DISCUSSION ON METHODOLOGY OF APPLYING BUILDING THERMAL SIMULATIONIN IN CONCEPTUAL DESIGN

Yingxin Zhu, Chunhai Xia, and Borong Lin

Department of Building Science, School of Architecture, Tsinghua University
Beijing 100084, China

ABSTRACT

In order to realize “design by simulation” in building design, this paper discusses the methodology of applying building thermal simulation in the building conceptual design stage. The conceptual design stage is divided into four sub-stages and the framework of design by simulation in the conceptual design stage has been built. Moreover, energy saving potential assessment by simulation in the preliminary conceptual design stage is discussed in detail, including input/output information, calculation method and procedure, requirements and information from architects for architectural design, etc.. Natural ventilation design is used as the first trial in this study, its difference between in the detail conceptual design and in the preliminary conceptual design is discussed and the new simulation methodology is described. Such a research is aimed at avoiding wrong decision made in the conceptual design stage, and providing a better base for energy efficient design in the next stage by means of building thermal simulation tool.

INTRODUCTION

Since the energy crisis in 1970s, building thermal simulation has been developing widely and fast during the last decades. Nowadays, more and more architects, engineers and researchers can freely use different kinds of building thermal simulation tools such as EnergyPlus, DOE-2, DeST, ESP-r, TRNSYS, ECOTECT and so on. Although great development has been achieved, most tools are mainly developed focusing on more simulation method than on design process. The design process generally comprises conceptual design stage, preliminary design stage and detailed design stage. Most simulation tools have been used in preliminary design stage and detailed design stage, or used as the building performance assessment tools after design or construction. It is hardly to find cases of building performance simulation application in conceptual design stage. In fact, the important parameters affecting building thermal performance are mainly considered in the conceptual design stage, including shape, orientation, window-to-wall ratio (WWR), interior space layout and so on. As a result, building thermal simulation in the conceptual design stage is crucial to improve building thermal performance and the importance has been discussed in a lot of literatures (K.J. Lomas 1992, Mottillo Maria 2001, Thornton Samuel B. 1997). Therefore, more efforts should be made to bring simulation into design, especially in the conceptual design stage.

However, several difficulties exist in applying current building simulation tools into the conceptual design as follows:

(1) Some building simulation tools are claimed that they can be applied in the conceptual design stage, but can only give little assistance to architects in the end of conceptual design stage while large changes of design can not be accepted. According to the investigation on choosing energy saving components in 67 buildings by Pieter de Wilde (2004), although 57% of the total 303 energy saving components are decided to be applied in the conceptual design stage, but tools can not be available to support design decision until the preliminary design stage starts.

(2) In the conceptual design stage, the architects and owners want to know the rough thermal performance of the building, but current simulation tools can only provide exact result in the preliminary design stage with detail input information, some of which are impossible to be acquired during this stage.

(3) Most building simulation tools are originally developed for HVAC engineers, so the input/output parameters and the description method of available information are not consistent with architect’s concept in the conceptual design stage.

Therefore, it is difficult to find a buidling simulation tool to meet the requirement of architects or owners in the conceptual design stage. Some obstacles should be eliminated and new tools need to be developed.

The opinion of "design by step and simulation by step" was firstly proposed and practised by Yi Jiang when his group started to develope DeST, a Designer’s Simulation Toolkits from the begining of 1990s(T. Hong, 1997). The simulation process in DeST is divided into several steps to meet the requirement of different stages in HVAC system design, and the input/output paramters as well as simulation algorithms are different in different steps (DeST Devlopment Group 2006). DeST provides a good simulation tool for HVAC desigers and the methodology of DeST can be introduced into the architecture design to improve building thermal performance in early design stage.

In order to follow the principle "design by step and simulation by step" in the conceptual design stage, several issues are discussed in detail as followis :

(1) Subdivision of conceputal design stage and their characteristics.

(2) The requirement of architects on building thermal simulation tools for architecture design in each sub-stages.

(3) What kinds of information are available for building thermal simualtion in different sub-stages?

(4) How the simulation procedure should be?

Furthermore, a framework to realize thermal simulation in the conceptual design stage is built in the next step, and natural ventilation simulation in early stage is taken as the first trial.

SUBDIVISION OF CONCEPTUAL DESIGN STAGE

In the subtask “Design Process Analysis” of IEA ANNEX 30 (Markku Jokela 1998), the whole building construction process is divided into six stages**:** conceptual design, preliminary design, detailed design, commissioning phase, facilities management and renovations. Conceptual design is the first step and the large-scale elements of the building are usually determined during this stage. When an architect finishes conceptual design, main part of the building has been decided preliminarily, which can only be modified slightly in the later stages. Meanwhile, final concept of the building is achieved one by one step. Therefore, conceptual design stage also needs to be divided into several sub-stages. L. Zhang’s suggestion (2001) said the conceptual design stage can be divided into four sub-stages: sketch design, layout design, preliminary conceptual design and detail conceptual design. Considering the design task in different periods, the design tasks and available information for simulation can be described as Tab.1 shows.

Table 1 Sub- stages of conceptual design

SUB-STAGE	TASKS	KNOWN INFORMATION FOR SIMULATION
Sketch design	Analyze design specification and form the basic concept of the building.	None
Layout design	Deal with the relationship with surrounding environment, design layout of building cluster and design landscape	Building size, building cluster layout as well as waterscape and greening
Preliminary conceptual design	Rough design of building’s shape, façade, interior space, structure, functional area division and so on	Building function, rough plan drawing, rough elevation drawing
Detailed conceptual design	Detailed deign of building’s plan, façade and shape; selecting building material for structure and main facades.	Detailed plan drawing, detailed elevation drawing, building structure materials and their physical properties, room function.

PROCEDURE OF “SIMULATION BY STEP”

In order to realize “simulation by step”, the building design work in the whole process can be sorted as two parts: architect’s contribution and simulation tool’s contribution. As described in Fig.1, when architect achieves a design scheme in each sub-stage, the building simulation tool should provide predicted result to assess the design. If the design scheme can meet both architect and owner’s requirement, design process will go on to the next sub-stage; otherwise, the current design should be modified.

The initial concept of the building and the culture element contained in the building are mainly discussed in the sketch design stage. “Building” in this period is expressed as a very simple shape, which even doesn’t look like a building. For example, Ronchamp Chapel designed by Corbusier looks like an ear not a building in the sketch design stage. On the other hand, architect expects his thinking work not to be broken as far as possible. Therefore, building simulation tool is unnecessary in this stage.

In the layout stage, architect begins to consider the relationship between adjacent buildings, rough building shape, building height as well as landscape environment surrounding the building. Reducing heat island effect, improving natural ventilation application potential for single building, ensuring enough duration of sunshine are the main aspects that should be took into account with building simulation tools. Single building design includes two stages: (1) in the preliminary conceptual design stage, architect mainly considers the large-scale elements of the building, such as building shape, façade type(WWR), division of interior space, structure type, building function as well as application of passive energy saving technologies; (2) in the detailed conceptual design stage, building elements are discussed in details and, including determine materials of structure and main facades, thermal parameters of walls and windows as well as some slight modification. Once the preliminary conceptual design is finished, major change of the design can hardly be accepted. If energy inefficient problems exist in the preliminary conceptual design, high-performance building components may have to be used to counteract this defect, which will increase the total investment. Current building thermal simulation tools always require all detailed building information as input data, which can only be available until the end of conceptual design stage. Therefore, new building thermal simulation tools should be developed with the following functions in the preliminary conceptual design stage:

(1) Predict the possibility of architectural scheme in realizing energy efficient and its cost.

(2) Give the comparison between energy conservation potentials of different building design schemes, and aid the designer to make decision.

(3) Provide analysis of the influence of different parameters on building thermal performance.

(4) Help to make clear the key points in the later design sub-stages, especially the detail design of material.

For function (1), (2) and (4), the energy efficient possibility assessment method in the preliminary stage should be developed, which will be discussed in detail in the natural ventilation design. For function (3), sensitivity analysis of different parameters can be applied, which has been discussed in many literatures (K.J. Lomas 1992, Mottillo Maria 2001, Thornton Samuel B. 1997).

NATURAL VENTILATION DESING

Because of its energy saving potential and its dependence on internal space design, most architects prefer to conduct natural ventilation into building concept. Meanwhile, atrium, solar chimney, ventilation shaft and other natural ventilation components have significant influence on building design, the energy saving potential of which needs to be confirmed as early as possible. The design of natural ventilation can be divided into three sub-stages (Fig.2). In the layout design stage, building layout and shape are designed according to the wind pressure coefficient on the façade. In the preliminary conceptual design stage, main air paths are decided. In the detail conceptual design stage, design of all air paths is finished, which can be dealt with by the conventional ventilation simulation tools.

Following section will focus on the new simulation methodology of natural ventilation in the preliminary conceptual design stage and new evaluation index to aid architects' design.

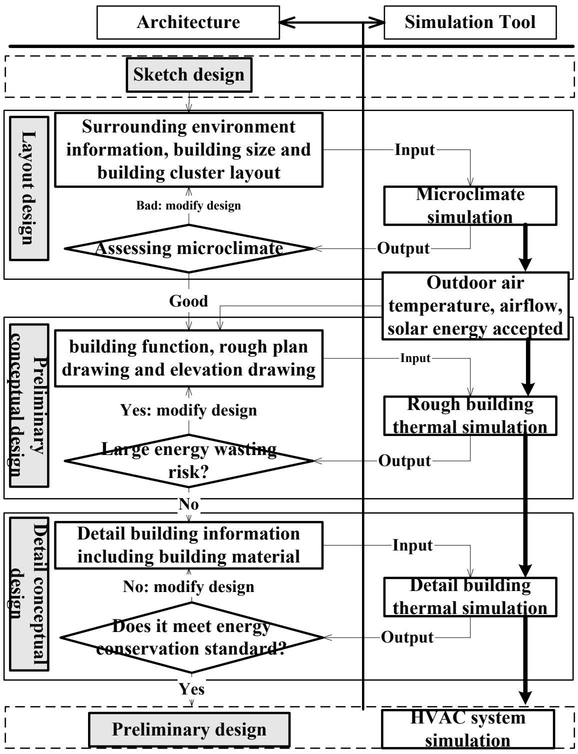


Figure 1 Framework of design by simulation in the conceptual design stage

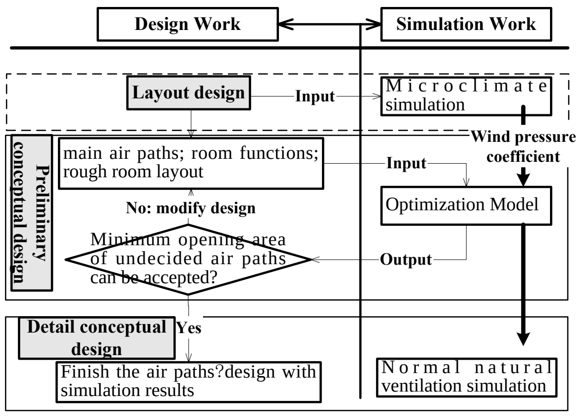


Figure 2 Conceptual design process of natural ventilation

Mathematical Model

Natural ventilation of whole building depends significantly on the aperture area and resistance coefficient of the air paths, which are usually acquired step by step. In the preliminary conceptual design stage, only some main air paths are considered. Other paths will be designed in detail conceptual design stage or preliminary design stage. As seen in Table 2, ventilation network model and building thermal model can be solved simultaneously to obtain indoor temperature and air flow volume of each path in detail conceptual design stage when all the information of air paths can be achieved. If the indoor air temperature is higher than requirement, the designer can change the aperture area until all the indoor temperature is lower than the upper limit.

Table 2 Comparison of available information for natural ventilation simulation

	PRELIMINARY CONCEPTUAL STAGE	DETAIL CONCEPTUAL STAGE
Input	allowable limit of occupied rooms' indoor temperature; main air paths' opening area; all air paths' resistance coefficient (rough value)	air paths' opening area and resistance coefficient;
Output	all rooms' indoor temperature; all air paths' air flow volume; subsidiary air paths' opening area	all rooms' indoor temperature; all air paths' air flow volume;

However, in the preliminary conceptual design stage, the detail design of the rooms, façade and roof has not been done yet. Only the information of main air paths (such as atrium and solar chimney) can be acquired for natural ventilation simulation. Although, other air paths' opening area and resistance coefficient can be assumed and the same simulation method in the detail conceptual stage can be adopted, several problems still can not be avoided:

(1) The number of data need to be assumed such as the information of unknown air paths is too large;

(2) Whole building's ventilation strongly depends on the assumed air paths, and different assumption will lead to different results;

(3) From the standpoint of design process, the main work in the preliminary conceptual stage should be focused on designing main air paths. Too much relating to the subsidiary air paths, which should be designed in the later stage, has deviated from the principle of "design by step and simulation by step".

Considering that the design work of following stage will be the opening area and types of the subsidiary air paths, the allowable minimum sum of undecided air paths' opening area (F_{sum}) is used as the index to evaluate different ventilation network. As the restriction, the indoor temperature of occupied spaces can not exceed the upper limit.

Based on the theory of hydrodynamic network, a room is defined as a node while an air path is defined as a branch. The relationship of the nodes and branches can be described with relevant matrix A, in which

$$A(i,j)=\begin{cases}+1, & b_j \text{ connects to } n_i \text{ and flows into } n_i \\ -1, & b_j \text{ connects to } n_i \text{ and flows out from } n_i \\ 0, & b_j \text{ doesn't connects to } n_i\end{cases}.$$

b_j denotes the branch j, and n_i denotes the node i. The size of **A** is n×m，where n is the total number of rooms and m is the total number of air paths. Furthermore, define $\mathbf{A_{out}}$ to describe the air flow from node to branch and heat flux in the branch can be calculated as G•($A_{out}{}^{T}$T), where **G** is the air volume in the branch (m^3/s) and **T** is the temperature of the node.

$$A_{out}(i,j)=\begin{cases}+1, & b_j \text{ connects to } n_i \text{ and flows into } b_j \\ 0, & \text{other}\end{cases}.$$

Based on the state space method (Y. Jiang 1982), the heat balance equation of single room can be expressed as:

$$\begin{aligned} t_a(\tau) &= t_{bz}(\tau) + \sum_j \Phi_{j,0} t_j(\tau) + \Phi_{hvac} q_{hvac}(\tau) \\ &\quad + \Phi_{hvac} C_P \rho_0 G_{out}(\tau)(t_{out}(\tau) - t_a(\tau)) \\ &\quad + \sum_j \Phi_{hvac} C_P \rho G_j(\tau)(t_j(\tau) - t_a(\tau)) \end{aligned} \quad (1)$$

Φ is the coefficient that reflects different thermal process's influence on the current temperature, and detail calculation method of different Φ can be found in (Tsinghua University DeST development group 2006). t_j is the temperature of adjacent room, and t_{bz} denotes the influence of history temperature and current other thermal process, excluding current heating/cooling supplied by HVAC system, ventilation and heat transfer of adjacent room. When calculate current t_a under natural ventilation, t_{bz} is known and q_{hvac} equals zero. Introducing **A** and $\mathbf{A_{out}}$ into heat balance equation, eq.(1) can be rewrote as a matrix form.

$$\begin{aligned} &\mathbf{T} = \mathbf{T_{bz}} + \mathbf{\Phi_0 T} + \mathbf{\Phi_{hvac}} C_P \rho \mathbf{A}\left[\mathbf{G} \cdot \mathbf{A_{out}^T}(\mathbf{T} - \mathbf{T_{out}})\right] \\ &\Rightarrow C_P \rho \mathbf{A}\left[(\mathbf{I}\cdot\mathbf{G})\mathbf{\Phi_{hvac}}\mathbf{A_{out}^T}(\mathbf{T} - \mathbf{T_{out}})\right] + (\mathbf{\Phi_0} - \mathbf{I})\mathbf{T} = -\mathbf{T_{bz}} \end{aligned} \quad (2)$$

Define B_f ((m-n)× m) as basic loop matrix, and

$$B_f(i,j)=\begin{cases}+1, & \text{air flows in branch } j \text{ with the same direction of loop } i \\ -1, & \text{air flows in branch } j \text{ with the opposite direction of loop } i \\ 0, & \text{branch } j \text{ dosen't belong to loop } i\end{cases}.$$

In ventilation network, the dependent air volume is defined as $\mathbf{G_L}$ ((m-n)×1), and then $\mathbf{G}=\mathbf{B_f}^{\mathbf{T}}\mathbf{G_L}$. The same as kirchhoff's voltage law, pressure loss of each basic loop can be expressed as

$$\mathbf{B_f \Delta H} = \mathbf{B_f}\left[\left(\mathbf{I}\cdot\frac{\mathbf{s}}{\mathbf{F}^2}\right)(\mathbf{I}\cdot|\mathbf{G}|)\mathbf{G} + g\boldsymbol{\rho}\cdot\mathbf{Z} - \mathbf{DH}\right] = \mathbf{0}. \quad (3)$$

Vector **s** and **F** are the resistance coefficient and opening area of each branch respectively, vector **Z** is the vertical height along the air flow direction between the two ends of the branch, and **DH** is the pressure head provided by wind pressure and the temperature difference in the branch. Vector **ρ** is the air density in each branch and is decided by the air temperature.

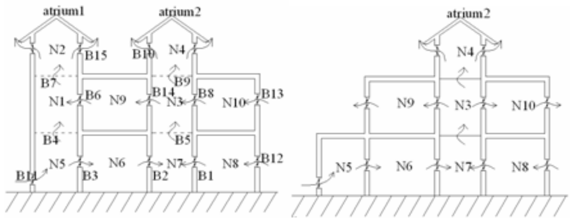
The opening type of each branch can be roughly confirmed and **s** value can be obtained. If the known main air paths' opening area is $\mathbf{F_2}$ and the undecided air paths' opening area is $\mathbf{F_1}$. The number of variables of $\mathbf{F_1}$ and $\mathbf{F_2}$ are m_1 and m_2 respectively. The total number of eq.(2) and eq.(3) is m, while the unknown variables are **T**(n), $\mathbf{G_L}$(m-n) and $\mathbf{F_1}$(m_1). The number of variables is larger than the number of equations, therefore, infinite solutions exist. As discussed above, the minimum sum of $\mathbf{F_1}$ is required for evaluating natural ventilation design. Therefore, an optimization model can be built as

$$\begin{cases} C_P\rho_0\mathbf{A}\left[(\mathbf{I}\cdot\mathbf{G})\mathbf{\Phi_{hvac}}\mathbf{A}_{\mathbf{out}}^{\mathrm{T}}(\mathbf{T}-\mathbf{T_{out}})\right]+(\mathbf{\Phi_0}-\mathbf{I})\mathbf{T}=-\mathbf{T_{bz}} \\ \mathbf{B_f}\left[\left(\mathbf{I}\cdot\dfrac{\mathbf{s}}{\mathbf{F}^2}\right)(\mathbf{I}\cdot|\mathbf{G}|)\mathbf{G}+g\boldsymbol{\rho}\cdot\mathbf{Z}-\mathbf{DH}\right]=\mathbf{0} \\ \mathbf{F}=\left[\mathbf{F}_1 \quad \mathbf{F}_2\right]^{\mathrm{T}} \\ \mathbf{G}=\mathbf{B}_{\mathbf{f}}^{\mathrm{T}}\mathbf{G}_{\mathrm{L}} \\ 0\le\mathbf{T}_1 \\ 0\le\mathbf{T}_2\le 29 \\ 0\le\mathbf{F}_1 \\ \min sum(\mathbf{F}_1) \end{cases} \quad . \quad (4)$$

$\mathbf{T_1}$ is the temperature of the occupied room, which should not exceed 29℃ under natural ventilation. $\mathbf{T_2}$ is the temperature of the auxiliary room, which doesn't need to be controlled. For the optimization issue in eq.(4) with linear objective equation and nonlinear constraint equations, SQP algorithm is applied (Guangcheng Zhang 2005) .

Case Study

For the building in Fig.2, two atriums are designed in (a) and one atrium is designed in (b). The two schemes have large difference in room layout and simulation should be carried out to aid architects to make decisions that whether two atriums are necessary.



(a) (b)

Figure 3 Scheme of natural ventilation

In Fig.3 (a), temperature standard of room N5~N10 is not exceed 29℃, opening area and resistance coefficient of B4, B5, B7 and B9 are known. In Fig.3 (b), only one atrium exists.

Applying optimization method to solve the problem, optimal opening area of each air path, indoor temperature and indoor air change rate (ACR) are shown in Tab.3~Tab.5. The air flow direction of each path is shown in Fig.3. Temperature of all the occupied rooms can meet the design standard. In the two-atrium scheme (a), air flows out of building across the paths on the ceiling of atriums (B10 and B15).While in the one-atrium scheme (b), air flows out of the building across the paths on the atrium's ceiling and external windows on the second floor (B6 and B13). Furthermore, air flowing across B10 in scheme (b) is 1167 m^3/h, while air flowing across B6 and B13 in scheme (b) is 5035 m^3/h. In other words, the contribution of solar chimney on the third floor in scheme (b) to natural ventilation is less than the two atriums in scheme (a).

F_{sum} of scheme (a) and scheme (b) are 26.8 m^2 and 31.3 m^2 respectively. Therefore, in order to maintain same indoor thermal environment, less aperture area is needed in scheme (a). Architects can decide to select the schemes by the minimum of aperture area

Table 3 Opening area of air path (m^2)

SCHEME	**B1**	**B2**	**B3**	**B4**	**B5**	**B6**	**B7**	**B8**
(a)	0.1	1.6	1.6	40.0	40.0	3.3	40.0	4.4
(b)	3.7	3.7	2.8	/	40.0	5.8	/	1.4
SCHEME	**B9**	**B10**	**B11**	**B12**	**B13**	**B14**	**B15**	**total**
(a)	40.0	3.2	1.1	0.1	4.4	3.2	2.6	26.8
(b)	40.0	0.5	3.3	4.1	1.7	4.4	/	31.3

Table 4 Indoor temperature (℃)

SCHEME	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**	**N9**	**N10**
(a)	30.5	32.1	24.7	27.6	25.7	29.0	29.0	24.4	29.0	22.5
(b)	/	/	25.8	31.7	27.8	29.0	25.0	21.3	29.0	29.0

Table 5 ACR of room (h^{-})

SCHEME	**N1**	**N2**	**N3**	**N4**	**N5**	**N6**	**N7**	**N8**	**N9**	**N10**

(a)	31.8	31.8	39.1	21.1	20.5	4.2	8.1	0.9	11.3	19.4
(b)	/	/	43.1	8.1	17.3	10.8	43.1	16.1	16.6	5.2

CONCLUSION

Successful application of building simulation in the conceptual design stage is crucial to improve building thermal performance and can contribute to reducing energy consumption from the beginning. The conceptual design stage can be divided into four sub-stages for the procedure of "simulation by step". Meanwhile, the simulation stage is defined in consistent with design stage, including microclimate simulation, rough thermal simulation and detailed thermal simulation. Furthermore, the framework of design by simulation is built and several important issues are presented which needs further research.

In order to simulate natural ventilation in the preliminary conceptual design stage, difference of available information between preliminary conceptual design stage and detail conceptual design stage is discussed and an optimization model is developed as a trial of this research. The minimum sum of unknown air paths' opening area is applied to evaluate different ventilation network. The results can also aid the detail design of air paths in the future stages.

It is just a kick off for the research on applying building thermal simulation tools in the conceptual design stage and some bottle-necks in the research have been discussed briefly. Undoubtedly, a great deal of work is remained to be done in the further research.

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