1.011	1.507	0.048	-0.458	3.504
x_{12}	-0.104	0.141	-0.734	0.827	-0.381	0.173
x_{13}	0.002	0.069	0.033	0.838	-0.134	0.138
y_1	-1.995	0.786	-2.540	0.007	-3.535	-0.455
y_6	1.531	0.784	1.953	0.030	-0.005	3.066
x_1x_2	2.03E-14	2.32E-14	0.875	0.484	-2.52E-14	6.58E-14
x_1x_3	3.96E-15	2.23E-15	1.773	0.028	-4.17E-16	8.34E-15
x_1x_4	-1.53E-15	1.24E-15	-1.230	0.248	-3.97E-15	9.08E-16
x_1x_5	1.79E-14	1.80E-14	0.995	0.987	-1.74E-14	5.32E-14
x_1x_6	5.97E-15	6.82E-15	0.876	0.756	-7.40E-15	1.93E-14
x_1x_7	1.90E-15	7.39E-15	0.257	0.572	-1.26E-14	1.64E-14
x_1x_8	1.95E-13	3.21E-13	0.609	0.277	-4.33E-13	8.24E-13
x_1x_9	3.54E-14	4.81E-14	0.736	0.368	-5.89E-14	1.30E-13
x_1x_{10}	-5.38E-14	2.47E-14	-2.174	0.021	-1.02E-13	-5.28E-15
x_1x_{11}	4.77E-13	2.90E-13	1.644	0.152	-9.17E-14	1.05E-12
x_1x_{12}	1.88E-14	4.17E-14	0.449	0.958	-6.31E-14	1.01E-13
x_1x_{13}	-1.60E-14	2.14E-14	-0.748	0.355	-5.80E-14	2.60E-14
x_1y_1	1.46E-13	2.38E-13	0.616	0.336	-3.19E-13	6.12E-13
x_1y_6	-1.17E-13	2.39E-13	-0.491	0.425	-5.86E-13	3.51E-13
x_2x_3	-0.003	0.002	-1.474	0.163	-0.006	8.70E-04
x_2x_4	-0.003	0.001	-2.392	0.182	-0.006	-6.28E-04
x_2x_5	-0.021	0.020	-1.064	0.201	-0.059	0.018
x_2x_6	0.005	0.007	0.732	0.391	-0.009	0.019
x_2x_7	0.005	0.008	0.651	0.155	-0.011	0.022
x_2x_8	-0.649	0.320	-2.026	0.045	-1.277	-0.021
x_2x_9	0.116	0.049	2.368	0.026	0.020	0.211
x_2x_{10}	-0.040	0.024	-1.666	0.142	-0.088	0.007
x_2x_{11}	-0.132	0.329	-0.402	0.924	-0.777	0.513
x_2x_{12}	-0.071	0.045	-1.567	0.119	-0.160	0.018
x_2x_{13}	0.017	0.022	0.788	0.978	-0.026	0.061
x_2y_1	0.075	0.329	0.227	0.947	-0.569	0.719
x_2y_6	0.237	0.327	0.726	0.326	-0.403	0.877
x_3x_4	-1.34E-04	1.04E-04	-1.280	0.211	-3.38E-04	7.10E-05
x_3x_5	0.005	0.002	3.309	5.26E-04	0.002	0.008
x_3x_6	4.81E-04	5.52E-04	0.873	0.358	-6.00E-04	0.002
x_3x_7	-1.06E-04	6.16E-04	-0.173	0.569	-0.001	0.001
x_3x_8	-0.059	0.042	-1.406	0.126	-0.140	0.023

x_3x_9	-0.002	0.004	-0.516	0.984	-0.010	0.006
x_3x_{10}	7.38E-04	0.002	0.378	0.998	-0.003	0.005
x_3x_{11}	0.049	0.036	1.371	0.510	-0.021	0.118
x_3x_{12}	9.41E-04	0.003	0.278	0.860	-0.006	0.008
x_3x_{13}	5.42E-04	0.002	0.339	0.380	-0.003	0.004
x_3y_1	-0.007	0.020	-0.331	0.958	-0.046	0.033
x_3y_6	0.007	0.020	0.333	0.966	-0.033	0.046
x_4x_5	0.008	0.002	3.888	0.003	0.004	0.012
x_4x_6	0.003	7.90E-04	3.770	2.70E-04	0.001	0.005
x_4x_7	0.002	8.87E-04	2.032	0.053	6.38E-05	0.004
x_4x_8	0.020	0.018	1.142	0.115	-0.014	0.055
x_4x_9	-0.017	0.003	-5.640	2.01E-08	-0.022	-0.011
x_4x_{10}	0.002	0.001	1.749	0.166	-2.92E-04	0.005
x_4x_{11}	-0.025	0.016	-1.637	0.169	-0.056	0.005
x_4x_{12}	-0.002	0.003	-0.907	0.157	-0.007	0.003
x_4x_{13}	-0.001	0.001	-0.858	0.462	-0.003	0.001
x_4y_1	0.012	0.017	0.740	0.465	-0.020	0.045
x_4y_6	-0.016	0.017	-0.966	0.285	-0.049	0.017
x_5x_6	-0.089	0.017	-5.121	1.72E-05	-0.124	-0.055
x_5x_7	0.023	0.012	1.845	0.166	-0.001	0.047
x_5x_8	0.515	0.272	1.894	0.016	-0.018	1.047
x_5x_9	-0.162	0.041	-3.941	2.45E-04	-0.242	-0.081
x_5x_{10}	-0.004	0.020	-0.205	0.462	-0.043	0.035
x_5x_{11}	0.120	0.277	0.435	0.919	-0.422	0.663
x_5x_{12}	-0.005	0.036	-0.141	0.990	-0.075	0.065
x_5x_{13}	-0.020	0.019	-1.059	0.283	-0.056	0.017
x_5y_1	-0.211	0.191	-1.109	0.098	-0.585	0.162
x_5y_6	0.231	0.193	1.197	0.073	-0.147	0.609
x_6x_7	0.004	0.003	1.481	0.167	-0.001	0.009
x_6x_8	0.106	0.112	0.950	0.214	-0.113	0.325
x_6x_9	-0.005	0.015	-0.299	0.751	-0.035	0.025
x_6x_{10}	-0.004	0.007	-0.549	0.266	-0.017	0.010
x_6x_{11}	-0.134	0.117	-1.140	0.185	-0.364	0.096
x_6x_{12}	8.92E-04	0.013	0.071	0.736	-0.024	0.025
x_6x_{13}	0.006	0.007	0.900	0.362	-0.007	0.020
x_6y_1	-0.040	0.064	-0.627	0.184	-0.165	0.085
x_6y_6	0.053	0.065	0.805	0.133	-0.075	0.181
x_7x_8	-0.007	0.103	-0.072	0.873	-0.209	0.194
x_7x_9	-4.61E-04	0.017	-0.028	0.791	-0.033	0.032
x_7x_{10}	0.014	0.008	1.669	0.274	-0.002	0.030
x_7x_{11}	0.018	0.096	0.192	0.908	-0.169	0.206
x_7x_{12}	0.001	0.015	0.090	0.684	-0.027	0.030

x_7x_{13}	-0.005	0.007	-0.744	0.950	-0.019	0.009
x_7y_1	-0.018	0.090	-0.194	0.419	-0.195	0.160
x_7y_6	-0.015	0.090	-0.170	0.661	-0.192	0.162
x_8x_9	-0.075	0.905	-0.083	0.606	-1.849	1.699
x_8x_{10}	0.206	0.431	0.479	0.772	-0.638	1.050
x_8x_{11}	2.137	3.175	0.673	0.692	-4.085	8.360
x_8x_{12}	-0.730	0.645	-1.133	0.301	-1.994	0.534
x_8x_{13}	0.261	0.291	0.897	0.258	-0.309	0.832
x_8y_1	-1.063	3.700	-0.287	0.640	-8.314	6.188
x_8y_6	0.673	3.771	0.179	0.534	-6.717	8.064
x_9x_{10}	0.038	0.061	0.615	0.743	-0.082	0.157
x_9x_{11}	-0.547	0.636	-0.860	0.195	-1.793	0.699
x_9x_{12}	-0.125	0.092	-1.359	0.075	-0.304	0.055
x_9x_{13}	-0.027	0.043	-0.623	0.879	-0.112	0.058
x_9y_1	-0.246	0.537	-0.458	0.527	-1.299	0.807
x_9y_6	0.626	0.544	1.150	0.195	-0.441	1.693
$x_{10}x_{11}$	0.619	0.322	1.922	0.056	-0.012	1.250
$x_{10}x_{12}$	0.052	0.044	1.201	0.529	-0.033	0.138
$x_{10}x_{13}$	0.011	0.021	0.544	0.515	-0.030	0.052
$x_{10}y_1$	0.375	0.263	1.423	0.188	-0.141	0.891
$x_{10}y_6$	-0.431	0.269	-1.602	0.131	-0.959	0.096
$x_{11}x_{12}$	1.914	0.686	2.791	0.008	0.570	3.259
$x_{11}x_{13}$	-0.529	0.350	-1.513	0.200	-1.214	0.156
$x_{11}y_1$	4.043	3.752	1.077	0.904	-3.311	11.397
$x_{11}y_6$	-2.194	3.799	-0.577	0.730	-9.640	5.253
$x_{12}x_{13}$	0.054	0.041	1.318	0.416	-0.026	0.135
$x_{12}y_1$	0.394	0.460	0.855	0.899	-0.509	1.296
$x_{12}y_6$	-0.378	0.465	-0.812	0.957	-1.290	0.534
$x_{13}y_1$	-0.159	0.211	-0.754	0.955	-0.574	0.255
$x_{13}y_6$	0.210	0.214	0.983	0.778	-0.209	0.630
y_1y_6	8.919	2.141	4.166	2.84E-07	4.723	13.116
x_1^2	4.23E-26	1.88E-26	2.250	0.026	5.46E-27	7.92E-26
x_2^2	-0.304	0.021	-14.421	3.07E-44	-0.346	-0.263
x_3^2	-1.50E-04	1.16E-04	-1.296	0.387	-3.78E-04	7.71E-05
x_4^2	4.94E-06	1.21E-04	0.041	0.485	-2.32E-04	2.41E-04
x_5^2	-0.060	0.017	-3.481	3.53E-04	-0.094	-0.026
x_6^2	-0.004	0.001	-3.414	4.77E-04	-0.006	-0.002
x_7^2	-0.004	0.005	-0.866	0.408	-0.014	0.005
x_8^2	-3.987	2.510	-1.589	0.161	-8.906	0.932
x_9^2	-0.233	0.090	-2.589	0.008	-0.409	-0.057
x_{10}^2	-0.004	0.021	-0.200	0.622	-0.045	0.036
x_{11}^2	-12.156	2.248	-5.407	7.36E-09	-16.563	-7.750

x_{12}^2	-0.020	0.073	-0.276	0.972	-0.164	0.124
x_{13}^2	-0.011	0.017	-0.623	0.504	-0.045	0.023
y_1^2	-3.162	1.046	-3.022	1.12E-04	-5.212	-1.111
y_6^2	-4.984	1.136	-4.387	5.07E-08	-7.211	-2.758

Table F.6 Target similarity criterion y_5 regression coefficients

Variables	**Coefficients**	**Standard Deviation**	**t Value**	**p Value**	**95% Confidence Interval**	
c	0.214	0.173	1.233	0.559	-0.126	0.553
x_1	-1.52E-13	8.74E-14	-1.740	0.102	-3.23E-13	1.92E-14
x_2	0.529	0.080	6.607	1.94E-09	0.372	0.686
x_3	0.002	0.008	0.245	0.902	-0.014	0.017
x_4	-0.002	0.006	-0.243	0.567	-0.014	0.011
x_5	-0.100	0.075	-1.346	0.646	-0.246	0.046
x_6	-0.070	0.027	-2.610	0.025	-0.123	-0.017
x_7	-0.035	0.041	-0.833	0.570	-0.116	0.047
x_8	0.695	1.126	0.617	0.763	-1.512	2.901
x_9	0.384	0.165	2.334	0.039	0.062	0.707
x_{10}	-0.036	0.085	-0.427	0.766	-0.204	0.131
x_{11}	1.009	1.075	0.938	0.107	-1.099	3.116
x_{12}	-0.122	0.150	-0.813	0.832	-0.417	0.173
x_{13}	0.017	0.074	0.232	0.967	-0.128	0.162
y_1	-2.512	0.836	-3.006	0.002	-4.150	-0.874
y_6	1.958	0.834	2.349	0.011	0.324	3.592
x_1x_2	2.55E-14	2.47E-14	1.033	0.428	-2.29E-14	7.39E-14
x_1x_3	4.57E-15	2.38E-15	1.924	0.028	-8.64E-17	9.23E-15
x_1x_4	-2.11E-15	1.32E-15	-1.594	0.107	-4.70E-15	4.85E-16
x_1x_5	2.25E-14	1.92E-14	1.175	0.881	-1.50E-14	6.01E-14
x_1x_6	5.94E-15	7.26E-15	0.819	0.797	-8.28E-15	2.02E-14
x_1x_7	-2.36E-16	7.86E-15	-0.030	0.724	-1.56E-14	1.52E-14
x_1x_8	2.88E-13	3.41E-13	0.844	0.239	-3.81E-13	9.56E-13
x_1x_9	4.98E-14	5.12E-14	0.974	0.273	-5.05E-14	1.50E-13
x_1x_{10}	-5.97E-14	2.63E-14	-2.271	0.024	-1.11E-13	-8.18E-15
x_1x_{11}	5.70E-13	3.09E-13	1.846	0.133	-3.51E-14	1.17E-12
x_1x_{12}	2.86E-14	4.44E-14	0.644	0.896	-5.84E-14	1.16E-13
x_1x_{13}	-1.49E-14	2.28E-14	-0.655	0.388	-5.96E-14	2.97E-14
x_1y_1	3.89E-13	2.53E-13	1.537	0.067	-1.07E-13	8.84E-13
x_1y_6	-3.63E-13	2.54E-13	-1.428	0.097	-8.62E-13	1.36E-13
x_2x_3	-0.003	0.002	-1.708	0.065	-0.007	4.80E-04
x_2x_4	-0.006	0.002	-4.017	0.005	-0.009	-0.003
x_2x_5	-0.022	0.021	-1.047	0.307	-0.063	0.019

x_2x_6	0.012	0.008	1.513	0.081	-0.003	0.027
x_2x_7	2.73E-04	0.009	0.030	0.375	-0.017	0.018
x_2x_8	-0.708	0.341	-2.078	0.047	-1.376	-0.040
x_2x_9	0.165	0.052	3.175	0.002	0.063	0.266
x_2x_{10}	-0.054	0.026	-2.091	0.090	-0.104	-0.003
x_2x_{11}	0.152	0.350	0.434	0.406	-0.534	0.838
x_2x_{12}	-0.084	0.048	-1.727	0.055	-0.178	0.011
x_2x_{13}	0.016	0.024	0.679	0.962	-0.030	0.062
x_2y_1	0.224	0.349	0.642	0.637	-0.461	0.909
x_2y_6	0.135	0.348	0.387	0.613	-0.547	0.816
x_3x_4	-1.02E-04	1.11E-04	-0.920	0.364	-3.20E-04	1.16E-04
x_3x_5	0.005	0.002	3.269	9.62E-04	0.002	0.009
x_3x_6	6.44E-04	5.87E-04	1.097	0.253	-5.06E-04	0.002
x_3x_7	-1.70E-04	6.56E-04	-0.260	0.546	-0.001	0.001
x_3x_8	-0.074	0.044	-1.667	0.083	-0.161	0.013
x_3x_9	-0.001	0.004	-0.294	0.723	-0.010	0.007
x_3x_{10}	9.06E-04	0.002	0.436	0.977	-0.003	0.005
x_3x_{11}	0.043	0.038	1.137	0.824	-0.031	0.117
x_3x_{12}	-5.68E-04	0.004	-0.157	0.611	-0.008	0.006
x_3x_{13}	0.001	0.002	0.666	0.335	-0.002	0.004
x_3y_1	0.002	0.021	0.078	0.712	-0.040	0.044
x_3y_6	-0.002	0.022	-0.073	0.726	-0.044	0.041
x_4x_5	0.009	0.002	3.965	0.003	0.004	0.013
x_4x_6	0.003	8.40E-04	4.164	5.17E-05	0.002	0.005
x_4x_7	0.002	9.44E-04	1.926	0.082	-3.25E-05	0.004
x_4x_8	0.021	0.019	1.138	0.110	-0.015	0.058
x_4x_9	-0.019	0.003	-6.199	4.69E-10	-0.026	-0.013
x_4x_{10}	0.003	0.001	1.784	0.127	-2.59E-04	0.006
x_4x_{11}	-0.022	0.017	-1.302	0.222	-0.054	0.011
x_4x_{12}	-9.32E-04	0.003	-0.347	0.312	-0.006	0.004
x_4x_{13}	-0.002	0.001	-1.483	0.268	-0.004	6.11E-04
x_4y_1	0.012	0.018	0.691	0.511	-0.022	0.047
x_4y_6	-0.015	0.018	-0.852	0.350	-0.050	0.020
x_5x_6	-0.092	0.019	-4.967	3.17E-05	-0.129	-0.056
x_5x_7	0.026	0.013	2.005	0.210	5.88E-04	0.052
x_5x_8	0.376	0.289	1.301	0.084	-0.191	0.943
x_5x_9	-0.235	0.044	-5.385	2.21E-07	-0.321	-0.150
x_5x_{10}	0.003	0.021	0.132	0.913	-0.038	0.044
x_5x_{11}	0.227	0.295	0.770	0.651	-0.351	0.804
x_5x_{12}	-0.012	0.038	-0.322	0.995	-0.087	0.062
x_5x_{13}	-0.031	0.020	-1.595	0.116	-0.070	0.007
x_5y_1	-0.285	0.203	-1.404	0.055	-0.682	0.113

x_5y_6	0.338	0.205	1.648	0.029	-0.064	0.740
x_6x_7	0.005	0.003	1.673	0.180	-8.16E-04	0.010
x_6x_8	0.038	0.119	0.316	0.682	-0.195	0.270
x_6x_9	-0.022	0.016	-1.362	0.145	-0.054	0.010
x_6x_{10}	-0.002	0.007	-0.324	0.547	-0.017	0.012
x_6x_{11}	-0.048	0.125	-0.384	0.685	-0.292	0.197
x_6x_{12}	2.98E-04	0.013	0.022	0.603	-0.026	0.026
x_6x_{13}	0.003	0.007	0.425	0.738	-0.011	0.017
x_6y_1	-0.063	0.068	-0.924	0.101	-0.196	0.070
x_6y_6	0.078	0.070	1.125	0.068	-0.058	0.215
x_7x_8	-0.009	0.109	-0.085	0.888	-0.224	0.205
x_7x_9	-0.006	0.018	-0.316	0.928	-0.040	0.029
x_7x_{10}	0.015	0.009	1.689	0.241	-0.002	0.032
x_7x_{11}	0.019	0.102	0.184	0.846	-0.181	0.218
x_7x_{12}	0.012	0.016	0.746	0.386	-0.019	0.042
x_7x_{13}	-0.003	0.008	-0.431	0.592	-0.018	0.012
x_7y_1	-0.018	0.096	-0.186	0.402	-0.206	0.171
x_7y_6	-0.013	0.096	-0.133	0.611	-0.201	0.175
x_8x_9	0.194	0.963	0.201	0.379	-1.693	2.081
x_8x_{10}	-0.001	0.458	-0.002	0.774	-0.899	0.897
x_8x_{11}	2.835	3.377	0.840	0.595	-3.784	9.454
x_8x_{12}	-1.477	0.686	-2.154	0.027	-2.821	-0.133
x_8x_{13}	0.551	0.310	1.778	0.040	-0.056	1.157
x_8y_1	-1.714	3.935	-0.436	0.800	-9.428	5.999
x_8y_6	1.018	4.011	0.254	0.612	-6.843	8.880
x_9x_{10}	2.71E-04	0.065	0.004	0.707	-0.127	0.128
x_9x_{11}	-0.425	0.676	-0.628	0.323	-1.750	0.901
x_9x_{12}	-0.149	0.097	-1.531	0.025	-0.340	0.042
x_9x_{13}	-0.003	0.046	-0.055	0.674	-0.093	0.088
x_9y_1	0.045	0.571	0.078	0.893	-1.075	1.165
x_9y_6	0.227	0.579	0.391	0.574	-0.908	1.361
$x_{10}x_{11}$	0.815	0.343	2.380	0.015	0.144	1.487
$x_{10}x_{12}$	0.079	0.046	1.711	0.182	-0.012	0.170
$x_{10}x_{13}$	-0.002	0.022	-0.069	0.880	-0.045	0.042
$x_{10}y_1$	0.366	0.280	1.308	0.220	-0.183	0.915
$x_{10}y_6$	-0.396	0.286	-1.383	0.184	-0.957	0.165
$x_{11}x_{12}$	2.366	0.730	3.242	0.001	0.935	3.796
$x_{11}x_{13}$	-0.629	0.372	-1.693	0.082	-1.358	0.099
$x_{11}y_1$	3.936	3.991	0.986	0.905	-3.887	11.758
$x_{11}y_6$	-1.387	4.041	-0.343	0.617	-9.308	6.534
$x_{12}x_{13}$	0.046	0.044	1.049	0.742	-0.040	0.131
$x_{12}y_1$	0.401	0.490	0.819	0.868	-0.559	1.361

$x_{12}y_6$	-0.397	0.495	-0.803	0.919	-1.368	0.573
$x_{13}y_1$	-0.112	0.225	-0.498	0.864	-0.553	0.329
$x_{13}y_6$	0.162	0.228	0.712	0.972	-0.284	0.608
y_1y_6	7.164	2.277	3.146	3.66E-05	2.700	11.628
x_1^2	4.19E-26	2.00E-26	2.096	0.046	2.72E-27	8.11E-26
x_2^2	-0.338	0.022	-15.050	2.68E-47	-0.382	-0.294
x_3^2	-1.69E-04	1.23E-04	-1.372	0.282	-4.11E-04	7.25E-05
x_4^2	6.96E-05	1.28E-04	0.542	0.924	-1.82E-04	3.21E-04
x_5^2	-0.067	0.018	-3.671	4.87E-04	-0.103	-0.031
x_6^2	-0.004	0.001	-3.551	4.45E-04	-0.007	-0.002
x_7^2	-0.004	0.005	-0.840	0.291	-0.014	0.006
x_8^2	-4.256	2.669	-1.594	0.160	-9.488	0.976
x_9^2	-0.247	0.096	-2.577	0.011	-0.434	-0.059
x_{10}^2	0.003	0.022	0.147	0.961	-0.040	0.046
x_{11}^2	-14.818	2.392	-6.196	3.01E-11	-19.505	-10.130
x_{12}^2	-0.013	0.078	-0.171	0.905	-0.166	0.140
x_{13}^2	-0.012	0.019	-0.625	0.592	-0.048	0.025
y_1^2	-2.320	1.113	-2.085	0.003	-4.501	-0.139
y_6^2	-4.146	1.208	-3.431	6.94E-06	-6.514	-1.777

Table F.7 Target similarity criterion y_6 regression coefficients

Variables	**Coefficients**	**Standard Deviation**	**t Value**	**p Value**	**95% Confidence Interval**	
c	0.324	0.252	1.285	0.421	-0.170	0.819
x_1	2.05E-13	1.33E-13	1.541	0.049	-5.59E-14	4.67E-13
x_2	1.190	0.103	11.599	3.20E-32	0.989	1.391
x_3	-0.002	0.012	-0.130	0.503	-0.025	0.022
x_4	-0.013	0.010	-1.361	0.051	-0.032	0.006
x_5	0.211	0.114	1.860	0.051	-0.011	0.434
x_6	0.044	0.041	1.080	0.248	-0.036	0.125
x_7	-0.027	0.063	-0.418	0.996	-0.151	0.098
x_8	-0.976	1.686	-0.579	0.442	-4.280	2.328
x_9	0.754	0.244	3.083	0.008	0.275	1.233
x_{10}	-0.114	0.125	-0.911	0.622	-0.358	0.131
x_{11}	5.049	1.516	3.331	5.65E-05	2.078	8.020
x_{12}	-0.657	0.222	-2.956	0.050	-1.092	-0.221
x_{13}	0.149	0.111	1.347	0.622	-0.068	0.365
x_1x_2	-3.56E-14	3.29E-14	-1.082	0.209	-1.00E-13	2.89E-14
x_1x_3	-3.29E-15	3.69E-15	-0.893	0.034	-1.05E-14	3.94E-15
x_1x_4	3.25E-15	2.04E-15	1.595	0.114	-7.43E-16	7.24E-15
x_1x_5	-3.47E-14	2.96E-14	-1.173	0.152	-9.27E-14	2.33E-14

x_1x_6	-1.72E-15	1.11E-14	-0.155	0.758	-2.34E-14	2.00E-14
x_1x_7	-2.65E-14	1.23E-14	-2.156	0.051	-5.06E-14	-2.41E-15
x_1x_8	-3.50E-13	5.26E-13	-0.666	0.578	-1.38E-12	6.81E-13
x_1x_9	-4.65E-14	7.66E-14	-0.607	0.824	-1.97E-13	1.04E-13
x_1x_{10}	3.18E-15	4.09E-14	0.078	0.949	-7.69E-14	8.33E-14
x_1x_{11}	-9.30E-13	4.66E-13	-1.996	0.002	-1.84E-12	-1.68E-14
x_1x_{12}	-4.78E-14	6.71E-14	-0.713	0.235	-1.79E-13	8.38E-14
x_1x_{13}	1.08E-14	3.47E-14	0.310	0.079	-5.73E-14	7.89E-14
x_2x_3	0.003	0.003	1.128	0.454	-0.002	0.008
x_2x_4	5.83E-04	0.002	0.289	0.752	-0.003	0.005
x_2x_5	0.001	0.028	0.046	0.730	-0.053	0.056
x_2x_6	0.008	0.010	0.754	0.615	-0.012	0.028
x_2x_7	0.019	0.012	1.589	0.388	-0.004	0.042
x_2x_8	0.106	0.459	0.231	0.405	-0.793	1.005
x_2x_9	-0.044	0.068	-0.646	0.299	-0.176	0.089
x_2x_{10}	0.007	0.034	0.198	0.411	-0.059	0.073
x_2x_{11}	-2.526	0.443	-5.707	2.05E-08	-3.393	-1.658
x_2x_{12}	0.033	0.064	0.509	0.478	-0.093	0.158
x_2x_{13}	-0.043	0.030	-1.444	0.170	-0.102	0.016
x_3x_4	2.53E-05	1.69E-04	0.150	0.524	-3.05E-04	3.56E-04
x_3x_5	0.002	0.003	0.672	0.471	-0.003	0.007
x_3x_6	3.24E-04	9.08E-04	0.357	0.911	-0.001	0.002
x_3x_7	-5.84E-04	0.001	-0.572	0.495	-0.003	0.001
x_3x_8	-0.315	0.068	-4.639	2.19E-05	-0.449	-0.182
x_3x_9	0.004	0.007	0.626	0.605	-0.009	0.017
x_3x_{10}	-0.006	0.003	-1.734	0.047	-0.012	7.28E-04
x_3x_{11}	0.400	0.055	7.329	8.97E-15	0.293	0.507
x_3x_{12}	0.015	0.006	2.783	0.009	0.005	0.026
x_3x_{13}	-0.003	0.003	-0.987	0.082	-0.008	0.003
x_4x_5	-0.010	0.003	-3.013	0.012	-0.017	-0.003
x_4x_6	-7.70E-04	0.001	-0.590	0.832	-0.003	0.002
x_4x_7	0.004	0.001	2.632	0.007	9.85E-04	0.007
x_4x_8	-0.012	0.029	-0.405	0.928	-0.069	0.045
x_4x_9	-0.019	0.005	-4.048	4.48E-04	-0.028	-0.010
x_4x_{10}	0.009	0.002	4.211	1.63E-04	0.005	0.014
x_4x_{11}	0.080	0.025	3.213	8.52E-04	0.031	0.128
x_4x_{12}	-0.001	0.004	-0.349	0.756	-0.009	0.007
x_4x_{13}	0.001	0.002	0.635	0.239	-0.003	0.005
x_5x_6	0.020	0.029	0.698	0.532	-0.036	0.077
x_5x_7	0.014	0.021	0.672	0.524	-0.026	0.054
x_5x_8	0.748	0.441	1.695	0.038	-0.117	1.613
x_5x_9	-0.303	0.065	-4.667	1.31E-05	-0.430	-0.175

x_5x_{10}	0.059	0.032	1.812	0.266	-0.005	0.122
x_5x_{11}	-0.069	0.438	-0.157	0.424	-0.928	0.790
x_5x_{12}	0.015	0.058	0.260	0.611	-0.099	0.130
x_5x_{13}	0.005	0.030	0.158	0.654	-0.054	0.064
x_6x_7	0.004	0.004	0.987	0.392	-0.004	0.013
x_6x_8	-0.181	0.181	-1.004	0.511	-0.536	0.173
x_6x_9	-0.038	0.025	-1.549	0.174	-0.086	0.010
x_6x_{10}	0.004	0.011	0.310	0.827	-0.019	0.026
x_6x_{11}	-0.162	0.185	-0.877	0.105	-0.524	0.200
x_6x_{12}	0.012	0.021	0.570	0.835	-0.029	0.052
x_6x_{13}	-0.007	0.011	-0.598	0.669	-0.029	0.015
x_7x_8	0.004	0.169	0.025	0.609	-0.328	0.336
x_7x_9	-0.005	0.027	-0.202	0.997	-0.058	0.047
x_7x_{10}	-0.003	0.014	-0.201	0.522	-0.030	0.024
x_7x_{11}	-0.114	0.151	-0.754	0.343	-0.410	0.182
x_7x_{12}	0.012	0.024	0.497	0.473	-0.035	0.059
x_7x_{13}	0.009	0.012	0.795	0.606	-0.014	0.032
x_8x_9	5.516	1.428	3.863	1.90E-05	2.717	8.315
x_8x_{10}	-1.874	0.703	-2.663	0.010	-3.252	-0.495
x_8x_{11}	-7.312	5.035	-1.452	0.071	-17.181	2.557
x_8x_{12}	-2.775	1.052	-2.637	0.001	-4.838	-0.712
x_8x_{13}	1.778	0.474	3.748	2.74E-04	0.848	2.707
x_9x_{10}	-0.135	0.096	-1.407	0.186	-0.324	0.053
x_9x_{11}	-3.133	0.974	-3.217	2.13E-04	-5.041	-1.224
x_9x_{12}	-0.054	0.144	-0.372	0.102	-0.336	0.229
x_9x_{13}	-0.165	0.068	-2.412	0.016	-0.299	-0.031
$x_{10}x_{11}$	1.135	0.508	2.236	0.066	0.140	2.130
$x_{10}x_{12}$	0.171	0.071	2.412	0.009	0.032	0.311
$x_{10}x_{13}$	-0.054	0.034	-1.584	0.209	-0.121	0.013
$x_{11}x_{12}$	9.751	1.092	8.933	1.69E-20	7.612	11.891
$x_{11}x_{13}$	-4.022	0.559	-7.197	1.39E-16	-5.117	-2.926
$x_{12}x_{13}$	-0.043	0.066	-0.654	0.252	-0.172	0.086
x_1^2	-2.03E-26	3.10E-26	-0.654	0.331	-8.10E-26	4.05E-26
x_2^2	-0.671	0.027	-24.802	2.80E-124	-0.724	-0.618
x_3^2	1.04E-04	1.91E-04	0.545	0.973	-2.71E-04	4.79E-04
x_4^2	-1.48E-04	2.00E-04	-0.742	0.531	-5.40E-04	2.43E-04
x_5^2	-0.002	0.029	-0.068	0.934	-0.058	0.054
x_6^2	-0.001	0.002	-0.708	0.631	-0.005	0.002
x_7^2	-0.008	0.008	-1.031	0.156	-0.024	0.007
x_8^2	9.349	4.145	2.256	0.029	1.226	17.472
x_9^2	0.103	0.142	0.724	0.109	-0.175	0.381
x_{10}^2	0.053	0.034	1.562	0.205	-0.014	0.120

x_{11}^2	-6.971	3.476	-2.006	0.405	-13.784	-0.159
x_{12}^2	0.200	0.120	1.666	0.060	-0.035	0.435
x_{13}^2	0.016	0.029	0.577	0.087	-0.040	0.073

Table F.8 Target similarity criterion y_7 regression coefficients

Variables	**Coefficients**	**Standard Deviation**	**t Value**	**p Value**	**95% Confidence Interval**	
c	0.058	0.090	0.643	0.526	-0.118	0.233
x_1	-9.10E-14	4.52E-14	-2.014	0.030	-1.80E-13	-2.44E-15
x_2	0.140	0.041	3.391	1.53E-04	0.059	0.222
x_3	0.002	0.004	0.465	0.771	-0.006	0.010
x_4	0.004	0.003	1.185	0.152	-0.003	0.010
x_5	-0.011	0.039	-0.292	0.520	-0.087	0.064
x_6	0.005	0.014	0.386	0.204	-0.022	0.033
x_7	-0.038	0.021	-1.782	0.091	-0.080	0.004
x_8	0.375	0.582	0.644	0.874	-0.766	1.516
x_9	-0.005	0.085	-0.057	0.410	-0.172	0.162
x_{10}	-0.058	0.044	-1.304	0.875	-0.144	0.029
x_{11}	1.294	0.556	2.328	0.025	0.204	2.384
x_{12}	0.017	0.078	0.213	0.716	-0.136	0.169
x_{13}	-0.010	0.038	-0.265	0.711	-0.085	0.065
y_1	0.318	0.432	0.735	0.983	-0.529	1.165
y_6	-0.106	0.431	-0.246	0.672	-0.951	0.739
x_1x_2	8.79E-15	1.28E-14	0.688	0.980	-1.62E-14	3.38E-14
x_1x_3	2.06E-15	1.23E-15	1.677	0.013	-3.47E-16	4.47E-15
x_1x_4	-4.19E-17	6.84E-16	-0.061	0.758	-1.38E-15	1.30E-15
x_1x_5	5.78E-15	9.91E-15	0.583	0.958	-1.36E-14	2.52E-14
x_1x_6	1.54E-15	3.75E-15	0.411	0.853	-5.81E-15	8.90E-15
x_1x_7	2.44E-15	4.06E-15	0.600	0.494	-5.53E-15	1.04E-14
x_1x_8	1.26E-13	1.76E-13	0.716	0.178	-2.19E-13	4.72E-13
x_1x_9	1.70E-14	2.65E-14	0.641	0.224	-3.49E-14	6.88E-14
x_1x_{10}	-1.02E-14	1.36E-14	-0.746	0.285	-3.68E-14	1.65E-14
x_1x_{11}	2.53E-13	1.60E-13	1.582	0.079	-6.03E-14	5.65E-13
x_1x_{12}	9.95E-15	2.30E-14	0.433	0.700	-3.51E-14	5.50E-14
x_1x_{13}	-8.39E-15	1.18E-14	-0.712	0.242	-3.15E-14	1.47E-14
x_1y_1	-2.26E-14	1.31E-13	-0.173	0.585	-2.79E-13	2.34E-13
x_1y_6	2.20E-14	1.32E-13	0.167	0.616	-2.36E-13	2.80E-13
x_2x_3	6.62E-04	9.85E-04	0.673	0.559	-0.001	0.003
x_2x_4	5.23E-04	8.00E-04	0.654	0.582	-0.001	0.002
x_2x_5	-0.014	0.011	-1.263	0.126	-0.035	0.008
x_2x_6	-0.006	0.004	-1.399	0.204	-0.013	0.002

x_2x_7	0.004	0.005	0.846	0.272	-0.005	0.013
x_2x_8	0.179	0.176	1.017	0.308	-0.166	0.525
x_2x_9	0.028	0.027	1.047	0.582	-0.024	0.081
x_2x_{10}	-0.044	0.013	-3.314	0.001	-0.070	-0.018
x_2x_{11}	-0.365	0.181	-2.013	0.106	-0.719	-0.010
x_2x_{12}	-0.020	0.025	-0.787	0.438	-0.069	0.029
x_2x_{13}	0.014	0.012	1.148	0.844	-0.010	0.038
x_2y_1	-0.156	0.181	-0.866	0.255	-0.511	0.198
x_2y_6	0.232	0.180	1.293	0.111	-0.120	0.585
x_3x_4	-1.27E-04	5.75E-05	-2.207	0.033	-2.39E-04	-1.42E-05
x_3x_5	0.001	8.42E-04	1.234	0.053	-6.12E-04	0.003
x_3x_6	-1.72E-04	3.03E-04	-0.565	0.841	-7.66E-04	4.23E-04
x_3x_7	-9.93E-05	3.39E-04	-0.293	0.424	-7.64E-04	5.65E-04
x_3x_8	-0.004	0.023	-0.159	0.915	-0.049	0.041
x_3x_9	-0.002	0.002	-0.730	0.867	-0.006	0.003
x_3x_{10}	3.02E-04	0.001	0.280	0.689	-0.002	0.002
x_3x_{11}	0.016	0.020	0.838	0.852	-0.022	0.055
x_3x_{12}	2.17E-04	0.002	0.117	0.601	-0.003	0.004
x_3x_{13}	1.10E-04	8.80E-04	0.125	0.241	-0.002	0.002
x_3y_1	-0.013	0.011	-1.159	0.611	-0.035	0.009
x_3y_6	0.011	0.011	1.019	0.674	-0.010	0.033
x_4x_5	0.004	0.001	3.848	0.021	0.002	0.006
x_4x_6	6.45E-04	4.34E-04	1.485	0.597	-2.07E-04	0.001
x_4x_7	0.002	4.88E-04	3.374	0.003	6.90E-04	0.003
x_4x_8	0.004	0.010	0.391	0.736	-0.015	0.023
x_4x_9	-0.006	0.002	-3.849	1.95E-04	-0.009	-0.003
x_4x_{10}	0.002	7.61E-04	2.051	0.023	6.95E-05	0.003
x_4x_{11}	-0.010	0.009	-1.206	0.314	-0.027	0.006
x_4x_{12}	-0.004	0.001	-2.912	0.005	-0.007	-0.001
x_4x_{13}	6.39E-05	6.63E-04	0.096	0.977	-0.001	0.001
x_4y_1	-0.023	0.009	-2.478	0.046	-0.041	-0.005
x_4y_6	0.020	0.009	2.222	0.082	0.002	0.038
x_5x_6	-0.062	0.010	-6.498	1.44E-07	-0.081	-0.044
x_5x_7	0.016	0.007	2.341	0.050	0.003	0.029
x_5x_8	-0.011	0.150	-0.076	0.617	-0.304	0.282
x_5x_9	-0.042	0.023	-1.878	0.201	-0.087	0.002
x_5x_{10}	0.008	0.011	0.698	0.650	-0.014	0.029
x_5x_{11}	-0.073	0.152	-0.479	0.844	-0.372	0.226
x_5x_{12}	-0.016	0.020	-0.812	0.422	-0.055	0.023
x_5x_{13}	-0.002	0.010	-0.169	0.499	-0.022	0.018
x_5y_1	-0.045	0.105	-0.426	0.956	-0.250	0.161
x_5y_6	0.030	0.106	0.283	0.983	-0.178	0.238

x_6x_7	0.002	0.001	1.492	0.172	-6.88E-04	0.005
x_6x_8	-0.024	0.061	-0.386	0.815	-0.144	0.097
x_6x_9	-0.009	0.008	-1.056	0.492	-0.025	0.008
x_6x_{10}	7.64E-04	0.004	0.200	0.266	-0.007	0.008
x_6x_{11}	-0.149	0.065	-2.305	0.030	-0.275	-0.022
x_6x_{12}	-0.003	0.007	-0.452	0.420	-0.017	0.010
x_6x_{13}	0.002	0.004	0.441	0.888	-0.006	0.009
x_6y_1	0.029	0.035	0.835	0.758	-0.040	0.098
x_6y_6	-0.021	0.036	-0.571	0.951	-0.091	0.050
x_7x_8	0.041	0.057	0.734	0.850	-0.069	0.152
x_7x_9	0.010	0.009	1.036	0.201	-0.008	0.027
x_7x_{10}	0.001	0.005	0.285	0.696	-0.008	0.010
x_7x_{11}	-0.006	0.053	-0.107	0.700	-0.109	0.097
x_7x_{12}	-0.016	0.008	-2.023	0.417	-0.032	-5.12E-04
x_7x_{13}	9.79E-04	0.004	0.250	0.576	-0.007	0.009
x_7y_1	-0.077	0.050	-1.551	0.111	-0.175	0.020
x_7y_6	0.052	0.050	1.054	0.253	-0.045	0.150
x_8x_9	-0.905	0.498	-1.818	0.184	-1.882	0.071
x_8x_{10}	0.325	0.237	1.372	0.541	-0.139	0.790
x_8x_{11}	1.627	1.747	0.932	0.459	-1.796	5.051
x_8x_{12}	0.297	0.355	0.837	0.530	-0.398	0.992
x_8x_{13}	-0.109	0.160	-0.681	0.723	-0.423	0.205
x_8y_1	-1.943	2.035	-0.954	0.916	-5.932	2.047
x_8y_6	1.623	2.075	0.782	0.842	-2.443	5.689
x_9x_{10}	0.096	0.034	2.858	0.007	0.030	0.162
x_9x_{11}	-0.433	0.350	-1.239	0.244	-1.119	0.252
x_9x_{12}	0.002	0.050	0.032	0.807	-0.097	0.100
x_9x_{13}	-0.028	0.024	-1.186	0.354	-0.075	0.019
x_9y_1	-1.015	0.296	-3.432	1.23E-04	-1.594	-0.435
x_9y_6	1.289	0.299	4.305	2.03E-06	0.702	1.876
$x_{10}x_{11}$	0.117	0.177	0.662	0.461	-0.230	0.464
$x_{10}x_{12}$	0.021	0.024	0.891	0.606	-0.026	0.068
$x_{10}x_{13}$	0.020	0.012	1.720	0.198	-0.003	0.042
$x_{10}y_1$	-0.017	0.145	-0.117	0.767	-0.301	0.267
$x_{10}y_6$	-0.013	0.148	-0.089	0.974	-0.303	0.277
$x_{11}x_{12}$	0.241	0.377	0.639	0.606	-0.499	0.981
$x_{11}x_{13}$	-0.216	0.192	-1.122	0.837	-0.593	0.161
$x_{11}y_1$	-1.323	2.064	-0.641	0.261	-5.369	2.723
$x_{11}y_6$	1.594	2.090	0.762	0.223	-2.503	5.691
$x_{12}x_{13}$	0.042	0.023	1.858	0.048	-0.002	0.086
$x_{12}y_1$	0.258	0.253	1.020	0.895	-0.238	0.755
$x_{12}y_6$	-0.251	0.256	-0.980	0.909	-0.753	0.251

$x_{13}y_1$	-0.046	0.116	-0.395	0.565	-0.274	0.182
$x_{13}y_6$	0.081	0.118	0.685	0.737	-0.150	0.311
y_1y_6	10.397	1.178	8.826	5.41E-21	8.088	12.705
x_1^2	1.99E-26	1.03E-26	1.920	0.082	-4.18E-28	4.01E-26
x_2^2	-0.098	0.012	-8.402	6.61E-18	-0.120	-0.075
x_3^2	-1.86E-05	6.38E-05	-0.292	0.862	-1.44E-04	1.06E-04
x_4^2	-1.02E-04	6.64E-05	-1.533	0.126	-2.32E-04	2.84E-05
x_5^2	-0.029	0.009	-3.037	0.002	-0.047	-0.010
x_6^2	-0.002	6.42E-04	-2.852	0.017	-0.003	-5.73E-04
x_7^2	9.48E-04	0.003	0.355	0.645	-0.004	0.006
x_8^2	-3.160	1.381	-2.289	0.161	-5.866	-0.454
x_9^2	-0.104	0.049	-2.111	0.012	-0.201	-0.007
x_{10}^2	-0.005	0.011	-0.447	0.726	-0.027	0.017
x_{11}^2	-4.090	1.237	-3.306	3.87E-05	-6.514	-1.665
x_{12}^2	-0.026	0.040	-0.650	0.407	-0.105	0.053
x_{13}^2	-0.014	0.010	-1.439	0.223	-0.033	0.005
y_1^2	-4.523	0.576	-7.857	2.60E-17	-5.651	-3.395
y_6^2	-5.253	0.625	-8.405	2.63E-19	-6.478	-4.028

Table F.9 Target similarity criterion y_8 regression coefficients

Variables	**Coefficients**	**Standard Deviation**	**t Value**	**p Value**	**95% Confidence Interval**	
c	0.057	0.138	0.411	0.877	-0.214	0.328
x_1	-1.06E-13	6.97E-14	-1.516	0.101	-2.42E-13	3.09E-14
x_2	0.329	0.064	5.150	3.73E-07	0.204	0.454
x_3	0.006	0.006	0.960	0.684	-0.006	0.018
x_4	0.005	0.005	0.955	0.083	-0.005	0.015
x_5	-0.054	0.059	-0.902	0.859	-0.170	0.063
x_6	-0.021	0.021	-1.000	0.643	-0.063	0.021
x_7	-0.026	0.033	-0.784	0.439	-0.091	0.039
x_8	0.542	0.898	0.603	0.902	-1.218	2.302
x_9	0.114	0.131	0.871	0.714	-0.143	0.372
x_{10}	-0.064	0.068	-0.945	0.808	-0.198	0.069
x_{11}	1.726	0.857	2.013	0.023	0.045	3.406
x_{12}	-0.073	0.120	-0.605	0.720	-0.308	0.163
x_{13}	0.009	0.059	0.145	0.843	-0.107	0.124
y_1	-0.203	0.666	-0.305	0.454	-1.509	1.103
y_6	-0.016	0.665	-0.024	0.656	-1.319	1.287
x_1x_2	1.78E-14	1.97E-14	0.902	0.486	-2.08E-14	5.64E-14
x_1x_3	1.62E-15	1.89E-15	0.853	0.142	-2.10E-15	5.33E-15
x_1x_4	-5.75E-16	1.05E-15	-0.545	0.594	-2.64E-15	1.49E-15

x_1x_5	7.64E-15	1.53E-14	0.500	0.744	-2.23E-14	3.76E-14
x_1x_6	1.74E-15	5.79E-15	0.301	0.822	-9.60E-15	1.31E-14
x_1x_7	3.68E-15	6.27E-15	0.587	0.595	-8.60E-15	1.60E-14
x_1x_8	2.30E-14	2.72E-13	0.085	0.529	-5.10E-13	5.56E-13
x_1x_9	-1.77E-15	4.08E-14	-0.043	0.818	-8.18E-14	7.82E-14
x_1x_{10}	-2.13E-14	2.10E-14	-1.013	0.229	-6.24E-14	1.99E-14
x_1x_{11}	3.92E-13	2.46E-13	1.594	0.155	-9.01E-14	8.75E-13
x_1x_{12}	2.78E-14	3.54E-14	0.785	0.583	-4.16E-14	9.72E-14
x_1x_{13}	-1.75E-14	1.82E-14	-0.961	0.301	-5.31E-14	1.82E-14
x_1y_1	-7.04E-14	2.02E-13	-0.349	0.836	-4.65E-13	3.25E-13
x_1y_6	8.24E-14	2.03E-13	0.406	0.924	-3.15E-13	4.80E-13
x_2x_3	-6.14E-04	0.002	-0.404	0.854	-0.004	0.002
x_2x_4	-9.66E-04	0.001	-0.784	0.656	-0.003	0.001
x_2x_5	-0.032	0.017	-1.899	0.039	-0.064	0.001
x_2x_6	-0.004	0.006	-0.694	0.563	-0.016	0.008
x_2x_7	0.006	0.007	0.777	0.240	-0.008	0.020
x_2x_8	-0.170	0.272	-0.626	0.485	-0.703	0.363
x_2x_9	0.049	0.041	1.189	0.312	-0.032	0.130
x_2x_{10}	-0.062	0.020	-3.030	0.004	-0.102	-0.022
x_2x_{11}	-0.578	0.279	-2.070	0.169	-1.125	-0.031
x_2x_{12}	-0.055	0.039	-1.418	0.163	-0.130	0.021
x_2x_{13}	0.023	0.019	1.247	0.979	-0.013	0.060
x_2y_1	-0.159	0.279	-0.570	0.478	-0.705	0.387
x_2y_6	0.383	0.277	1.383	0.132	-0.160	0.926
x_3x_4	-1.67E-04	8.86E-05	-1.888	0.082	-3.41E-04	6.35E-06
x_3x_5	0.003	0.001	2.028	0.006	8.77E-05	0.005
x_3x_6	7.75E-05	4.68E-04	0.166	0.563	-8.40E-04	9.95E-04
x_3x_7	-3.17E-04	5.23E-04	-0.606	0.184	-0.001	7.08E-04
x_3x_8	-0.025	0.035	-0.694	0.343	-0.094	0.045
x_3x_9	-0.003	0.004	-0.852	0.730	-0.010	0.004
x_3x_{10}	1.75E-04	0.002	0.105	0.627	-0.003	0.003
x_3x_{11}	0.055	0.030	1.840	0.208	-0.004	0.115
x_3x_{12}	0.001	0.003	0.392	0.845	-0.005	0.007
x_3x_{13}	-3.57E-04	0.001	-0.263	0.487	-0.003	0.002
x_3y_1	-0.007	0.017	-0.434	0.864	-0.041	0.026
x_3y_6	0.006	0.017	0.321	0.776	-0.028	0.039
x_4x_5	0.007	0.002	3.972	0.005	0.003	0.010
x_4x_6	0.002	6.70E-04	2.722	0.027	5.10E-04	0.003
x_4x_7	0.002	7.53E-04	2.853	0.006	6.72E-04	0.004
x_4x_8	0.012	0.015	0.814	0.289	-0.017	0.042
x_4x_9	-0.011	0.002	-4.293	2.36E-05	-0.016	-0.006
x_4x_{10}	0.002	0.001	1.992	0.089	3.80E-05	0.005

x_4x_{11}	-0.020	0.013	-1.540	0.315	-0.046	0.006
x_4x_{12}	-0.003	0.002	-1.430	0.147	-0.007	0.001
x_4x_{13}	-6.08E-04	0.001	-0.595	0.462	-0.003	0.001
x_4y_1	-0.016	0.014	-1.101	0.386	-0.043	0.012
x_4y_6	0.012	0.014	0.851	0.591	-0.016	0.040
x_5x_6	-0.084	0.015	-5.700	2.32E-06	-0.113	-0.055
x_5x_7	0.020	0.011	1.919	0.099	-4.28E-04	0.041
x_5x_8	0.219	0.231	0.949	0.065	-0.233	0.671
x_5x_9	-0.088	0.035	-2.531	0.051	-0.156	-0.020
x_5x_{10}	0.004	0.017	0.255	0.458	-0.029	0.037
x_5x_{11}	-0.118	0.235	-0.504	0.672	-0.579	0.342
x_5x_{12}	-0.040	0.030	-1.333	0.241	-0.100	0.019
x_5x_{13}	-0.007	0.016	-0.420	0.462	-0.037	0.024
x_5y_1	-0.162	0.162	-0.999	0.349	-0.478	0.155
x_5y_6	0.187	0.164	1.144	0.253	-0.133	0.508
x_6x_7	0.003	0.002	1.159	0.226	-0.002	0.007
x_6x_8	0.050	0.095	0.524	0.243	-0.136	0.235
x_6x_9	-0.009	0.013	-0.655	0.640	-0.034	0.017
x_6x_{10}	-0.002	0.006	-0.401	0.172	-0.014	0.009
x_6x_{11}	-0.192	0.099	-1.927	0.050	-0.387	0.003
x_6x_{12}	-0.010	0.011	-0.932	0.334	-0.031	0.011
x_6x_{13}	0.005	0.006	0.925	0.423	-0.006	0.017
x_6y_1	-0.018	0.054	-0.341	0.459	-0.125	0.088
x_6y_6	0.033	0.055	0.589	0.315	-0.076	0.141
x_7x_8	0.018	0.087	0.211	0.992	-0.152	0.189
x_7x_9	0.006	0.014	0.458	0.450	-0.021	0.034
x_7x_{10}	0.005	0.007	0.701	0.611	-0.009	0.019
x_7x_{11}	-0.029	0.081	-0.363	0.410	-0.188	0.130
x_7x_{12}	-0.018	0.012	-1.421	0.508	-0.042	0.007
x_7x_{13}	-8.11E-04	0.006	-0.134	0.655	-0.013	0.011
x_7y_1	-0.065	0.077	-0.843	0.131	-0.215	0.086
x_7y_6	0.030	0.077	0.397	0.271	-0.120	0.180
x_8x_9	-0.622	0.768	-0.810	0.751	-2.127	0.883
x_8x_{10}	0.336	0.365	0.919	0.513	-0.380	1.052
x_8x_{11}	3.194	2.693	1.186	0.232	-2.084	8.473
x_8x_{12}	-0.006	0.547	-0.011	0.877	-1.078	1.066
x_8x_{13}	-0.208	0.247	-0.843	0.651	-0.692	0.276
x_8y_1	0.928	3.138	0.296	0.224	-5.223	7.079
x_8y_6	-1.220	3.199	-0.382	0.193	-7.490	5.049
x_9x_{10}	0.108	0.052	2.090	0.069	0.007	0.210
x_9x_{11}	-0.585	0.539	-1.086	0.301	-1.642	0.471
x_9x_{12}	-0.060	0.078	-0.776	0.553	-0.213	0.092

x_9x_{13}	-0.070	0.037	-1.908	0.106	-0.143	0.002
x_9y_1	-1.008	0.456	-2.213	0.015	-1.902	-0.115
x_9y_6	1.415	0.462	3.064	0.001	0.510	2.319
$x_{10}x_{11}$	0.219	0.273	0.801	0.639	-0.316	0.754
$x_{10}x_{12}$	0.046	0.037	1.240	0.481	-0.027	0.118
$x_{10}x_{13}$	0.027	0.018	1.545	0.149	-0.007	0.062
$x_{10}y_1$	0.194	0.223	0.867	0.733	-0.244	0.631
$x_{10}y_6$	-0.233	0.228	-1.021	0.581	-0.681	0.214
$x_{11}x_{12}$	1.055	0.582	1.813	0.116	-0.086	2.196
$x_{11}x_{13}$	-0.328	0.297	-1.108	0.586	-0.910	0.253
$x_{11}y_1$	-0.332	3.183	-0.104	0.409	-6.570	5.907
$x_{11}y_6$	1.406	3.223	0.436	0.277	-4.911	7.723
$x_{12}x_{13}$	0.064	0.035	1.824	0.055	-0.005	0.132
$x_{12}y_1$	0.263	0.391	0.673	0.966	-0.503	1.028
$x_{12}y_6$	-0.234	0.395	-0.593	0.910	-1.008	0.540
$x_{13}y_1$	-0.062	0.179	-0.344	0.630	-0.413	0.290
$x_{13}y_6$	0.119	0.182	0.656	0.869	-0.237	0.475
y_1y_6	11.144	1.816	6.136	4.35E-13	7.584	14.703
x_1^2	3.36E-26	1.60E-26	2.109	0.035	2.38E-27	6.49E-26
x_2^2	-0.223	0.018	-12.447	5.11E-35	-0.258	-0.188
x_3^2	-7.94E-05	9.84E-05	-0.807	0.745	-2.72E-04	1.13E-04
x_4^2	-1.37E-04	1.02E-04	-1.336	0.051	-3.37E-04	6.39E-05
x_5^2	-0.045	0.015	-3.045	0.002	-0.073	-0.016
x_6^2	-0.003	9.90E-04	-2.745	0.006	-0.005	-7.77E-04
x_7^2	-0.004	0.004	-0.854	0.499	-0.012	0.005
x_8^2	-3.592	2.129	-1.687	0.152	-7.765	0.580
x_9^2	-0.124	0.076	-1.624	0.039	-0.273	0.026
x_{10}^2	-0.009	0.018	-0.488	0.606	-0.043	0.026
x_{11}^2	-8.320	1.907	-4.362	8.25E-07	-12.058	-4.582
x_{12}^2	-7.54E-04	0.062	-0.012	0.817	-0.123	0.121
x_{13}^2	-0.017	0.015	-1.144	0.258	-0.046	0.012
y_1^2	-4.773	0.888	-5.378	1.51E-10	-6.512	-3.033
y_6^2	-5.632	0.964	-5.844	2.38E-12	-7.521	-3.743

Table F.10 Target similarity criterion y_9 regression coefficients

Variables	Coefficients	Standard Deviation	t Value	p Value	95% Confidence Interval	
c	0.055	0.162	0.338	0.946	-0.262	0.371
x_1	-9.72E-14	8.15E-14	-1.193	0.198	-2.57E-13	6.25E-14
x_2	0.484	0.075	6.484	1.23E-09	0.338	0.631
x_3	0.009	0.007	1.197	0.514	-0.006	0.023

x_4	0.002	0.006	0.336	0.184	-0.010	0.013
x_5	-0.074	0.070	-1.064	0.747	-0.210	0.062
x_6	-0.043	0.025	-1.726	0.137	-0.092	0.006
x_7	-3.51E-04	0.039	-0.009	0.799	-0.076	0.075
x_8	0.480	1.050	0.457	0.808	-1.578	2.539
x_9	0.187	0.154	1.218	0.393	-0.114	0.488
x_{10}	-0.046	0.080	-0.582	0.614	-0.202	0.110
x_{11}	1.815	1.003	1.809	0.019	-0.151	3.781
x_{12}	-0.070	0.140	-0.501	0.969	-0.345	0.205
x_{13}	-0.011	0.069	-0.165	0.599	-0.146	0.124
y_1	-0.691	0.779	-0.886	0.243	-2.218	0.837
y_6	0.257	0.778	0.331	0.519	-1.267	1.781
x_1x_2	1.51E-14	2.30E-14	0.654	0.591	-3.01E-14	6.02E-14
x_1x_3	1.43E-15	2.22E-15	0.647	0.181	-2.91E-15	5.78E-15
x_1x_4	-1.06E-15	1.23E-15	-0.862	0.415	-3.48E-15	1.35E-15
x_1x_5	1.64E-14	1.79E-14	0.915	0.953	-1.87E-14	5.14E-14
x_1x_6	4.30E-15	6.77E-15	0.636	0.931	-8.96E-15	1.76E-14
x_1x_7	1.48E-15	7.33E-15	0.201	0.743	-1.29E-14	1.58E-14
x_1x_8	9.83E-14	3.18E-13	0.309	0.400	-5.25E-13	7.22E-13
x_1x_9	1.53E-14	4.77E-14	0.319	0.657	-7.83E-14	1.09E-13
x_1x_{10}	-4.04E-14	2.45E-14	-1.644	0.077	-8.85E-14	7.75E-15
x_1x_{11}	4.71E-13	2.88E-13	1.636	0.182	-9.33E-14	1.04E-12
x_1x_{12}	2.78E-14	4.14E-14	0.670	0.711	-5.34E-14	1.09E-13
x_1x_{13}	-1.34E-14	2.13E-14	-0.632	0.407	-5.51E-14	2.82E-14
x_1y_1	-2.73E-14	2.36E-13	-0.116	0.645	-4.89E-13	4.35E-13
x_1y_6	4.59E-14	2.37E-13	0.193	0.752	-4.19E-13	5.11E-13
x_2x_3	-0.001	0.002	-0.811	0.504	-0.005	0.002
x_2x_4	-0.004	0.001	-2.532	0.081	-0.006	-8.25E-04
x_2x_5	-0.034	0.019	-1.748	0.064	-0.072	0.004
x_2x_6	0.004	0.007	0.500	0.574	-0.010	0.018
x_2x_7	0.003	0.008	0.332	0.306	-0.014	0.019
x_2x_8	-0.521	0.318	-1.639	0.089	-1.144	0.102
x_2x_9	0.085	0.048	1.747	0.093	-0.010	0.179
x_2x_{10}	-0.063	0.024	-2.626	0.023	-0.110	-0.016
x_2x_{11}	-0.228	0.327	-0.697	0.940	-0.868	0.412
x_2x_{12}	-0.088	0.045	-1.941	0.054	-0.176	8.35E-04
x_2x_{13}	0.015	0.022	0.660	0.657	-0.029	0.058
x_2y_1	0.007	0.326	0.023	0.977	-0.631	0.646
x_2y_6	0.305	0.324	0.942	0.339	-0.330	0.941
x_3x_4	-1.40E-04	1.04E-04	-1.354	0.210	-3.44E-04	6.28E-05
x_3x_5	0.003	0.002	2.043	0.010	1.26E-04	0.006
x_3x_6	-4.49E-05	5.47E-04	-0.082	0.769	-0.001	0.001

x_3x_7	-3.84E-04	6.12E-04	-0.629	0.213	-0.002	8.14E-04
x_3x_8	-0.040	0.041	-0.964	0.229	-0.121	0.041
x_3x_9	-0.002	0.004	-0.510	0.953	-0.010	0.006
x_3x_{10}	-3.66E-04	0.002	-0.188	0.439	-0.004	0.003
x_3x_{11}	0.063	0.035	1.794	0.317	-0.006	0.132
x_3x_{12}	-0.001	0.003	-0.298	0.403	-0.008	0.006
x_3x_{13}	6.50E-04	0.002	0.410	0.214	-0.002	0.004
x_3y_1	0.001	0.020	0.058	0.568	-0.038	0.040
x_3y_6	-0.003	0.020	-0.161	0.501	-0.043	0.036
x_4x_5	0.008	0.002	4.024	0.004	0.004	0.012
x_4x_6	0.003	7.83E-04	3.621	5.64E-04	0.001	0.004
x_4x_7	0.002	8.80E-04	2.187	0.070	2.00E-04	0.004
x_4x_8	0.020	0.018	1.167	0.137	-0.014	0.055
x_4x_9	-0.013	0.003	-4.468	8.50E-06	-0.019	-0.007
x_4x_{10}	0.003	0.001	1.994	0.113	4.64E-05	0.005
x_4x_{11}	-0.026	0.015	-1.659	0.247	-0.056	0.005
x_4x_{12}	-0.003	0.003	-1.015	0.197	-0.007	0.002
x_4x_{13}	-9.00E-04	0.001	-0.753	0.418	-0.003	0.001
x_4y_1	-0.015	0.016	-0.883	0.387	-0.047	0.018
x_4y_6	0.012	0.017	0.725	0.552	-0.020	0.044
x_5x_6	-0.094	0.017	-5.441	1.04E-05	-0.128	-0.060
x_5x_7	0.016	0.012	1.273	0.515	-0.008	0.040
x_5x_8	0.313	0.270	1.162	0.059	-0.215	0.842
x_5x_9	-0.156	0.041	-3.841	4.23E-04	-0.236	-0.077
x_5x_{10}	0.014	0.020	0.695	0.933	-0.025	0.052
x_5x_{11}	0.041	0.275	0.148	0.925	-0.498	0.579
x_5x_{12}	-0.033	0.036	-0.941	0.479	-0.103	0.036
x_5x_{13}	-0.022	0.018	-1.209	0.147	-0.058	0.014
x_5y_1	-0.234	0.189	-1.239	0.137	-0.605	0.136
x_5y_6	0.285	0.191	1.491	0.070	-0.090	0.660
x_6x_7	0.002	0.003	0.714	0.526	-0.003	0.007
x_6x_8	0.035	0.111	0.320	0.411	-0.182	0.253
x_6x_9	-0.016	0.015	-1.042	0.314	-0.046	0.014
x_6x_{10}	-7.34E-04	0.007	-0.107	0.487	-0.014	0.013
x_6x_{11}	-0.139	0.116	-1.196	0.218	-0.367	0.089
x_6x_{12}	-0.008	0.012	-0.641	0.682	-0.032	0.016
x_6x_{13}	0.005	0.007	0.720	0.522	-0.008	0.018
x_6y_1	-0.019	0.063	-0.299	0.427	-0.143	0.105
x_6y_6	0.033	0.065	0.513	0.302	-0.094	0.160
x_7x_8	-0.026	0.102	-0.255	0.709	-0.226	0.174
x_7x_9	-0.003	0.017	-0.174	0.940	-0.035	0.030
x_7x_{10}	0.009	0.008	1.140	0.450	-0.007	0.025

x_7x_{11}	-0.051	0.095	-0.536	0.351	-0.237	0.135
x_7x_{12}	-0.016	0.015	-1.119	0.577	-0.045	0.012
x_7x_{13}	-0.002	0.007	-0.226	0.542	-0.015	0.012
x_7y_1	-0.059	0.090	-0.656	0.120	-0.235	0.117
x_7y_6	0.026	0.090	0.294	0.233	-0.149	0.202
x_8x_9	0.286	0.898	0.318	0.458	-1.475	2.046
x_8x_{10}	0.039	0.427	0.092	0.989	-0.798	0.877
x_8x_{11}	2.286	3.150	0.726	0.468	-3.889	8.460
x_8x_{12}	-0.848	0.640	-1.326	0.276	-2.102	0.406
x_8x_{13}	0.087	0.289	0.301	0.496	-0.479	0.653
x_8y_1	2.398	3.671	0.653	0.119	-4.797	9.593
x_8y_6	-2.760	3.742	-0.738	0.098	-10.094	4.573
x_9x_{10}	0.062	0.061	1.028	0.452	-0.057	0.181
x_9x_{11}	-0.758	0.631	-1.201	0.211	-1.994	0.479
x_9x_{12}	-0.144	0.091	-1.588	0.109	-0.323	0.034
x_9x_{13}	-0.061	0.043	-1.412	0.278	-0.145	0.024
x_9y_1	-0.528	0.533	-0.990	0.303	-1.572	0.517
x_9y_6	0.952	0.540	1.762	0.073	-0.107	2.010
$x_{10}x_{11}$	0.391	0.320	1.224	0.407	-0.235	1.018
$x_{10}x_{12}$	0.070	0.043	1.630	0.329	-0.014	0.155
$x_{10}x_{13}$	0.024	0.021	1.167	0.190	-0.016	0.065
$x_{10}y_1$	0.210	0.261	0.804	0.844	-0.302	0.722
$x_{10}y_6$	-0.249	0.267	-0.932	0.709	-0.772	0.275
$x_{11}x_{12}$	1.645	0.681	2.417	0.036	0.311	2.980
$x_{11}x_{13}$	-0.420	0.347	-1.212	0.363	-1.100	0.260
$x_{11}y_1$	2.373	3.723	0.637	0.823	-4.924	9.671
$x_{11}y_6$	-0.512	3.770	-0.136	0.514	-7.900	6.877
$x_{12}x_{13}$	0.071	0.041	1.733	0.098	-0.009	0.150
$x_{12}y_1$	0.159	0.457	0.348	0.716	-0.737	1.055
$x_{12}y_6$	-0.129	0.462	-0.278	0.667	-1.034	0.777
$x_{13}y_1$	-0.146	0.210	-0.697	0.887	-0.557	0.265
$x_{13}y_6$	0.216	0.212	1.018	0.833	-0.200	0.632
y_1y_6	9.835	2.124	4.629	5.02E-09	5.671	13.999
x_1^2	3.47E-26	1.87E-26	1.857	0.073	-1.92E-27	7.12E-26
x_2^2	-0.303	0.021	-14.484	3.20E-45	-0.344	-0.262
x_3^2	-1.42E-04	1.15E-04	-1.232	0.515	-3.67E-04	8.38E-05
x_4^2	-8.45E-05	1.20E-04	-0.706	0.136	-3.19E-04	1.50E-04
x_5^2	-0.051	0.017	-2.977	0.004	-0.085	-0.017
x_6^2	-0.003	0.001	-2.956	0.003	-0.006	-0.001
x_7^2	-0.007	0.005	-1.463	0.141	-0.016	0.002
x_8^2	-2.280	2.490	-0.916	0.399	-7.161	2.600
x_9^2	-0.113	0.089	-1.271	0.107	-0.288	0.061

x_{10}^2	-0.006	0.020	-0.271	0.621	-0.046	0.035
x_{11}^2	-12.056	2.231	-5.404	2.78E-09	-16.429	-7.684
x_{12}^2	0.051	0.073	0.694	0.683	-0.092	0.193
x_{13}^2	-0.018	0.017	-1.040	0.257	-0.052	0.016
y_1^2	-4.067	1.038	-3.917	4.89E-07	-6.102	-2.032
y_6^2	-5.068	1.127	-4.496	7.44E-09	-7.278	-2.859

Table F.11 Target similarity criterion y_{10} regression coefficients

Variables	Coefficients	Standard Deviation	t Value	p Value	95% Confidence Interval	
c	0.075	0.171	0.439	0.956	-0.260	0.410
x_1	-8.82E-14	8.62E-14	-1.023	0.295	-2.57E-13	8.08E-14
x_2	0.570	0.079	7.213	2.88E-11	0.415	0.725
x_3	0.008	0.008	0.972	0.661	-0.008	0.023
x_4	-0.001	0.006	-0.211	0.425	-0.013	0.011
x_5	-0.069	0.074	-0.934	0.816	-0.213	0.075
x_6	-0.048	0.027	-1.828	0.097	-0.100	0.004
x_7	0.009	0.041	0.212	0.592	-0.071	0.089
x_8	0.438	1.111	0.394	0.811	-1.740	2.615
x_9	0.276	0.162	1.696	0.151	-0.043	0.594
x_{10}	-0.048	0.084	-0.566	0.689	-0.213	0.117
x_{11}	1.660	1.061	1.565	0.026	-0.420	3.740
x_{12}	-0.076	0.149	-0.514	0.955	-0.367	0.215
x_{13}	-0.007	0.073	-0.095	0.683	-0.150	0.136
y_1	-1.274	0.825	-1.545	0.084	-2.891	0.342
y_6	0.718	0.823	0.873	0.270	-0.895	2.330
x_1x_2	1.50E-14	2.44E-14	0.613	0.664	-3.28E-14	6.27E-14
x_1x_3	2.38E-15	2.34E-15	1.015	0.081	-2.22E-15	6.97E-15
x_1x_4	-1.54E-15	1.31E-15	-1.181	0.231	-4.10E-15	1.02E-15
x_1x_5	1.85E-14	1.89E-14	0.978	0.964	-1.86E-14	5.56E-14
x_1x_6	4.83E-15	7.16E-15	0.675	0.924	-9.20E-15	1.89E-14
x_1x_7	8.02E-16	7.75E-15	0.103	0.730	-1.44E-14	1.60E-14
x_1x_8	1.96E-13	3.37E-13	0.583	0.224	-4.63E-13	8.56E-13
x_1x_9	3.18E-14	5.05E-14	0.629	0.399	-6.72E-14	1.31E-13
x_1x_{10}	-5.20E-14	2.60E-14	-2.002	0.026	-1.03E-13	-1.08E-15
x_1x_{11}	5.54E-13	3.05E-13	1.819	0.150	-4.29E-14	1.15E-12
x_1x_{12}	3.40E-14	4.38E-14	0.777	0.731	-5.18E-14	1.20E-13
x_1x_{13}	-1.28E-14	2.25E-14	-0.568	0.401	-5.69E-14	3.13E-14
x_1y_1	1.75E-13	2.49E-13	0.700	0.242	-3.14E-13	6.63E-13
x_1y_6	-1.55E-13	2.51E-13	-0.616	0.313	-6.47E-13	3.38E-13
x_2x_3	-0.002	0.002	-1.144	0.235	-0.006	0.002

x_2x_4	-0.006	0.002	-4.076	0.003	-0.009	-0.003
x_2x_5	-0.038	0.021	-1.824	0.069	-0.078	0.003
x_2x_6	0.009	0.008	1.154	0.208	-0.006	0.023
x_2x_7	-9.68E-04	0.009	-0.109	0.533	-0.018	0.016
x_2x_8	-0.632	0.336	-1.879	0.061	-1.291	0.027
x_2x_9	0.138	0.051	2.689	0.008	0.037	0.238
x_2x_{10}	-0.068	0.025	-2.692	0.026	-0.118	-0.019
x_2x_{11}	0.135	0.345	0.389	0.401	-0.543	0.812
x_2x_{12}	-0.095	0.048	-1.999	0.032	-0.189	-0.002
x_2x_{13}	0.011	0.023	0.469	0.716	-0.035	0.056
x_2y_1	0.227	0.345	0.660	0.503	-0.448	0.903
x_2y_6	0.136	0.343	0.396	0.739	-0.536	0.808
x_3x_4	-1.10E-04	1.10E-04	-1.002	0.374	-3.25E-04	1.05E-04
x_3x_5	0.004	0.002	2.316	0.007	5.73E-04	0.007
x_3x_6	1.74E-04	5.79E-04	0.301	0.505	-9.60E-04	0.001
x_3x_7	-5.58E-04	6.47E-04	-0.863	0.185	-0.002	7.10E-04
x_3x_8	-0.048	0.044	-1.106	0.247	-0.134	0.037
x_3x_9	-0.002	0.004	-0.397	0.836	-0.010	0.007
x_3x_{10}	-5.56E-04	0.002	-0.271	0.364	-0.005	0.003
x_3x_{11}	0.054	0.037	1.459	0.591	-0.019	0.128
x_3x_{12}	-0.003	0.004	-0.846	0.199	-0.010	0.004
x_3x_{13}	0.001	0.002	0.678	0.199	-0.002	0.004
x_3y_1	0.002	0.021	0.099	0.590	-0.039	0.043
x_3y_6	-0.003	0.021	-0.144	0.570	-0.045	0.039
x_4x_5	0.009	0.002	4.113	0.002	0.005	0.013
x_4x_6	0.003	8.29E-04	3.921	1.18E-04	0.002	0.005
x_4x_7	0.002	9.31E-04	1.874	0.128	-8.05E-05	0.004
x_4x_8	0.026	0.019	1.407	0.084	-0.010	0.062
x_4x_9	-0.015	0.003	-4.841	8.55E-07	-0.021	-0.009
x_4x_{10}	0.003	0.001	2.178	0.062	3.16E-04	0.006
x_4x_{11}	-0.027	0.016	-1.644	0.232	-0.059	0.005
x_4x_{12}	-0.001	0.003	-0.391	0.464	-0.006	0.004
x_4x_{13}	-0.002	0.001	-1.222	0.225	-0.004	9.34E-04
x_4y_1	-0.007	0.017	-0.425	0.643	-0.042	0.027
x_4y_6	0.006	0.017	0.366	0.781	-0.028	0.041
x_5x_6	-0.101	0.018	-5.498	5.14E-06	-0.137	-0.065
x_5x_7	0.017	0.013	1.339	0.603	-0.008	0.043
x_5x_8	0.397	0.285	1.392	0.058	-0.162	0.956
x_5x_9	-0.194	0.043	-4.509	1.26E-05	-0.279	-0.110
x_5x_{10}	0.009	0.021	0.419	0.855	-0.032	0.049
x_5x_{11}	0.088	0.291	0.302	0.822	-0.482	0.658
x_5x_{12}	-0.045	0.038	-1.188	0.488	-0.118	0.029

x_5x_{13}	-0.031	0.019	-1.586	0.079	-0.069	0.007
x_5y_1	-0.267	0.200	-1.336	0.110	-0.660	0.125
x_5y_6	0.349	0.202	1.723	0.042	-0.048	0.745
x_6x_7	0.003	0.003	0.896	0.510	-0.003	0.008
x_6x_8	0.043	0.117	0.364	0.529	-0.187	0.272
x_6x_9	-0.023	0.016	-1.426	0.136	-0.054	0.009
x_6x_{10}	-0.003	0.007	-0.429	0.470	-0.017	0.011
x_6x_{11}	-0.113	0.123	-0.918	0.394	-0.354	0.128
x_6x_{12}	-0.013	0.013	-1.020	0.624	-0.039	0.012
x_6x_{13}	0.004	0.007	0.537	0.681	-0.010	0.018
x_6y_1	-0.044	0.067	-0.656	0.231	-0.175	0.087
x_6y_6	0.061	0.069	0.889	0.150	-0.074	0.196
x_7x_8	-0.071	0.108	-0.658	0.483	-0.282	0.140
x_7x_9	-0.012	0.017	-0.686	0.636	-0.046	0.022
x_7x_{10}	0.015	0.009	1.701	0.196	-0.002	0.032
x_7x_{11}	-0.054	0.100	-0.542	0.360	-0.251	0.142
x_7x_{12}	-0.010	0.015	-0.653	0.795	-0.040	0.020
x_7x_{13}	-7.19E-04	0.007	-0.096	0.392	-0.015	0.014
x_7y_1	-0.056	0.095	-0.593	0.142	-0.242	0.130
x_7y_6	0.026	0.095	0.272	0.257	-0.160	0.211
x_8x_9	0.715	0.950	0.752	0.264	-1.148	2.577
x_8x_{10}	-0.291	0.452	-0.643	0.465	-1.177	0.596
x_8x_{11}	1.468	3.333	0.440	0.713	-5.065	8.000
x_8x_{12}	-1.562	0.677	-2.307	0.029	-2.888	-0.235
x_8x_{13}	0.367	0.306	1.202	0.105	-0.232	0.966
x_8y_1	0.478	3.884	0.123	0.295	-7.134	8.090
x_8y_6	-0.933	3.958	-0.236	0.235	-8.691	6.826
x_9x_{10}	0.031	0.064	0.491	0.830	-0.094	0.157
x_9x_{11}	-0.753	0.667	-1.128	0.212	-2.060	0.555
x_9x_{12}	-0.168	0.096	-1.746	0.037	-0.357	0.021
x_9x_{13}	-0.042	0.046	-0.930	0.610	-0.132	0.047
x_9y_1	-0.077	0.564	-0.136	0.919	-1.182	1.029
x_9y_6	0.439	0.571	0.768	0.476	-0.681	1.559
$x_{10}x_{11}$	0.634	0.338	1.875	0.115	-0.029	1.296
$x_{10}x_{12}$	0.098	0.046	2.132	0.115	0.008	0.187
$x_{10}x_{13}$	0.019	0.022	0.878	0.295	-0.024	0.062
$x_{10}y_1$	0.296	0.276	1.070	0.656	-0.246	0.837
$x_{10}y_6$	-0.323	0.283	-1.143	0.564	-0.877	0.231
$x_{11}x_{12}$	2.211	0.720	3.070	0.005	0.799	3.622
$x_{11}x_{13}$	-0.576	0.367	-1.570	0.126	-1.295	0.143
$x_{11}y_1$	2.905	3.939	0.738	0.871	-4.815	10.626
$x_{11}y_6$	-0.379	3.988	-0.095	0.451	-8.196	7.438

$x_{12}x_{13}$	0.062	0.043	1.444	0.269	-0.022	0.147
$x_{12}y_1$	0.083	0.483	0.171	0.523	-0.865	1.030
$x_{12}y_6$	-0.071	0.489	-0.146	0.495	-1.029	0.886
$x_{13}y_1$	-0.154	0.222	-0.695	0.877	-0.589	0.281
$x_{13}y_6$	0.221	0.225	0.986	0.875	-0.219	0.662
y_1y_6	7.473	2.248	3.325	4.96E-06	3.067	11.878
x_1^2	3.00E-26	1.97E-26	1.521	0.178	-8.66E-27	6.87E-26
x_2^2	-0.342	0.022	-15.451	1.00E-49	-0.386	-0.299
x_3^2	-1.46E-04	1.22E-04	-1.200	0.559	-3.85E-04	9.26E-05
x_4^2	-8.16E-06	1.27E-04	-0.064	0.378	-2.56E-04	2.40E-04
x_5^2	-0.067	0.018	-3.706	8.69E-04	-0.103	-0.032
x_6^2	-0.004	0.001	-3.404	5.64E-04	-0.007	-0.002
x_7^2	-0.009	0.005	-1.785	0.051	-0.019	8.90E-04
x_8^2	-1.325	2.634	-0.503	0.640	-6.488	3.839
x_9^2	-0.133	0.094	-1.409	0.096	-0.318	0.052
x_{10}^2	0.002	0.022	0.092	0.885	-0.040	0.044
x_{11}^2	-14.450	2.360	-6.122	2.12E-11	-19.076	-9.824
x_{12}^2	0.075	0.077	0.978	0.493	-0.076	0.227
x_{13}^2	-0.017	0.018	-0.906	0.371	-0.053	0.019
y_1^2	-2.859	1.098	-2.603	1.80E-04	-5.012	-0.707
y_6^2	-3.984	1.193	-3.341	3.42E-06	-6.322	-1.647

Appendix G: Validation of Similarity Criteria for Test Cases

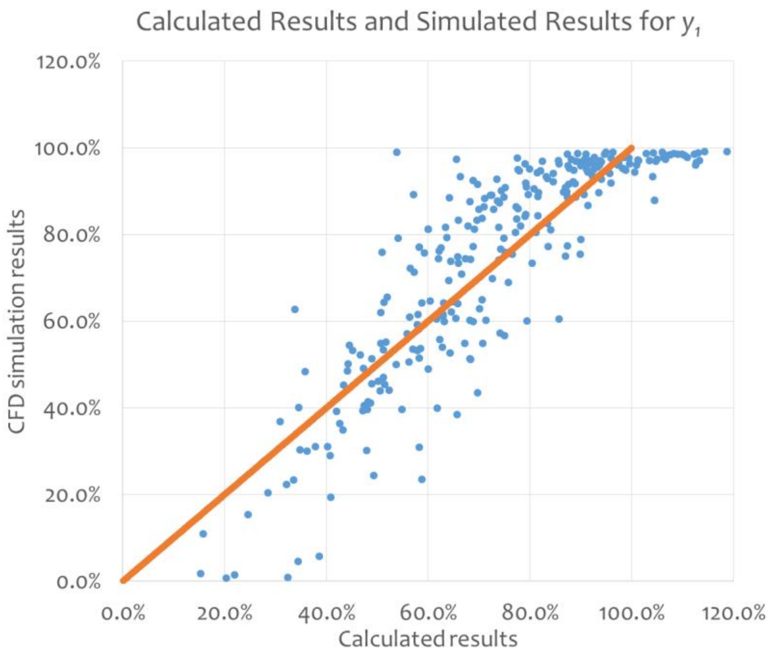

Figure G.1 Calculated results and simulated results of all test cases for y_1

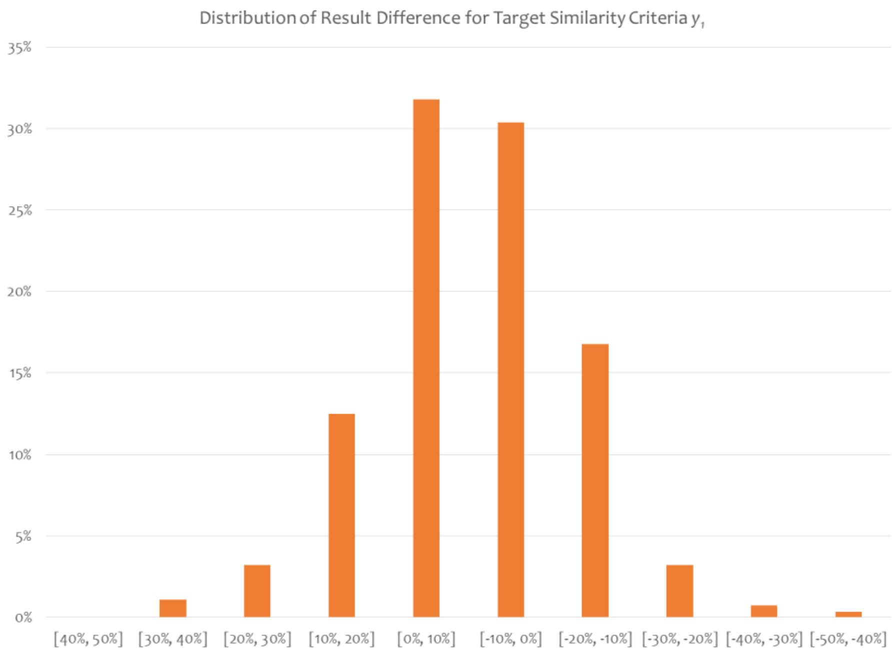

Figure G.2 Distribution of difference of calculations and simulations for y_1

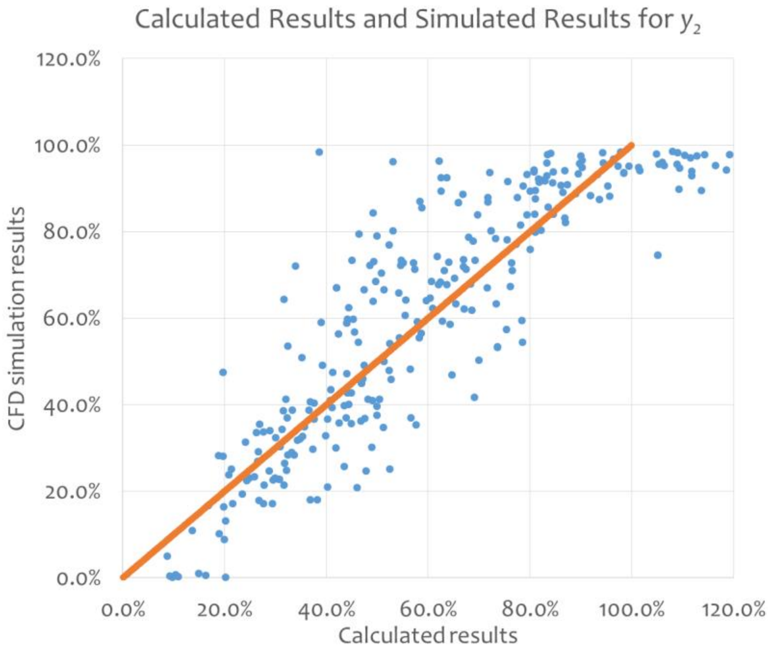

Figure G.3 Calculated results and simulated results of all test cases for y_2

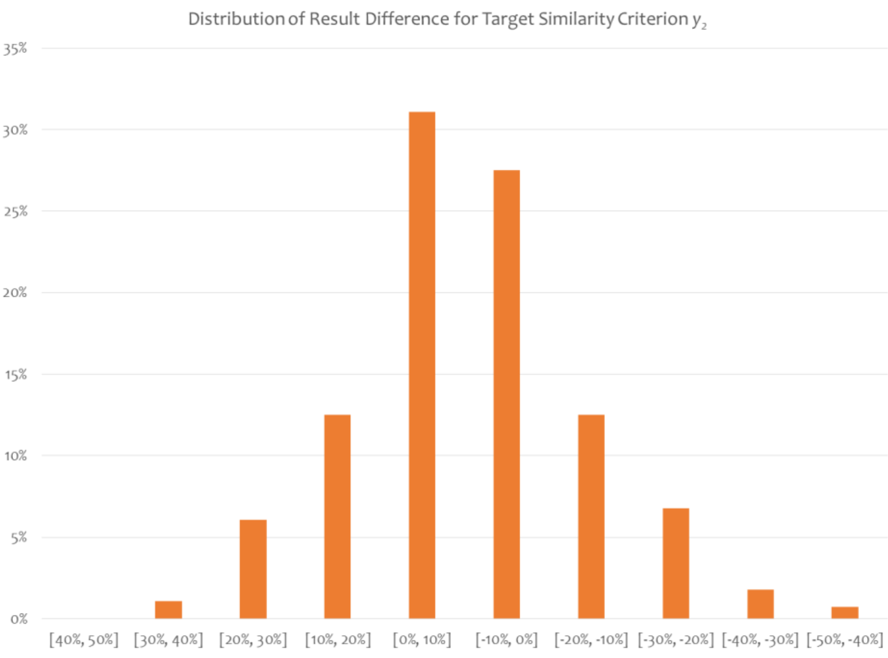

Figure G.4 Distribution of difference of calculations and simulations for y_2

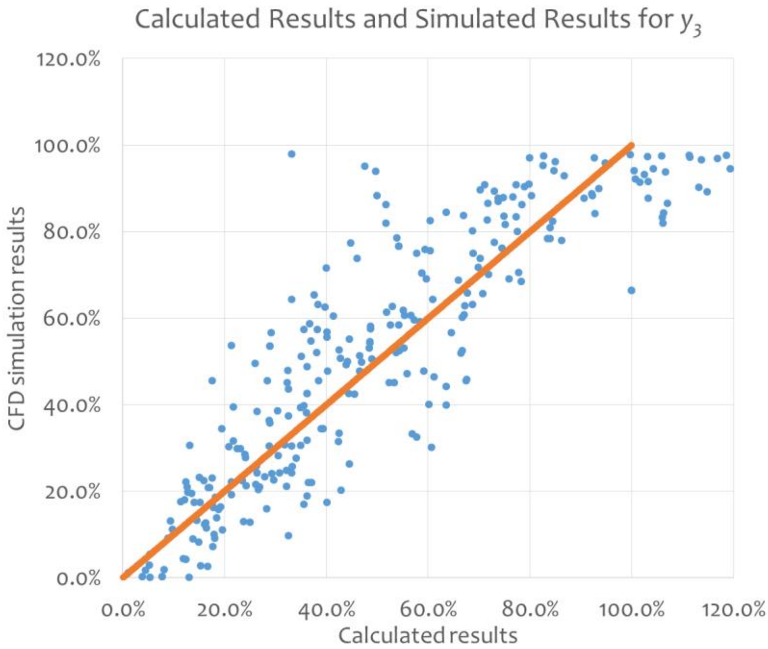

Figure G.5 Calculated results and simulated results of all test cases for y_3

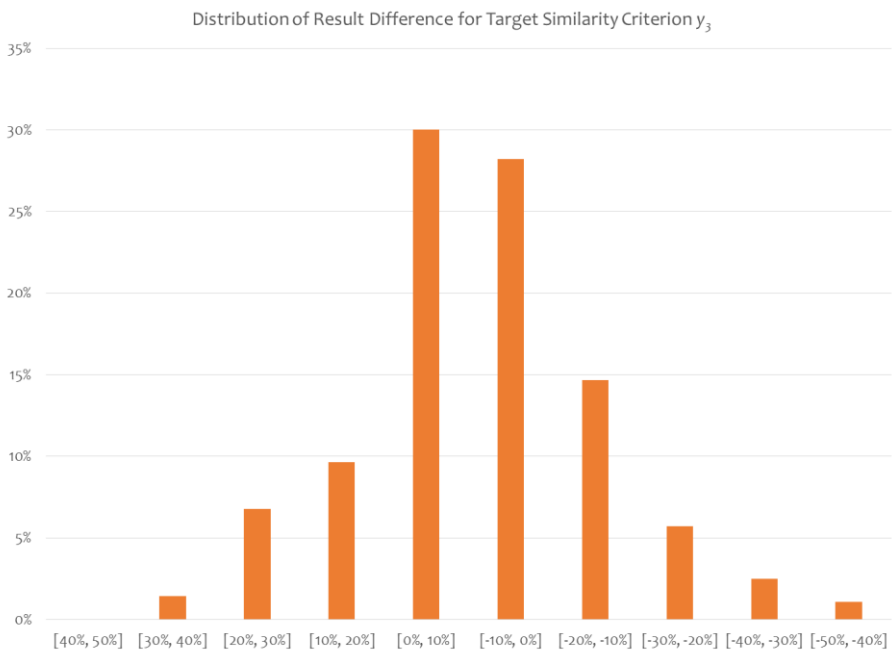

Figure G.6 Distribution of difference of calculations and simulations for y_3

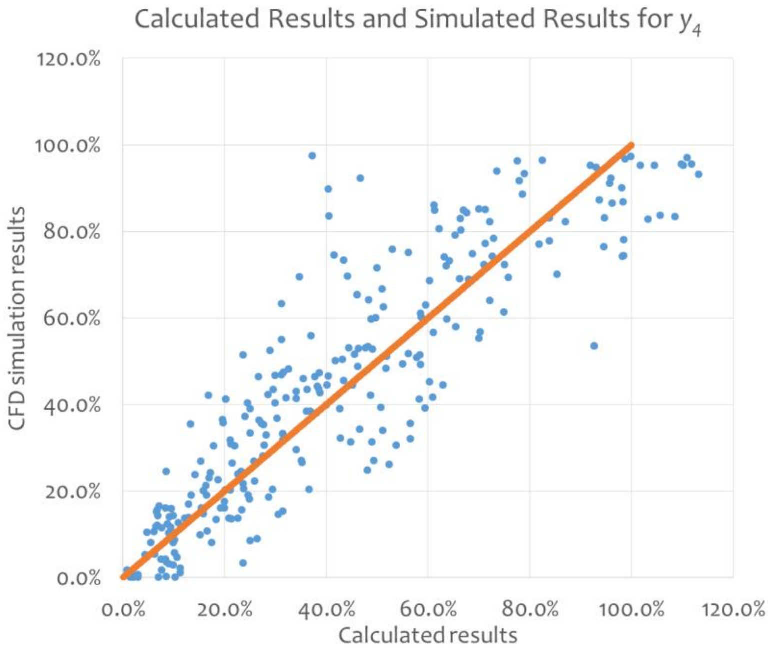

Figure G.7 Calculated results and simulated results of all test cases for y_4

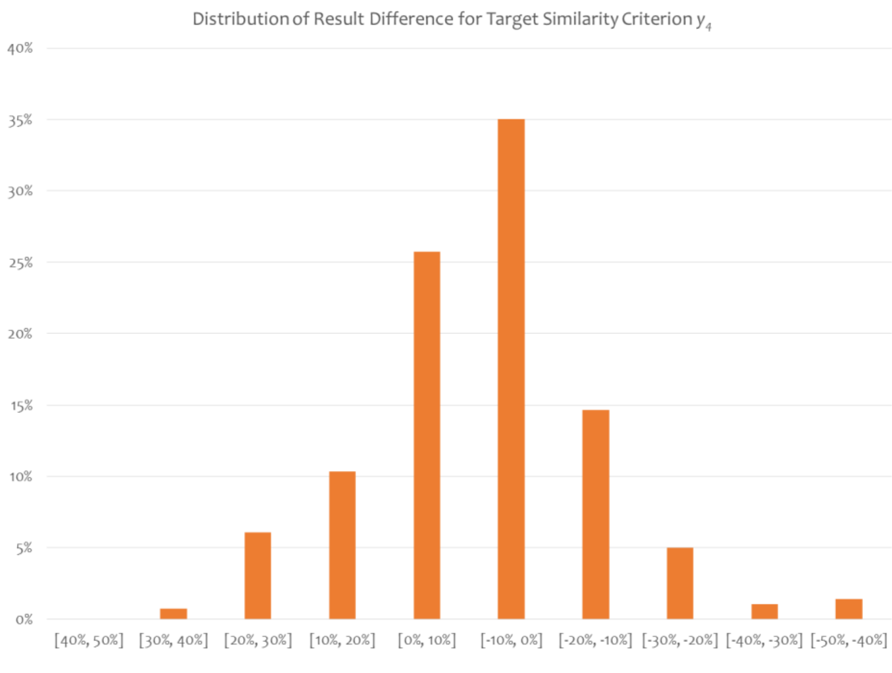

Figure G.8 Distribution of difference of calculations and simulations for y_4

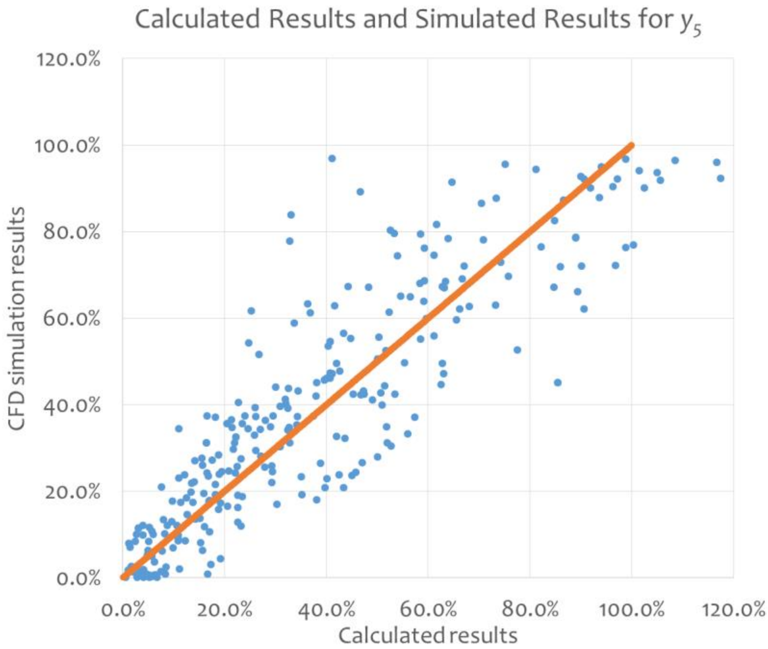

Figure G.9 Calculated results and simulated results of all test cases for y_5

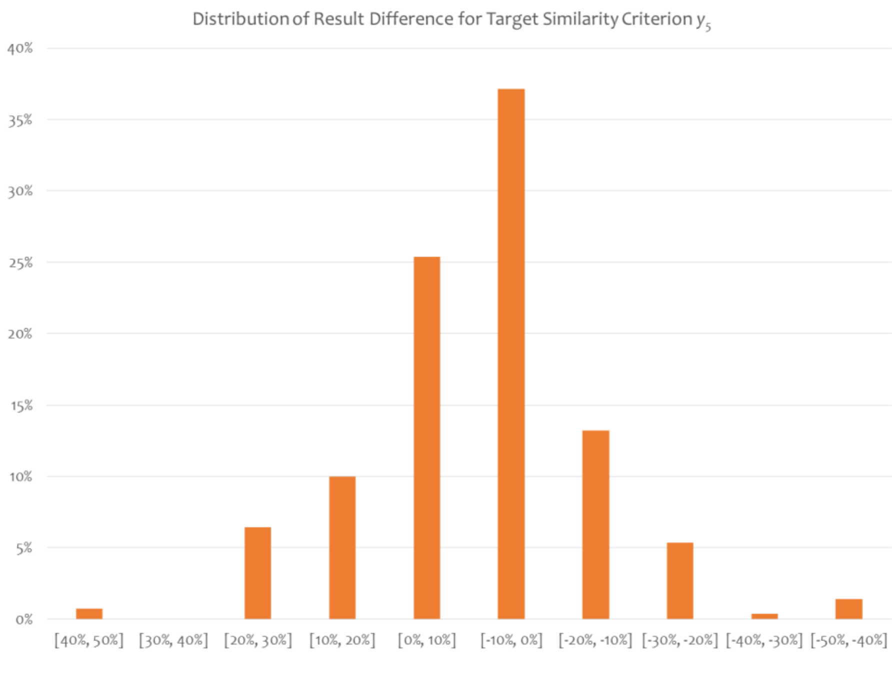

Figure G.10 Distribution of difference of calculations and simulations for y_5

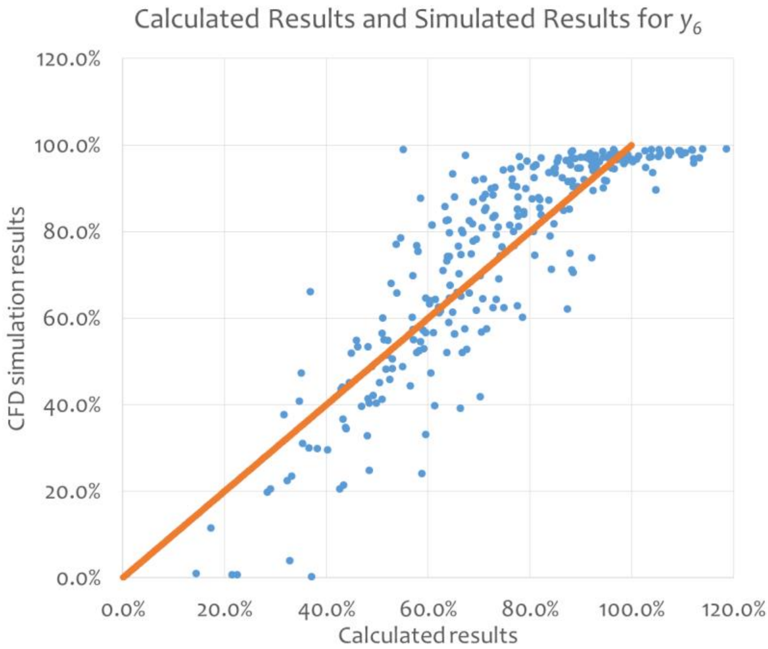

Figure G.11 Calculated results and simulated results of all test cases for y_6

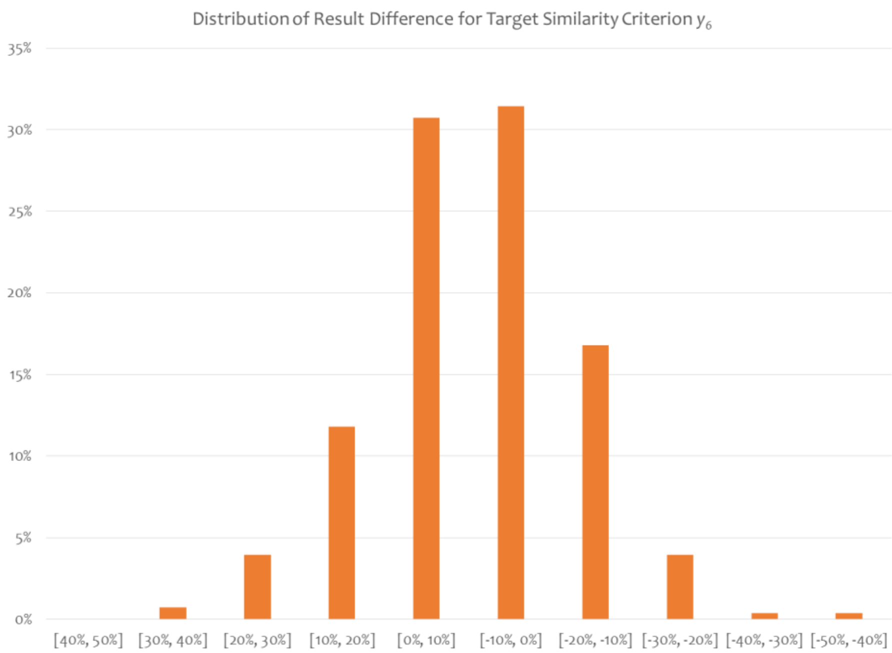

Figure G.12 Distribution of difference of calculations and simulations for y_6

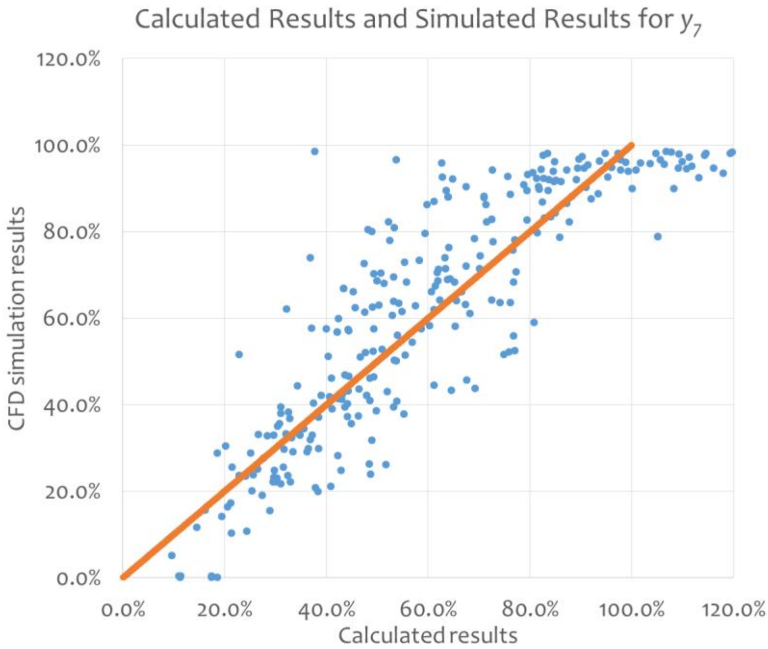

Figure G.13 Calculated results and simulated results of all test cases for y_7

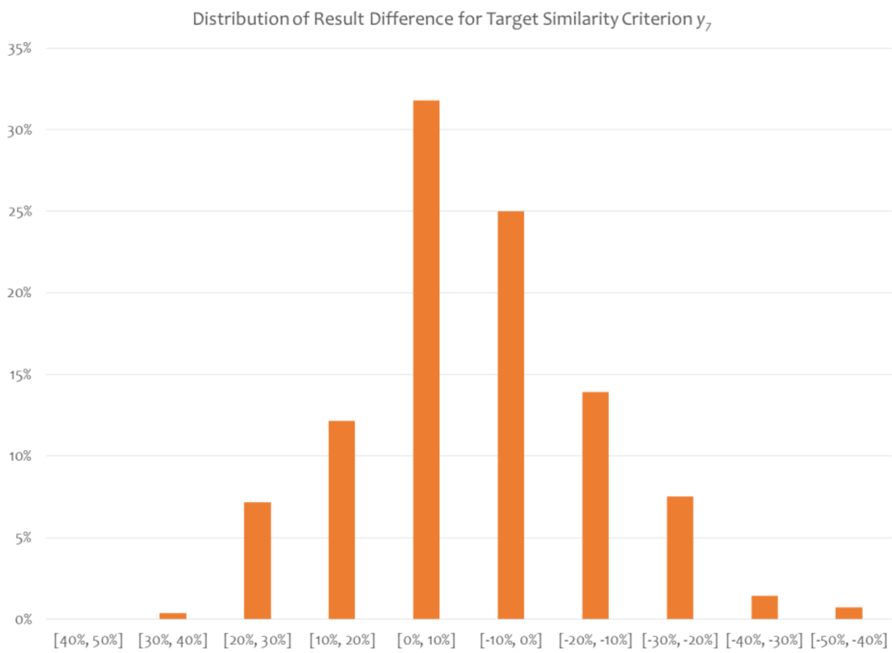

Figure G.14 Distribution of difference of calculations and simulations for y_7

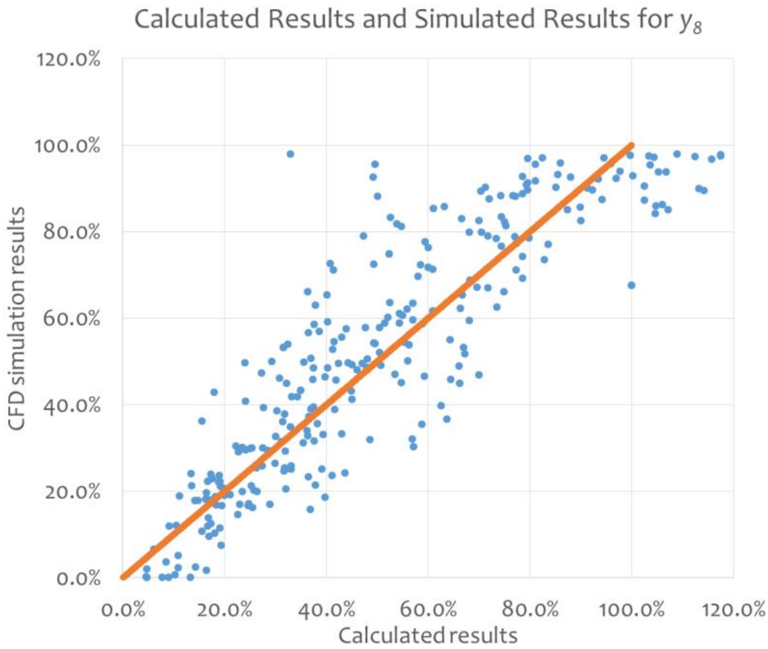

Figure G.15 Calculated results and simulated results of all test cases for y_8

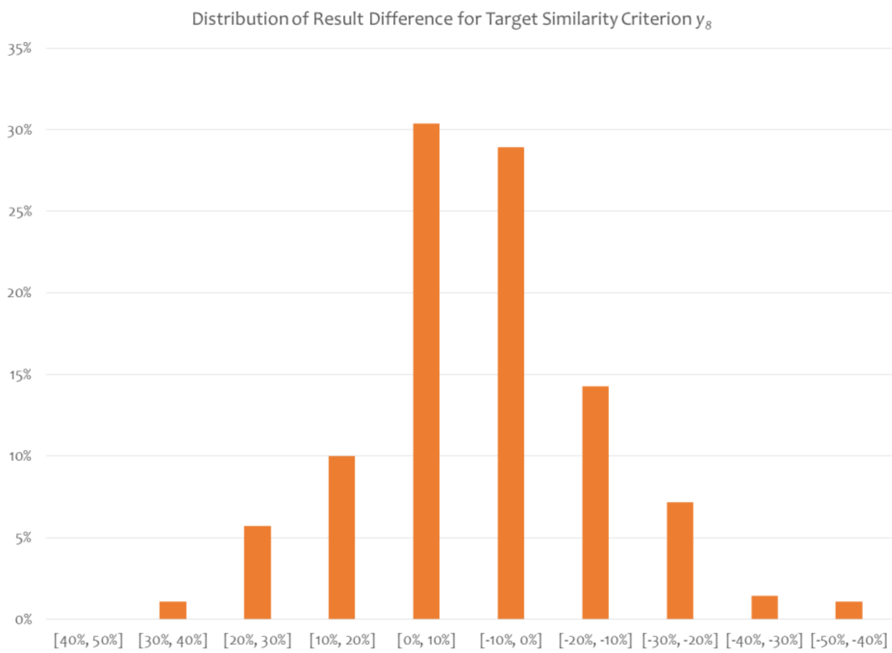

Figure G.16 Distribution of difference of calculations and simulations for y_8

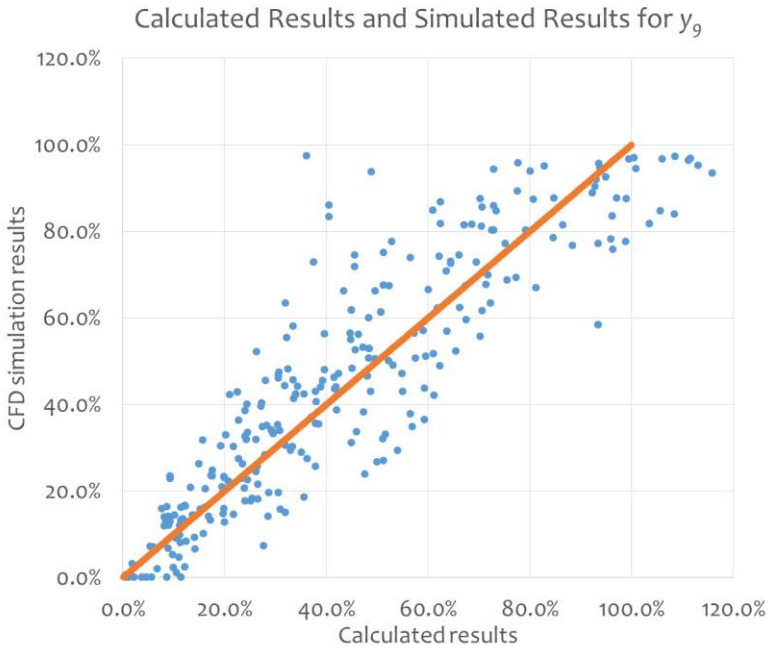

Figure G.17 Calculated results and simulated results of all test cases for y_9

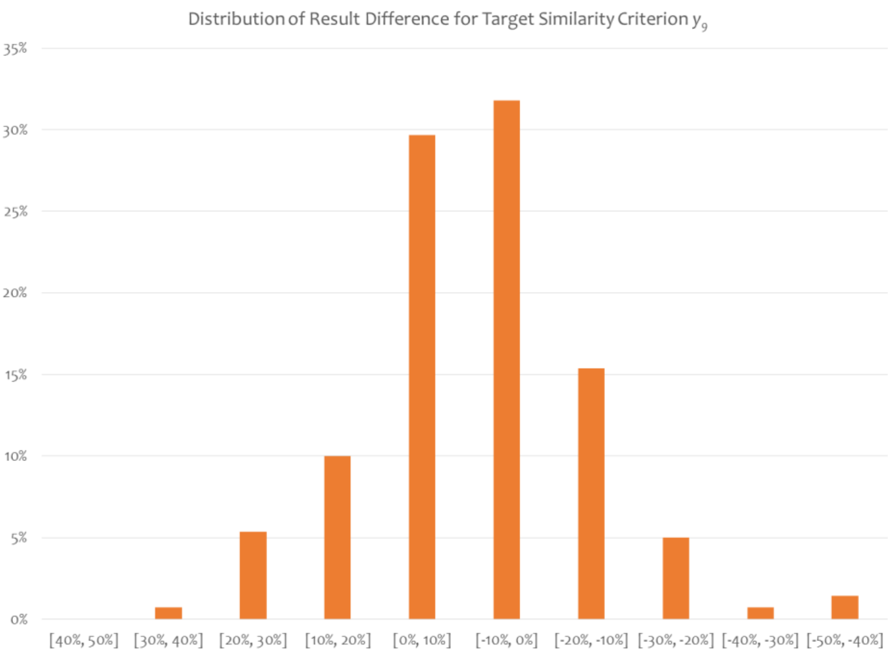

Figure G.18 Distribution of difference of calculations and simulations for y_9

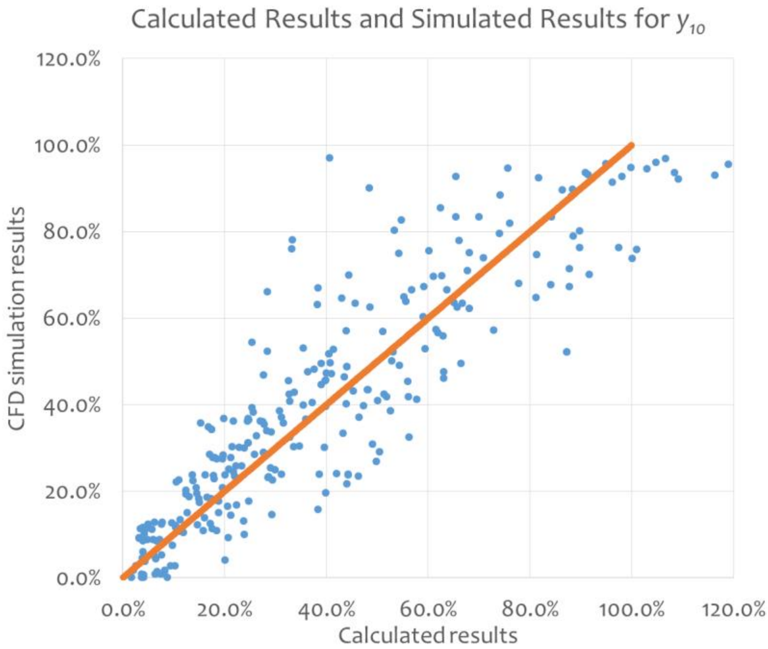

Figure G.19 Calculated results and simulated results of all test cases for y_{10}

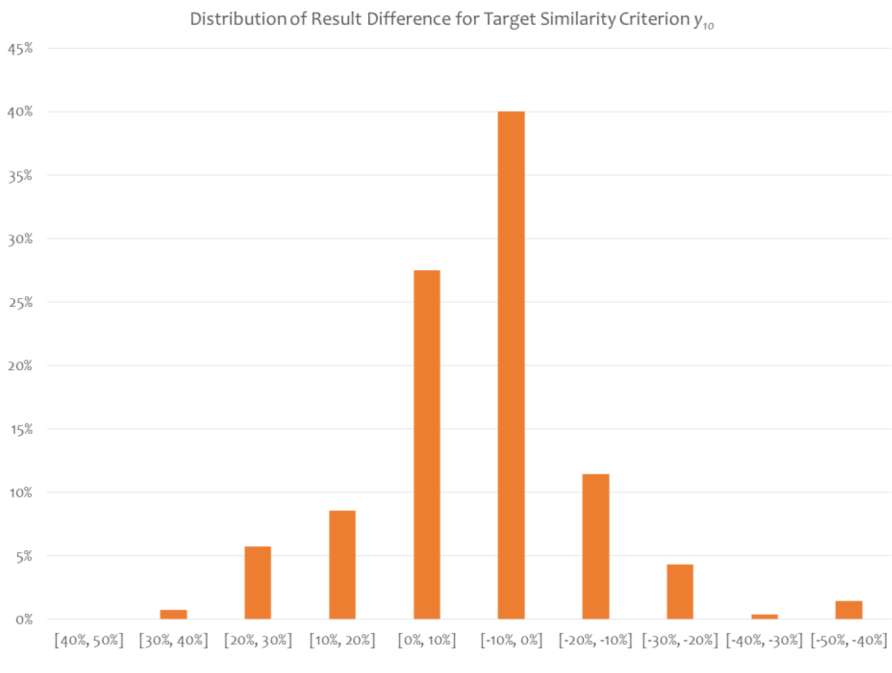

Figure G.20 Distribution of difference of calculations and simulations for y_{10}

Appendix H: Illustration of building form optimization process in Rhino Grasshopper

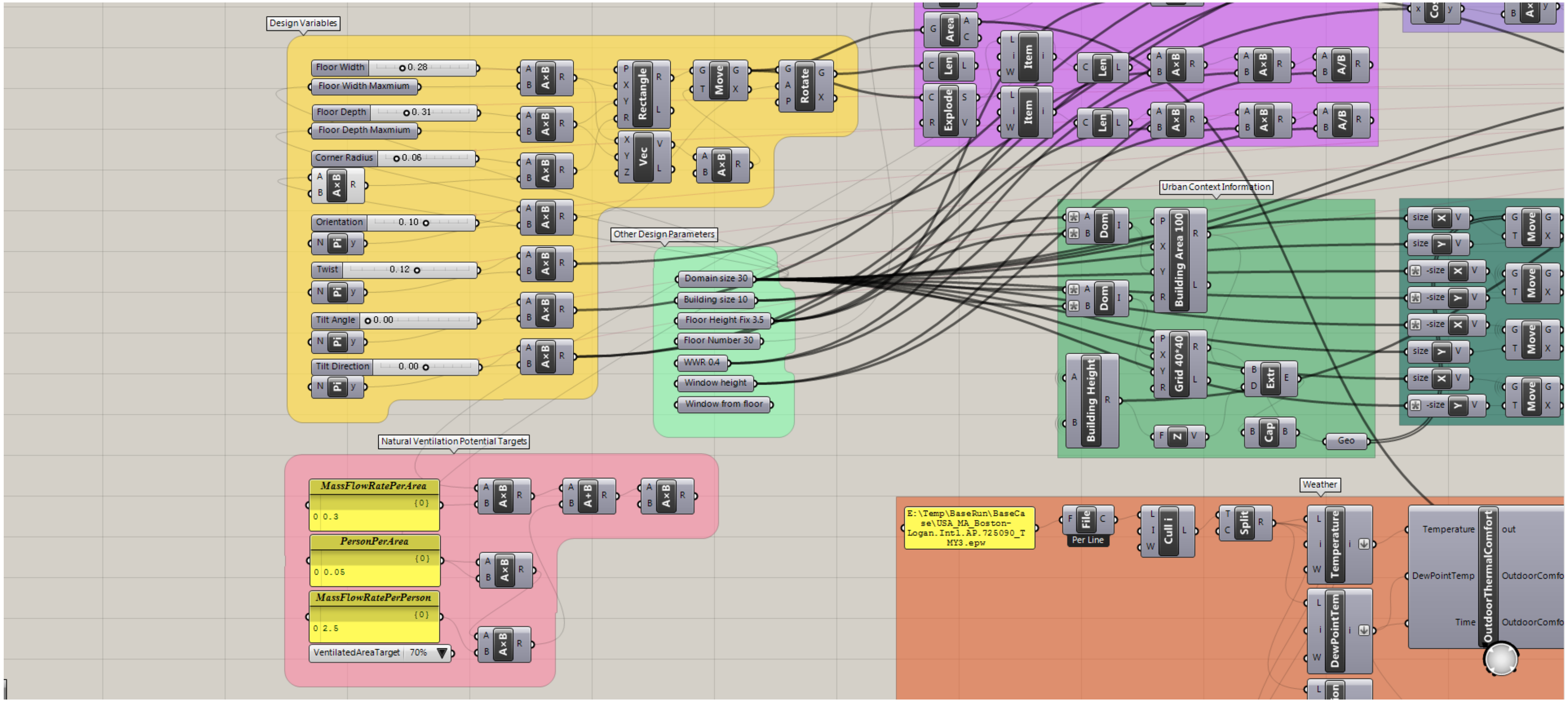

Figure H.1 Building form optimization in Rhino Grasshopper - inputs

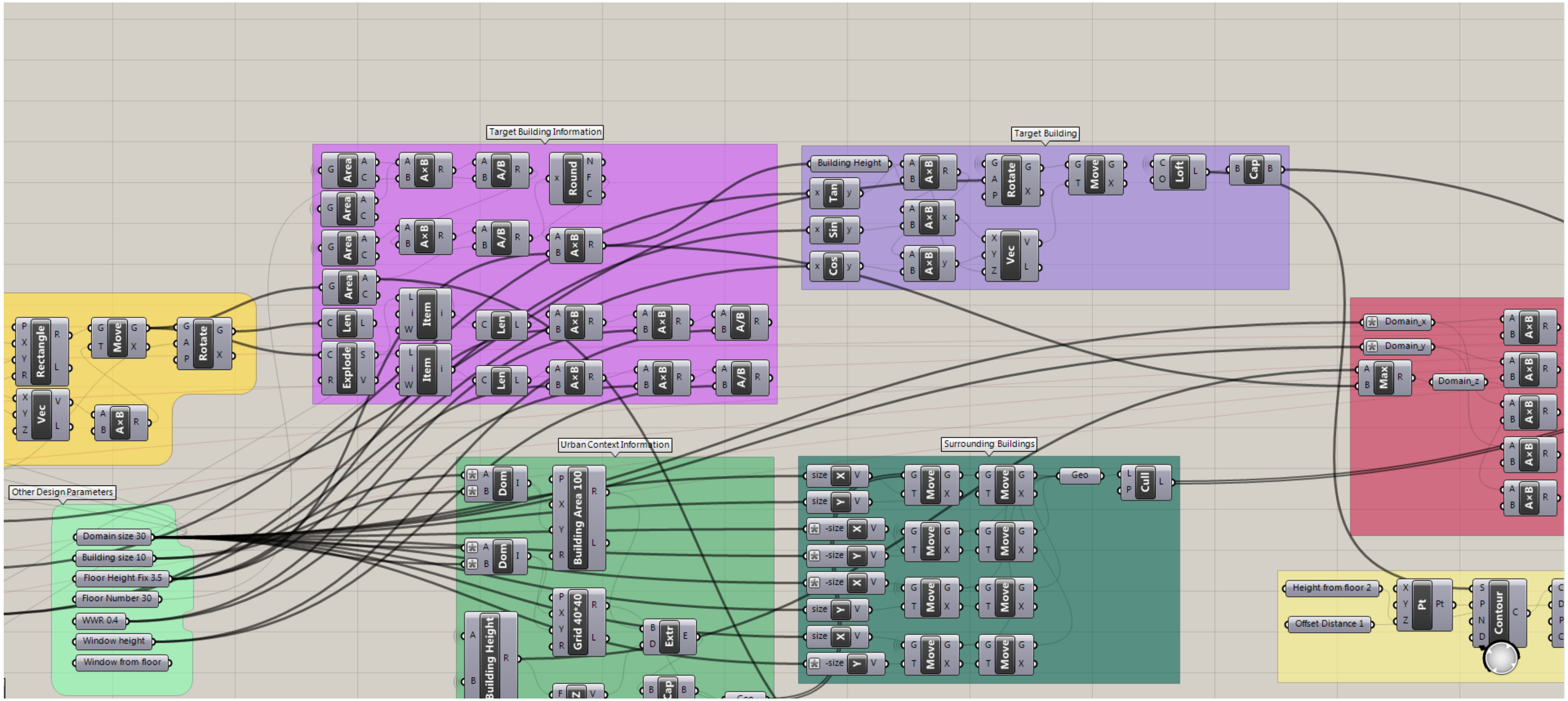

Figure H.2 Building form optimization in Rhino Grasshopper – target building

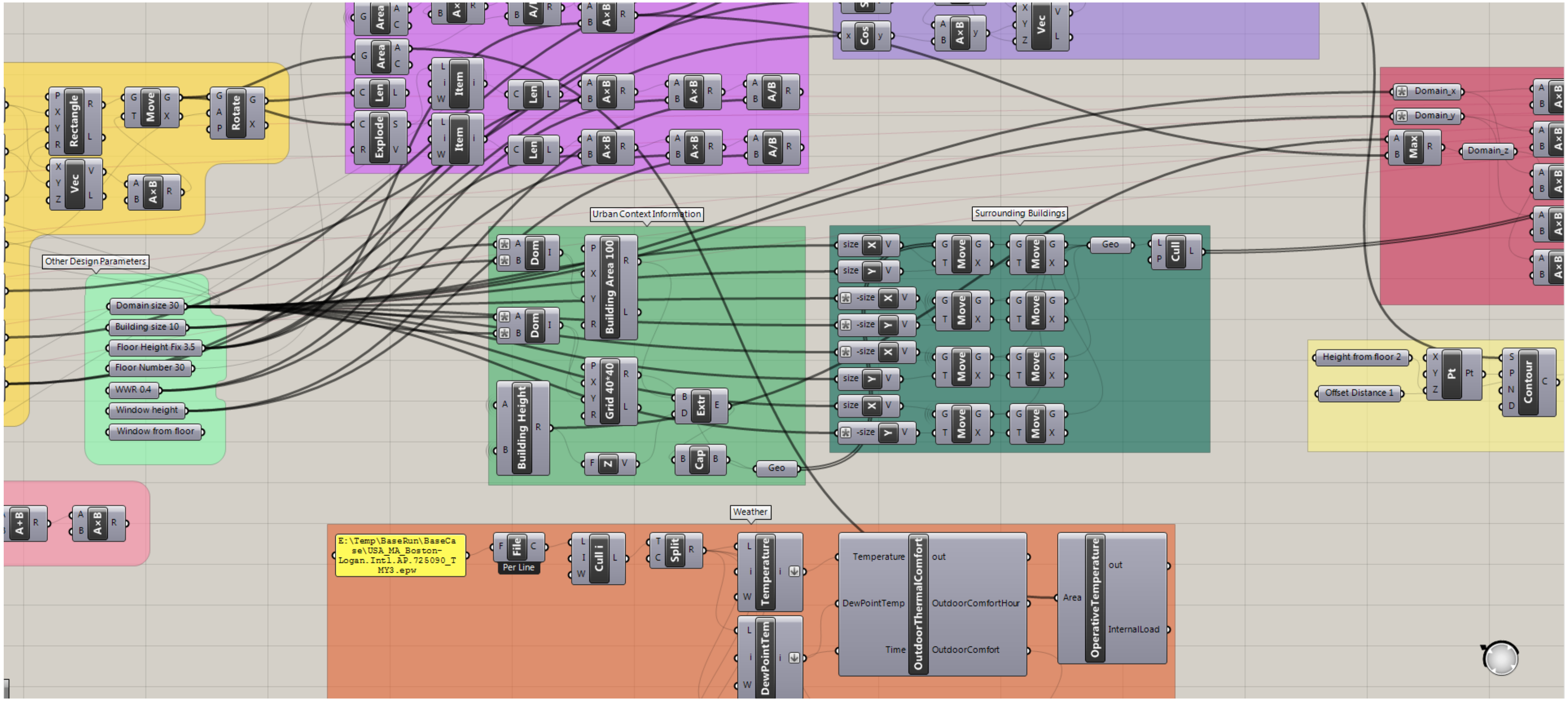

Figure H.3 Building form optimization in Rhino Grasshopper – urban context

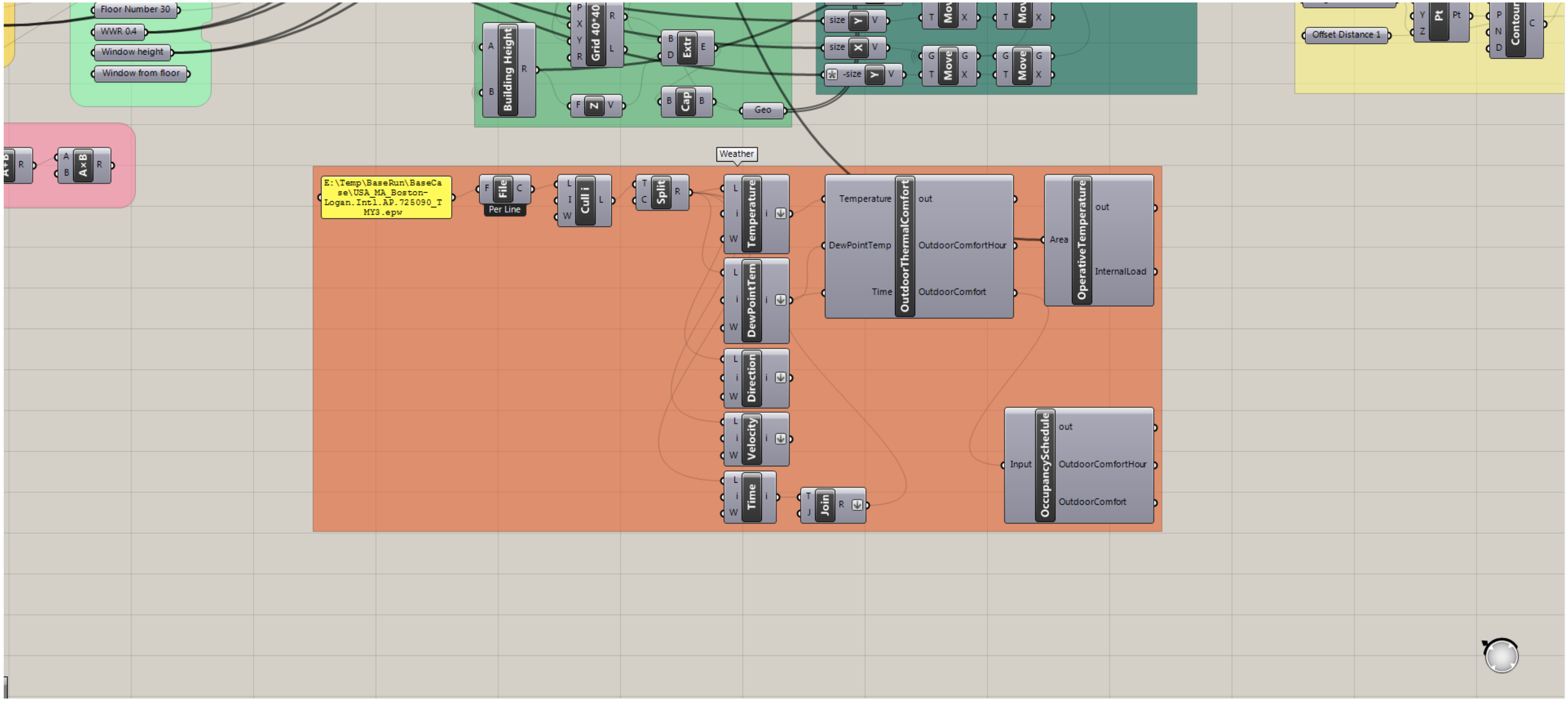

Figure H.4 Building form optimization in Rhino Grasshopper – weather conditions

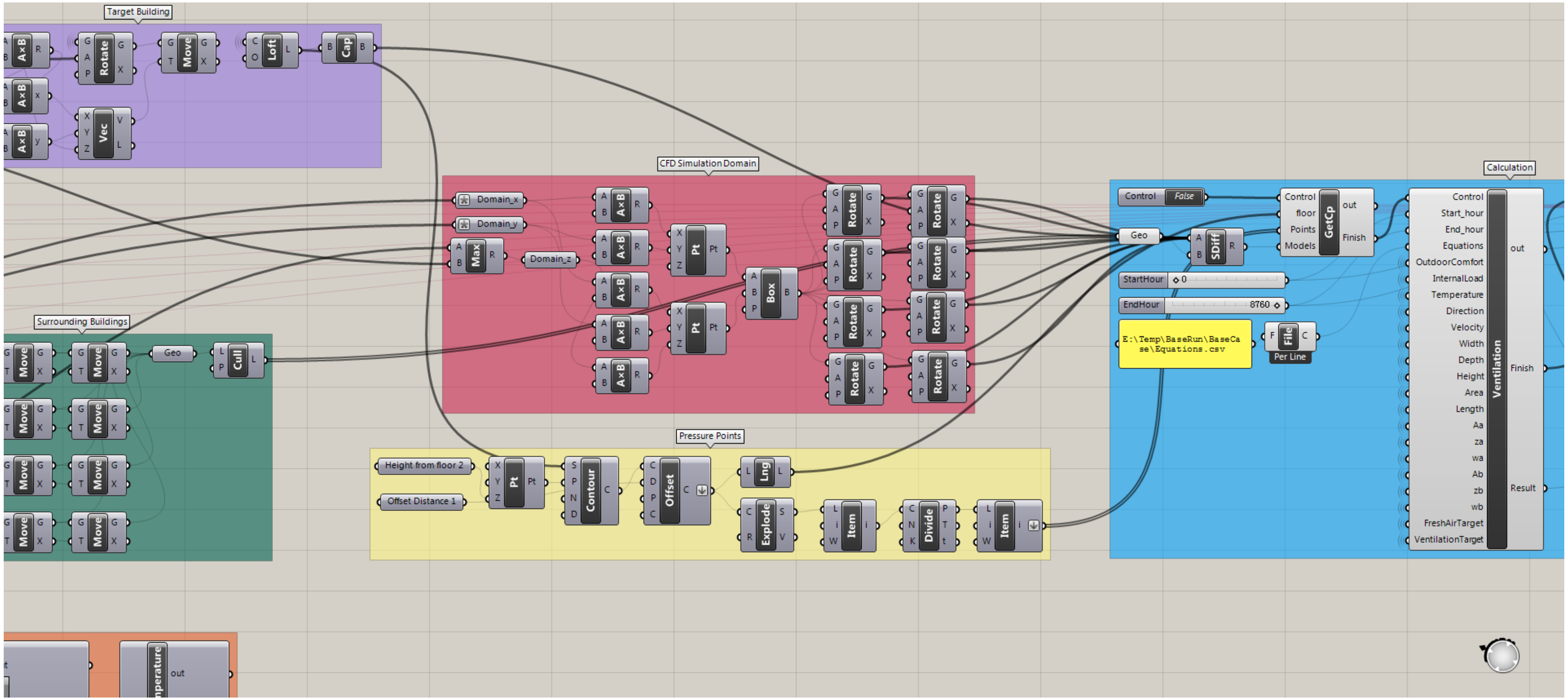

Figure H.5 Building form optimization in Rhino Grasshopper – calculation preparation

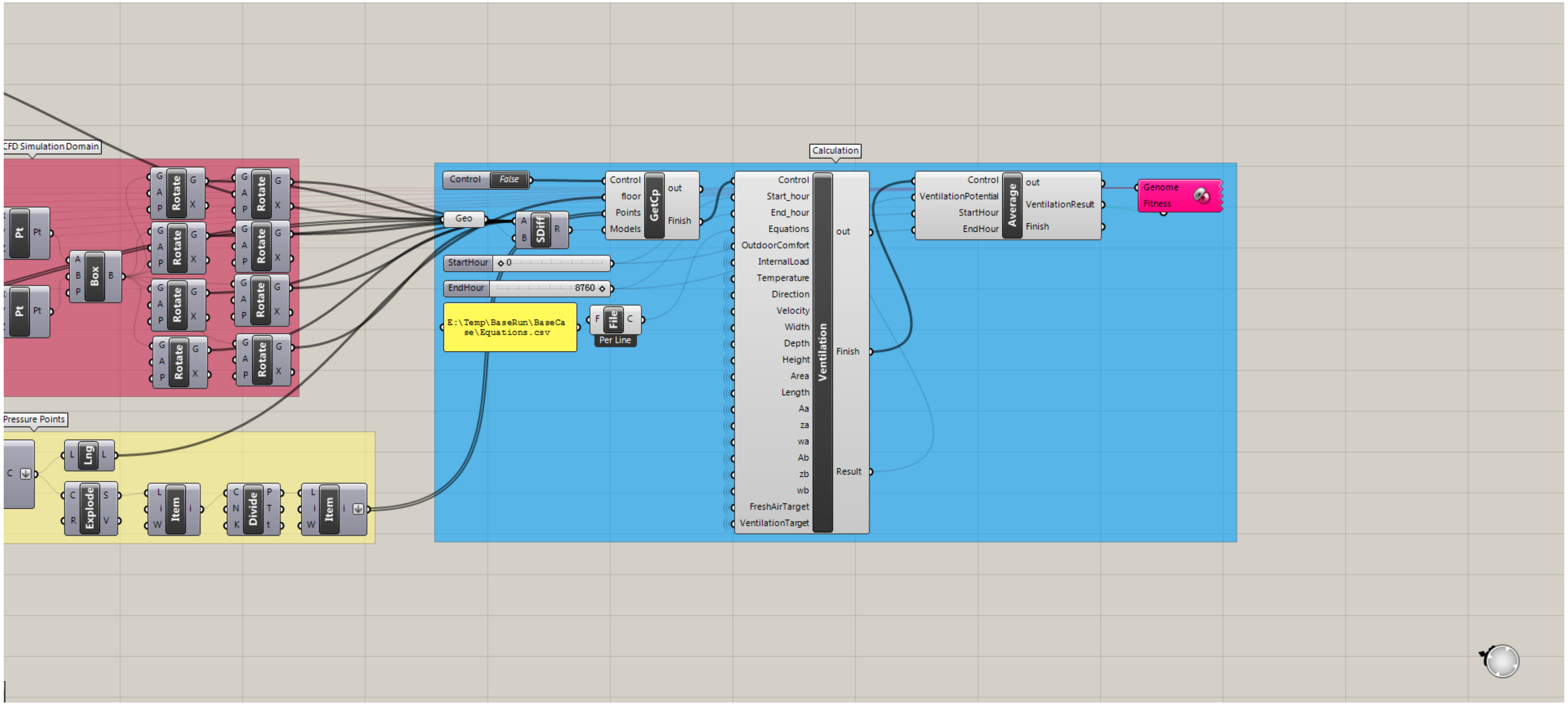

Figure H.6 Building form optimization in Rhino Grasshopper – calculation and optimization

Appendix I: Natural Ventilation Evaluation Scripts in Rhino Grasshopper

Automatically pressure coefficients database calculation by CFD simulation:

```
import rhinoscriptsyntax as rs
import scriptcontext as sc
import Rhino
import ConfigParser
import os
import shutil
import sys

# Change for each template
BaseCaseName = "BaseCase.wbpj"
CasePath = "E:\\Temp\\BaseRun\\"
BaseCasePath = "E:\\Temp\\BaseRun\\BaseCase\\"
BaseCaseFolderName = BaseCaseName.replace(".wbpj", "_files")


""" Run Control """
if Control == True and floor < 75:
    Finish = False
    for i in range (0, 8):
        CaseName = "Shape_Cp" + str(i+1) + ".wbpj"
        ModelName = "Grasshopper_Model" + str(i+1) + ".sat"
        CaseFolderName = CaseName.replace(".wbpj", "_files")

        Model = Models[i]
        Result_fname = CasePath + "Cp_Result_" + str(i) + ".dat"
        if os.path.exists(Result_fname):
            os.remove(Result_fname)

        # Prepare case
        casefile = CasePath + CaseName
        if os.path.exists(casefile):
            os.remove(casefile)
        casefolder = CasePath + CaseFolderName
        if os.path.exists(casefolder):
```

```
    shutil.rmtree(casefolder)
casefile_source = BaseCasePath + BaseCaseName
casefolder_source = BaseCasePath + BaseCaseFolderName
shutil.copy2(casefile_source, casefile)
shutil.copytree(casefolder_source, casefolder)

# Create Layer
sc.doc = Rhino.RhinoDoc.ActiveDoc
CurretLayerName = rs.CurrentLayer()
if not rs.IsLayer("Grasshooper_Model"):
    rs.AddLayer("Grasshooper_Model")
rs.CurrentLayer("Grasshooper_Model")

# Add model and check model watertight
Model_ids = rs.ObjectsByLayer("Grasshooper_Model", True)
rs.DeleteObjects(Model_ids)
ModelsSolid = True
geo_id = Model
sc.doc = ghdoc
doc_object = rs.coercerhinoobject(geo_id)

geometry = doc_object.Geometry
attributes = doc_object.Attributes

sc.doc = Rhino.RhinoDoc.ActiveDoc
rhino_id = sc.doc.Objects.Add(geometry, attributes)
rs.ObjectLayer(rhino_id, "Grasshooper_Model")
if not rs.IsObjectSolid(rhino_id):
    print("Geometry " + str(i + 1) + " in Model is not solid.")
    ModelsSolid = False
rs.CurrentLayer(CurretLayerName)

# Export Model file
Model_ids = rs.ObjectsByLayer("Grasshooper_Model", True)
if ModelsSolid == False:
    rs.CurrentLayer(CurretLayerName)
    rs.DeleteObjects(Model_ids)
    rs.DeleteLayer("Grasshooper_Model")
else:
    satName = CasePath + ModelName
    if os.path.exists(satName):
        os.remove(satName)
```

```
            rs.UnselectAllObjects
            rs.SelectObjects(Model_ids)
            rs.Command("_-Export " + satName + " Enter")

        # Delete result files
        filelist = [ f for f in os.listdir(CasePath) if
f.endswith(".txt") ]
        for f in filelist:
            os.remove(f)

        # Build case file
        fileName = CasePath + CaseName.replace("wbpj", "wbjn")
        if os.path.exists(fileName):
            os.remove(fileName)
        with open(fileName, 'w') as fileWriter:
            casefileName = casefile.replace("\\", "/")
            ModelFile = CasePath.replace("\\", "/") + ModelName

            fileWriter.write('# encoding: utf-8\n')
            fileWriter.write('# Release 16.1\n')
            fileWriter.write('SetScriptVersion(Version="16.1.91")\n')
            fileWriter.write('Open(FilePath="' + casefileName + '")\n')
            fileWriter.write('system1 = GetSystem(Name="FFF")\n')
            fileWriter.write('geometry1 =
system1.GetContainer(ComponentName="Geometry")\n')
            fileWriter.write('geometry1.SetFile(FilePath="' + ModelFile
+ '")\n')
            fileWriter.write('geometry1.UpdateCAD()\n')

            fileWriter.write('solutionComponent1 =
system1.GetComponent(Name="Solution")\n')

fileWriter.write('solutionComponent1.Update(AllDependencies=True)\n')
            fileWriter.write('solution1 =
system1.GetContainer(ComponentName="Solution")\n')
            fileWriter.write('solution1.Edit()\n')
            fileWriter.write('setup1 =
system1.GetContainer(ComponentName="Setup")\n')

            fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(cx-gui-do cx-set-list-tree-selections "NavigationPane*List_Tree1"
(list ))' + chr(39) + ')\n')
```

```
            fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(cx-gui-do cx-activate-item "MenuBar*SurfaceMenu*Point...")' +
chr(39) + ')\n')
            for n in range(0, floor):
                for i in range(0, 4):
                    fileWriter.write('setup1.SendCommand(Command="(cx-
gui-do cx-set-text-entry \\"Point Surface*TextEntry4(New Surface
Name)\\" \\"point-result-' + str("%04d" % (n*4 + i)) + '\\")(cx-gui-
do cx-set-real-entry-list \\"Point
Surface*Frame2(Coordinates)*Frame1*Table1*RealEntry1(x0)\\" ' +
chr(39) + '( ' + str(round(Points[n*4 + i][0], 2)) + '))(cx-gui-do
cx-set-real-entry-list \\"Point
Surface*Frame2(Coordinates)*Frame1*Table1*RealEntry2(y0)\\" ' +
chr(39) + '( ' + str(round(Points[n*4 + i][1], 2)) + '))(cx-gui-do
cx-set-real-entry-list \\"Point
Surface*Frame2(Coordinates)*Frame1*Table1*RealEntry3(z0)\\" ' +
chr(39) + '( ' + str(round(Points[n*4 + i][2], 2)) + '))(cx-gui-do
cx-activate-item \\"Point
Surface*PanelButtons*PushButton1(OK)\\")")\n')
            fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(cx-gui-do cx-activate-item "Point
Surface*PanelButtons*PushButton2(Cancel)")' + chr(39) + ')\n')
            fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(cx-gui-do cx-set-list-tree-selections "NavigationPane*List_Tree1"
(list "Setup"))(cx-gui-do cx-set-list-tree-selections
"NavigationPane*List_Tree1" (list "Results|Plots"))' + chr(39) +
')\n')
            fileWriter.write('setup1.SendCommand(Command="(cx-gui-do
cx-set-list-selections \\"Plots*Frame1*Table1*Frame1*List1(Plots)\\"
' + chr(39) + '( 0))(cx-gui-do cx-activate-item
\\"Plots*Frame1*Table1*Frame1*List1(Plots)\\")")\n')
            fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(cx-gui-do cx-activate-item "Plots*Frame1*Table1*PushButton2(Set
Up)")' + chr(39) + ')\n')
            fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(cx-gui-do cx-set-toggle-button "Solution XY
Plot*Frame1(Options)*ToggleBox1(Options)*CheckButton4(Write to File)"
#f)(cx-gui-do cx-activate-item "Solution XY
Plot*Frame1(Options)*ToggleBox1(Options)*CheckButton4(Write to
File)")' + chr(39) + ')\n')
            for n in range(0, floor):
                fileWriter.write('setup1.SendCommand(Command="(cx-gui-
```

```
do cx-set-list-selections \\"Solution XY
Plot*Frame9*Frame1*List1(Surfaces)\\" ' + chr(39) + '( ' + str(n*4 +
6) + ' ' + str(n*4 + 7) + ' ' + str(n*4 + 8) + ' ' + str(n*4 + 9) +
'))(cx-gui-do cx-activate-item \\"Solution XY
Plot*Frame9*Frame1*List1(Surfaces)\\")")\n')
            fileWriter.write('setup1.SendCommand(Command=r' +
chr(39) + '(cx-gui-do cx-activate-item "Solution XY
Plot*PanelButtons*PushButton1(OK)")(cx-gui-do cx-set-text-entry
"Select File*FilterText" "' + CasePath + '*")(cx-gui-do cx-activate-
item "Select File*Apply")(cx-gui-do cx-set-text-entry "Select
File*Text" "pressure_Cp' + str(i) + '_floor_' + str(n+1) +
'.txt")(cx-gui-do cx-activate-item "Select File*OK")' + chr(39) +
')\n')
          fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(cx-gui-do cx-activate-item "Solution XY
Plot*PanelButtons*PushButton2(Cancel)")' + chr(39) + ')\n')
          fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(%cx-warning-dialog "OK to close Fluent?" #f)(cx-gui-do cx-activate-
item "Warning*OK")' + chr(39) + ')\n')
          fileWriter.write('setup1.SendCommand(Command=' + chr(39) +
'(cx-gui-do cx-activate-item "MenuBar*FileMenu*Close Fluent")(cx-gui-
do cx-activate-item "Settings have
changed!*PanelButtons*PushButton1(OK)")' + chr(39) + ')\n')

          fileWriter.write('Save(Overwrite=True)\n')

       # Run Fluent with journal file
       BatPath = CasePath + CaseName.replace("wbpj", "bat")
       if os.path.exists(BatPath):
          os.remove(BatPath)
       BatFile = open(BatPath, 'w')
       BatFile.write('cd /d D:\\Program Files\\ANSYS
Inc\\v161\\Framework\\bin\\Win64\n')
       BatFile.write('runwb2.exe -R ' + fileName + ' -B\n')
       BatFile.close()

       os.system(BatPath)

       # Read result files
       Cp_Result = []
       for n in range(0, floor):
          Result = "0.00,0.00,0.00,0.00"
```

```
            Pressure_fname = CasePath + "pressure_Cp" + str(i) +
"_floor_" + str(n+1) + ".txt"
            if os.path.exists(Pressure_fname):
                with open(Pressure_fname) as file:
                    content = file.readlines()
                Cp_1 = float(content[4].split()[1])/61.25
                Cp_2 = float(content[8].split()[1])/61.25
                Cp_3 = float(content[12].split()[1])/61.25
                Cp_4 = float(content[16].split()[1])/61.25
                Result = str(round(Cp_1, 2)) + "," + str(round(Cp_2,
2)) + "," + str(round(Cp_3, 2)) + "," + str(round(Cp_4, 2))

            Cp_Result.append(Result)

        with open(Result_fname, 'w') as Result_File:
            Result_File.write('Cp of four points at every floor\n')
            for n in range(0, floor):
                Result_File.write(Cp_Result[n] + '\n')

    filelist = [ f for f in os.listdir(CasePath) if
f.endswith(".txt") ]
    for f in filelist:
        os.remove(f)
    Finish = True
```

Design-Based Natural Ventilation Potential evaluation:

```
import math
import os

# Constants
Density = 1.205 # kg/m3 at 20C
g = 9.8 # m/s2
v = 0.00001511 # m2/s at 20C
Cp_air =  1004.5 # J/kgK at 20C

# Path
CasePath = "E:\\Temp\\BaseRun\\"
Result_filename = CasePath + "Ventilation_Result.dat"
```

```
Result = []
ResultWrite = []

def NaturalVentilationPotential(Equations, Load, Tem, Floor,
TotalFloor, DifP, x, y, a, H, Af, L, Ai, zi, wi, Ao, zo, wo):
    EquationsBeta = []
    Equations_len = len(Equations)
    for i in range(0, Equations_len):
        string_list = Equations[i].split(",")
        string_len = len(string_list)
        for j in range (0, string_len):
            string_list[j] = float(string_list[j])
        EquationsBeta.append(string_list)
    Input_1 = H**3 * g / v**2
    Input_2 = DifP / Density / g / H
    Input_3 = Af / H**2
    Input_4 = L**2 / Af
    Input_5 = x**2 / Af
    Input_6 = y / x
    Input_7 = a * math.pi
    Input_8 = Ai / Af
    Input_9 = zi / H
    Input_10 = wi / H
    Input_11 = Ao / Af
    Input_12 = zo / H
    Input_13 = wo / H

    # Calculate Area_0.2_1.2 and Area_0.2_1.6
    Numbers = [Input_1, Input_2, Input_3, Input_4, Input_5, Input_6,
Input_7, Input_8, Input_9, Input_10, Input_11, Input_12, Input_13]
    Numbers_len = len(Numbers)
    Input = []
    Input.append(1)
    for i in range (0, Numbers_len):
        Input.append(Numbers[i])
    for i in range (0, Numbers_len):
        for j in range (i+1, Numbers_len):
            Input.append(Numbers[i]*Numbers[j])
    for i in range (0, Numbers_len):
        Input.append(Numbers[i]**2)
    Input_len = len(Input)
    Area_02_12 = 0
```

```
    Area_02_16 = 0
    for i in range (0, Input_len):
        Area_02_12 = Area_02_12 + Input[i]*EquationsBeta[1][i]
        Area_02_16 = Area_02_16 + Input[i]*EquationsBeta[6][i]

    # Calculate Mass result
    Numbers = [Input_1, Input_2, Input_3, Input_4, Input_5, Input_6,
Input_7, Input_8, Input_9, Input_10, Input_11, Input_12, Input_13,
Area_02_12, Area_02_16]
    Numbers_len = len(Numbers)
    Input = []
    Input.append(1)
    for i in range (0, Numbers_len):
        Input.append(Numbers[i])
    for i in range (0, Numbers_len):
        for j in range (i+1, Numbers_len):
            Input.append(Numbers[i]*Numbers[j])
    for i in range (0, Numbers_len):
        Input.append(Numbers[i]**2)
    Input_len = len(Input)
    Mass_number = 0
    for i in range (0, Input_len):
        Mass_number = Mass_number + Input[i]*EquationsBeta[0][i]
    Mass_number = math.exp(Mass_number)
    if Mass_number > 0:
        Mass = math.sqrt(Mass_number * Density**2 * g * H**5) # kg/s
    else:
        Mass = 0

    # Operative Temperature
    floorheight = Floor * 3.5 + 2
    Vel_height = 10 * (floorheight / 10)**0.28
    h_in = 3.076 # W/m2K ASHRAE 1985
    h_out_wall = 10.79 + 4.192 * Vel_height # W/m2K ASHRAE 1989
    h_out_win = 8.23 + 3.33 * Vel_height - 0.036 * Vel_height**2 #
W/m2K ASHRAE 1989
    h_out_ceiling = 4.04 # W/m2K ASHRAE 1985
    U_win = 3.24 # W/m2K EnergyPlus Baltimore
    R_wall = 1.17 # m2K/W EnergyPlus Baltimore
    R_ceiling = 5.18 # m2K/W EnergyPlus Baltimore

    h_win = h_in + U_win + h_out_win
```

```
    A_win = Ai + Ao
    h_wall = h_in + 1/R_wall + h_out_wall
    A_wall = L * H - A_win
    h_ceiling = h_in + 1/R_ceiling + h_out_ceiling
    A_ceiling = 0
    if Floor + 1 == TotalFloor:
        A_ceiling = Af

    del_T = Load / (Mass * Cp_air - h_wall * A_wall - h_win * A_win -
h_ceiling * A_ceiling)
    Tem_indoor = Tem + del_T
    Tem_rad = h_wall * del_T / h_in + Tem_indoor

    Tem_op = 0.5 * (Tem_indoor + Tem_rad)

    # Return result base on operative temperature
    Area_03_12 = 0
    Area_03_16 = 0
    Area_04_12 = 0
    Area_04_16 = 0
    Area_05_12 = 0
    Area_05_16 = 0
    Area_06_12 = 0
    Area_06_16 = 0

    if Tem_op < 18:
        return [0, 0, Tem_op]
    elif Tem_op <= 24:
        return [Mass, min(Area_02_12, Area_02_16), Tem_op]
    elif Tem_op <= 27:
        for i in range (0, Input_len):
            Area_03_12 = Area_03_12 + Input[i]*EquationsBeta[2][i]
            Area_03_16 = Area_03_16 + Input[i]*EquationsBeta[7][i]
        return [Mass, min(Area_03_12, Area_03_16), Tem_op]
    elif Tem_op <= 29:
        for i in range (0, Input_len):
            Area_04_12 = Area_04_12 + Input[i]*EquationsBeta[3][i]
            Area_04_16 = Area_04_16 + Input[i]*EquationsBeta[8][i]
        return [Mass, min(Area_04_12, Area_04_16), Tem_op]
    elif Tem_op <= 30:
        for i in range (0, Input_len):
            Area_05_12 = Area_05_12 + Input[i]*EquationsBeta[4][i]
```

```
            Area_05_16 = Area_05_16 + Input[i]*EquationsBeta[9][i]
        return [Mass, min(Area_05_12, Area_05_16), Tem_op]
    elif Tem_op <= 31:
        for i in range (0, Input_len):
            Area_06_12 = Area_06_12 + Input[i]*EquationsBeta[5][i]
            Area_06_16 = Area_06_16 + Input[i]*EquationsBeta[10][i]
        return [Mass, min(Area_02_12, Area_02_16), Tem_op]
    else:
        return [0, 0, Tem_op]


if Control == True and 35 < Area < 200:
    Finish = False
    # Read pressure file
    FileofCp = []
    ResultofCp = []
    for i in range (0, 8):
        # Result_fname = CasePath + "Backup\\Cp_Result_" + str(i) +
".dat"
        Result_fname = CasePath + "Cp_Result_" + str(i) + ".dat"
        with open(Result_fname) as f:
            FileofCp.append(f.readlines())
        Cp_len = len(FileofCp[i])
        Cp_Value = []
        for j in range(1, Cp_len):
            string_list = FileofCp[i][j].split(",")
            string_len = len(string_list)
            for k in range (0, string_len):
                string_list[k] = float(string_list[k])
            Cp_Value.append(string_list)
        ResultofCp.append(Cp_Value)


    for h in range (Start_hour, End_hour):
        # Weather
        Outdoor = OutdoorComfort[h]
        Tem = Temperature[h]
        Dir = Direction[h]
        Vel = Velocity[h]

        # Internal Load
        Load = InternalLoad[h]
```

```
# Pressure case
if Dir <= 22.5: # North
    Cp = ResultofCp[4]
elif Dir <= 67.5: # NorthEast
    Cp = ResultofCp[3]
elif Dir <= 112.5: # East
    Cp = ResultofCp[2]
elif Dir <= 157.5: # SouthEast
    Cp = ResultofCp[1]
elif Dir <= 202.5: # South
    Cp = ResultofCp[0]
elif Dir <= 247.5: # SouthWest
    Cp = ResultofCp[7]
elif Dir <= 292.5: # West
    Cp = ResultofCp[6]
elif Dir <= 337.5: # NorthWest
    Cp = ResultofCp[5]
else: # North
    Cp = ResultofCp[4]

VentilationPotential = []
VentilationPotentialWrite = []
for i in range (0, Cp_len-1):
    Ventilated = 0
    OperativeTempAve = 0
    if Outdoor == 1:

        MassFlowRate = []
        VentilatedArea = []
        OperativeTemp = []
        MassFlowRate.append(0)
        VentilatedArea.append(0)
        OperativeTemp.append(0)

        # Pressure
        Pressure_1 = Cp[i][0] * 0.5 * Density * Vel * Vel
        Pressure_2 = Cp[i][1] * 0.5 * Density * Vel * Vel
        Pressure_3 = Cp[i][2] * 0.5 * Density * Vel * Vel
        Pressure_4 = Cp[i][3] * 0.5 * Density * Vel * Vel

        # Cases 12
```

```
            DifP = Pressure_1 - Pressure_2
            if 0 < DifP <= 50:
                x = 0.5 * Depth
                y = 0.5 * Width
                a = 0.5
                Ai = Aa
                zi = za
                wi = wa
                Ao = Ab
                zo = zb
                wo = wb
                Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len - 1, DifP, x, y, a, Height, Area, Length, Ai,
zi, wi, Ao, zo, wo)
                MassFlowRate.append(Result_temp[0])
                VentilatedArea.append(Result_temp[1])
                OperativeTemp.append(Result_temp[2])

            # Cases 13
            DifP = Pressure_1 - Pressure_3
            if 0 < DifP <= 50:
                x = Depth
                y = 0
                a = 1
                Ai = Aa
                zi = za
                wi = wa
                Ao = Aa
                zo = za
                wo = wa
                Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len - 1, DifP, x, y, a, Height, Area, Length, Ai,
zi, wi, Ao, zo, wo)
                MassFlowRate.append(Result_temp[0])
                VentilatedArea.append(Result_temp[1])
                OperativeTemp.append(Result_temp[2])

            # Cases 14
            DifP = Pressure_1 - Pressure_4
            if 0 < DifP <= 50:
                x = 0.5 * Depth
                y = 0.5 * Width
```

```
                    a = 0.5
                    Ai = Aa
                    zi = za
                    wi = wa
                    Ao = Ab
                    zo = zb
                    wo = wb
                    Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
                    MassFlowRate.append(Result_temp[0])
                    VentilatedArea.append(Result_temp[1])
                    OperativeTemp.append(Result_temp[2])

                # Cases 23
                DifP = Pressure_2 - Pressure_3
                if 0 < DifP <= 50:
                    x = 0.5 * Width
                    y = 0.5 * Depth
                    a = 0.5
                    Ai = Ab
                    zi = zb
                    wi = wb
                    Ao = Aa
                    zo = za
                    wo = wa
                    Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
                    MassFlowRate.append(Result_temp[0])
                    VentilatedArea.append(Result_temp[1])
                    OperativeTemp.append(Result_temp[2])

                # Cases 24
                DifP = Pressure_2 - Pressure_4
                if 0 < DifP <= 50:
                    x = Width
                    y = 0
                    a = 1
                    Ai = Ab
                    zi = zb
                    wi = wb
```

```
            Ao = Ab
            zo = zb
            wo = wb
            Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
            MassFlowRate.append(Result_temp[0])
            VentilatedArea.append(Result_temp[1])
            OperativeTemp.append(Result_temp[2])

        # Cases 21
        DifP = Pressure_2 - Pressure_1
        if 0 < DifP <= 50:
            x = 0.5 * Width
            y = 0.5 * Depth
            a = 0.5
            Ai = Ab
            zi = zb
            wi = wb
            Ao = Aa
            zo = za
            wo = wa
            Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
            MassFlowRate.append(Result_temp[0])
            VentilatedArea.append(Result_temp[1])
            OperativeTemp.append(Result_temp[2])

        # Cases 34
        DifP = Pressure_3 - Pressure_4
        if 0 < DifP <= 50:
            x = 0.5 * Depth
            y = 0.5 * Width
            a = 0.5
            Ai = Aa
            zi = za
            wi = wa
            Ao = Ab
            zo = zb
            wo = wb
            Result_temp = NaturalVentilationPotential(Equations,
```

```
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
                MassFlowRate.append(Result_temp[0])
                VentilatedArea.append(Result_temp[1])
                OperativeTemp.append(Result_temp[2])

            # Cases 31
            DifP = Pressure_3 - Pressure_1
            if 0 < DifP <= 50:
                x = Depth
                y = 0
                a = 1
                Ai = Aa
                zi = za
                wi = wa
                Ao = Aa
                zo = za
                wo = wa
                Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
                MassFlowRate.append(Result_temp[0])
                VentilatedArea.append(Result_temp[1])
                OperativeTemp.append(Result_temp[2])

            # Cases 32
            DifP = Pressure_3 - Pressure_2
            if 0 < DifP <= 50:
                x = 0.5 * Depth
                y = 0.5 * Width
                a = 0.5
                Ai = Aa
                zi = za
                wi = wa
                Ao = Ab
                zo = zb
                wo = wb
                Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
                MassFlowRate.append(Result_temp[0])
                VentilatedArea.append(Result_temp[1])
```

```
            OperativeTemp.append(Result_temp[2])

        # Cases 41
        DifP = Pressure_4 - Pressure_1
        if 0 < DifP <= 50:
            x = 0.5 * Width
            y = 0.5 * Depth
            a = 0.5
            Ai = Ab
            zi = zb
            wi = wb
            Ao = Aa
            zo = za
            wo = wa
            Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
            MassFlowRate.append(Result_temp[0])
            VentilatedArea.append(Result_temp[1])
            OperativeTemp.append(Result_temp[2])

        # Cases 42
        DifP = Pressure_4 - Pressure_2
        if 0 < DifP <= 50:
            x = Width
            y = 0
            a = 1
            Ai = Ab
            zi = zb
            wi = wb
            Ao = Ab
            zo = zb
            wo = wb
            Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
            MassFlowRate.append(Result_temp[0])
            VentilatedArea.append(Result_temp[1])
            OperativeTemp.append(Result_temp[2])

        # Cases 43
        DifP = Pressure_4 - Pressure_3
```

```
                if 0 < DifP <= 50:
                    x = 0.5 * Width
                    y = 0.5 * Depth
                    a = 0.5
                    Ai = Ab
                    zi = zb
                    wi = wb
                    Ao = Aa
                    zo = za
                    wo = wa
                    Result_temp = NaturalVentilationPotential(Equations,
Load, Tem, i, Cp_len-1, DifP, x, y, a, Height, Area, Length, Ai, zi,
wi, Ao, zo, wo)
                    MassFlowRate.append(Result_temp[0])
                    VentilatedArea.append(Result_temp[1])
                    OperativeTemp.append(Result_temp[2])

                # Max Result as conclusion for this floor
                MassFlowRate_len = len(MassFlowRate)
                for j in range (0, MassFlowRate_len):
                    if MassFlowRate[j] > FreshAirTarget and
VentilatedArea[j] > VentilationTarget:
                        Ventilated = 1
                OperativeTemp_len = len(OperativeTemp)
                if OperativeTemp_len > 1:
                    OperativeTempAve = (sum(OperativeTemp) -
OperativeTemp[0]) / (OperativeTemp_len - 1)
                else:
                    OperativeTempAve = OperativeTemp[0]

            VentilationPotential.append(str(Ventilated))
            VentilationPotentialWrite.append(str(Ventilated) + '_' +
str(round(OperativeTempAve, 2)))

        Result.append(','.join(VentilationPotential))
        ResultWrite.append(str(Outdoor) + ',' +
','.join(VentilationPotentialWrite))

    # Write result
    Result_File = open(Result_filename, 'w')
    Result_File.write('Ventilation potential of outdoor weatehr and '
+ str(Cp_len - 1) + ' floors for every hour\n')
```

```
for ResultLine in ResultWrite:
    Result_File.write(ResultLine + '\n')
Result_File.close()

Finish = True
```

Appendix J: Genetic Algorithm Optimization Process

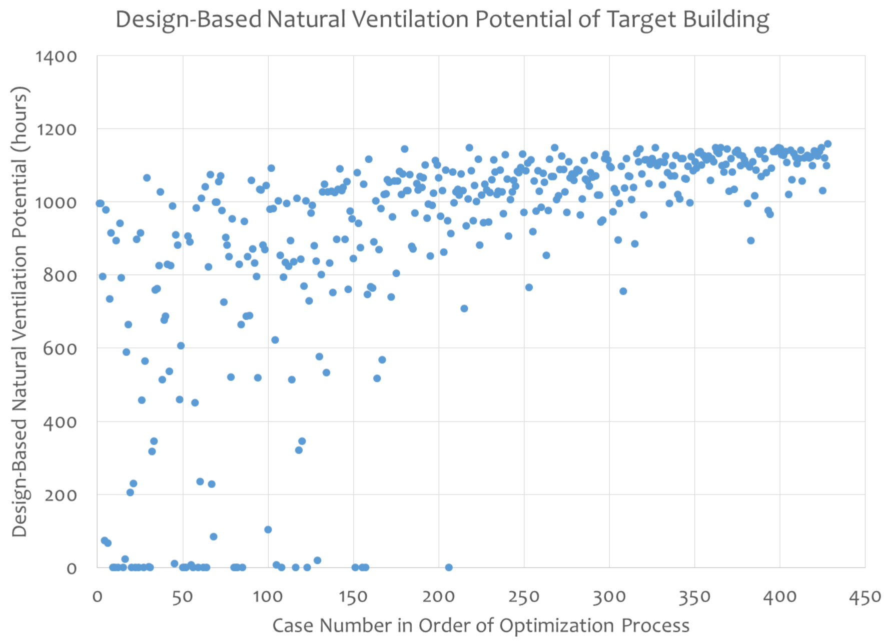

Figure J.1 Genetic algorithm optimization process – natural ventilation potential

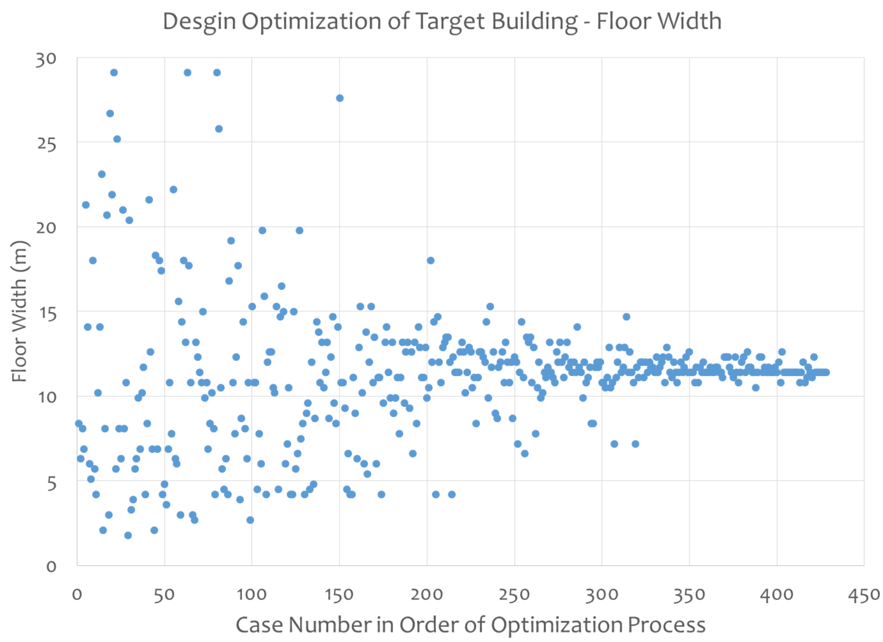

Figure J.2 Genetic algorithm optimization process – floor width

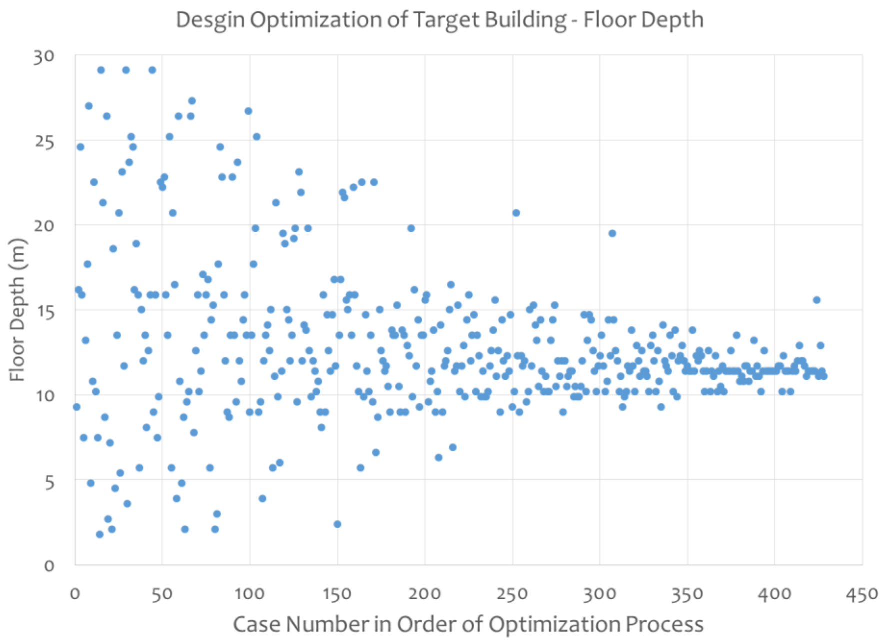

Figure J.3 Genetic algorithm optimization process – floor depth

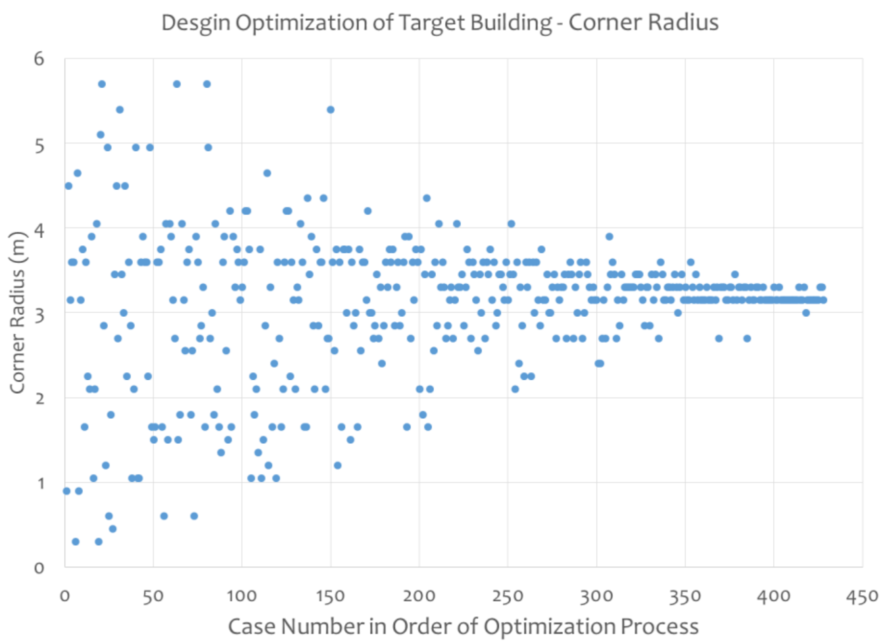

Figure J.4 Genetic algorithm optimization process – corner radius

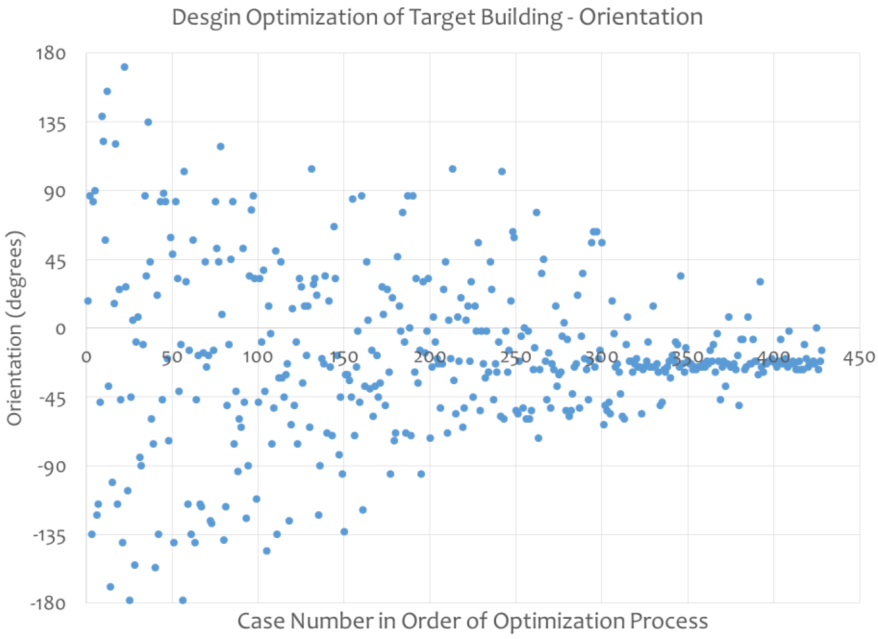

Figure J.5 Genetic algorithm optimization process – orientation

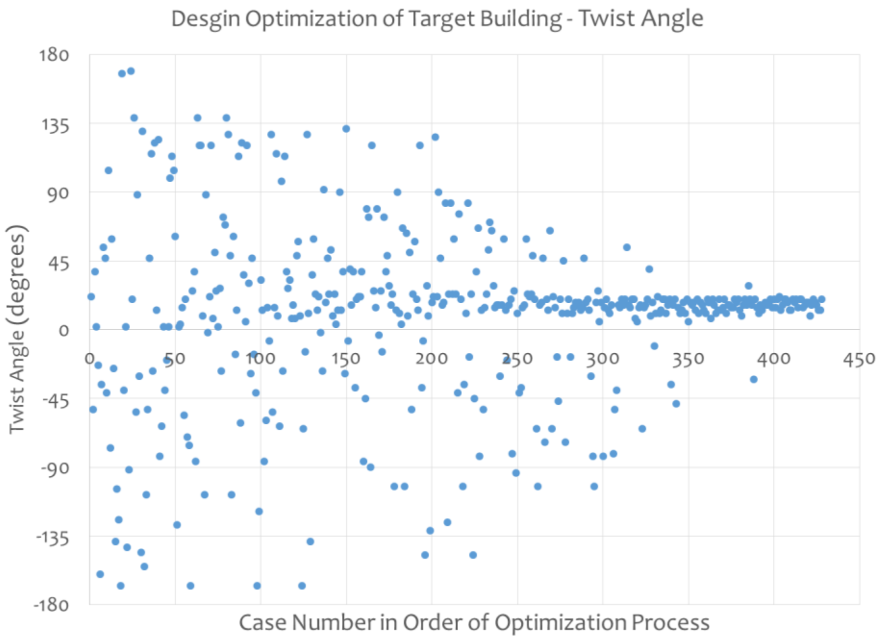

Figure J.6 Genetic algorithm optimization process – twist angle

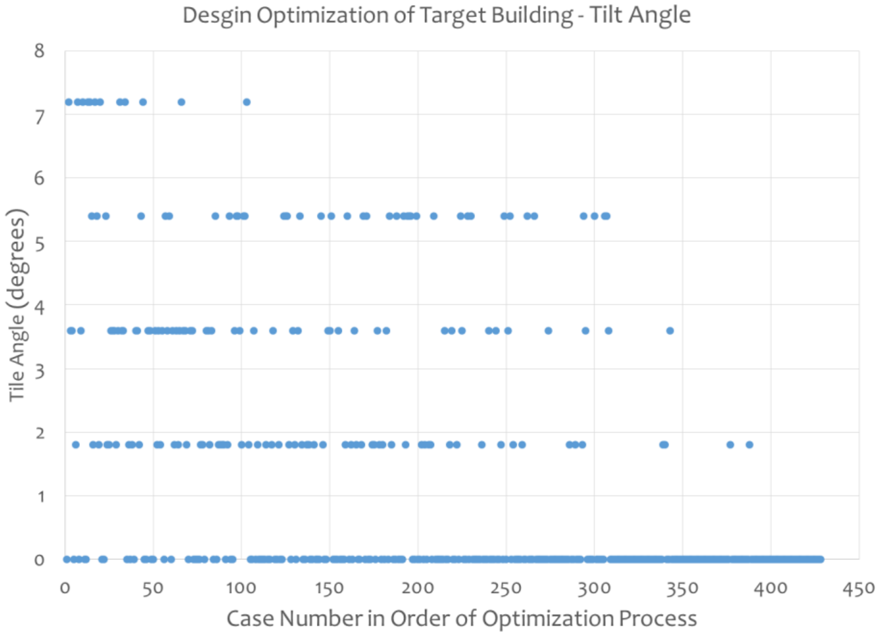

Figure J.7 Genetic algorithm optimization process – tile angle

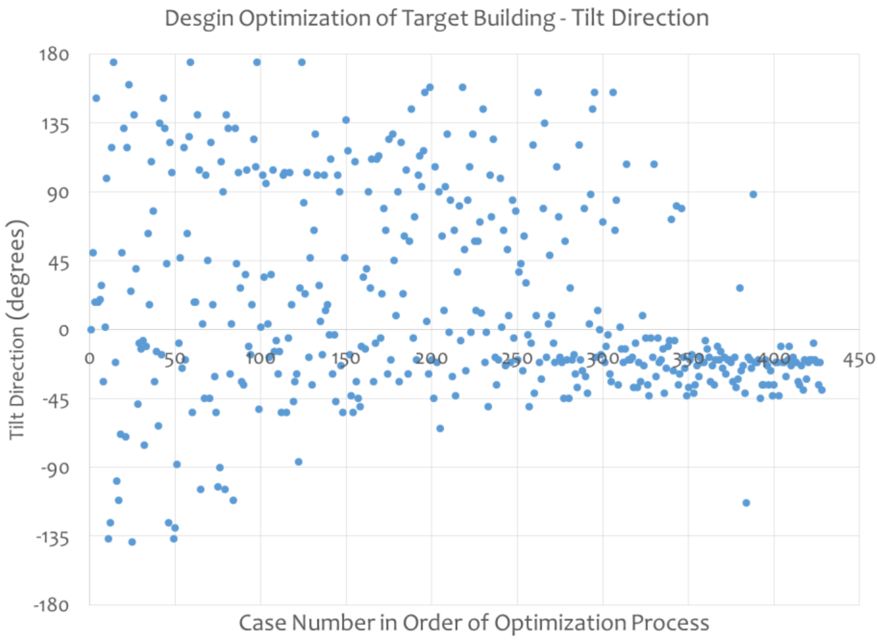

Figure J.8 Genetic algorithm optimization process – tile direction