A DECISION-SUPPORT FRAMEWORK FOR DESIGN OF NATURAL VENTILATION IN NON-RESIDENTIAL BUILDINGS

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ABSTRACT

This study develops a decision-support framework assisting the design of non-residential buildings with natural ventilation. The framework is composed of decision modules with input, analysis algorithms and output of natural ventilation design. The framework covers ventilation with natural driving force and mechanical-assisted ventilation. The framework has two major assessment levels: feasibility assessment and comparison of alternative natural ventilation approaches. The feasibility assessment modules assess the potential of the site with the design proposition for natural ventilation in terms of wind, temperature, humidity, noise and pollution conditions. All of the possible natural ventilation approaches and system designs are assessed by first applying constraints functions to each of the alternatives. Then the comparison of alternative approaches to natural ventilation continues by assessing the critical performance mandates that include energy savings, thermal comfort, acoustic control, indoor air quality and cost. Approaches are finally ranked based on their performance.

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CHAPTER 1 INTRODUCTION

1.1 PROBLEM STATEMENT

As a design and operating strategy, when properly understood and applied, natural ventilation (NV) can significantly reduce building energy consumption. Moreover, natural ventilation can provide both good indoor air quality and desirable thermal comfort conditions that can positively influence occupants' health and productivity, while providing an explicit connection to the outdoors. For these reasons**,** natural ventilation design and operating strategies are growing in popularity.

Natural ventilation as a design and operating strategy can be effective in many climate zones in the U.S. For example, Chen summarizes the months when various climate regions in the U.S. can potentially use natural ventilation [1]. He concludes that natural ventilation could be beneficially applied for several months in many U.S. locations**.** Unfortunately, natural ventilation is currently underutilized in non-residential buildings. While the majority of naturally ventilated non-residential buildings are in Europe, few have recently been constructed in the U.S. This may be because methods for integrating natural ventilation in non-residential buildings are not well known.

Compared to residential buildings, non-residential buildings often have much more demanding occupancy and room functions, larger plan-depth and building volume, and various performances and safety requirements that must be addressed. These greatly complicate the application of natural ventilation. To be most effective, the design of naturally ventilated buildings must begin early in the design process with the careful choice of appropriate building sites and an analysis of the feasibility and performance of alternative approaches. However, few designers are knowledgeable of the decisions that impact the integration of natural ventilation into buildings. The decisions related to this process must take into account both technical and architectural goals, while considering performance issues such as energy savings, thermal comfort, sound transmission, security, indoor air quality**,** and cost. These issues are interactive and incommensurate. In practice, there is a need for a systematic decision-support framework for designers who are considering the use of natural ventilation in non-residential buildings.

1.2 RESEARCH OBJECTIVES AND METHODOLOGY

1.2.1 Grounded Theory methodology

The objective of this research is to establish a decision-support framework to assist the design of non-residential buildings with natural ventilation. The Grounded Theory approach is ideal for this purpose.

Grounded Theory is an inductive, systematic theory generation methodology**,** based upon empirical observations or data, that was developed by Glaser and Strauss [2]. The major difference between grounded theory from other research methods is that it is emergent. It does not test a hypothesis**;** rather, its aim is to understand the research situation. Any data collection methods can be used for this purpose. Glaser and Strauss (1967, p. 65) state, “Different kinds of data give the analyst different views or vantage points from which to understand a category and to develop its properties; these different views we have called slices of data. While the [researcher] may use one technique of data collection primarily, theoretical sampling for saturation of a category allows a multifaceted investigation, in which there are no limits to the techniques of data collection, the way they are used, or the types of data acquired.”

Based on the Grounded Theory methodology, this research utilizes a progressive accessing of the literature throughout the whole research process as a major part of the data collection procedure; thus, the grounded analysis of the literature leads to the generation of the theoretical framework. At the early stage, when theory emerges, the research begins to identify categories and their properties (sub-categories). The process is called the note-taking or coding. Categories provide the means by which the theory can be integrated. Theoretical propositions will occur when coding. As categories emerge from the literature review, the research seeks to further increase diversity to strengthen the emerging theory by defining the properties of the categories and finding the relationship between them. Case studies and further literature review are the major sources of data for this purpose. In this stage, identified connections between categories are then recorded in memos. As the data collection and coding proceeds continues, if the core category and its linked categories saturate, which means reaching a point of “diminishing returns,” sorting begins with the grouping of memos. They are subsequently sequenced in certain order to clarify the theory. The literature review can still serve in the sorting stage by providing more data to code and compare with what has already been coded and generated. The order of the sorted memos provides the skeleton of the framework.

Therefore, to develop the framework, the research begins with (1) identification of sources of relevant knowledge, and (2) knowledge organization; these two steps are similar to the coding, memo taking and sorting procedures described above. The research then follows with (3) description, illustration, and adaptation, and (4) validation. Some steps are concurrent and the process may be iterative (Figure 1.1).

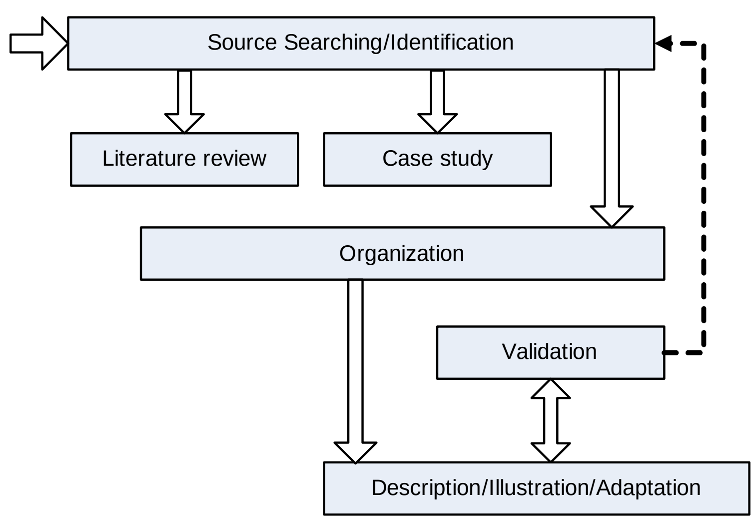


Figure 1.1 The process of the research

The research identifies issues related to the design for natural ventilation, structures the decision process related to those critical issues, and proposes assessment approaches with the inputs, analysis algorithms, and outputs for the decision-support structure for natural ventilation.

The inputs are determined in terms of the type of information required as well as their relationships to the assessment procedures and the output. After identifying the critical issues, the next step is developing a process of assessment. Indeed there will be multiple assessment procedures in the framework. The outcomes from the assessment procedures may be categorized as Binary (Yes or No), Scalar (Low to High), or Categorical, and these methods of assessment can also be found in the literature or through case studies and interviews. The output will likely depend on the level of design development, ranging from general system configuration decisions in the concept phase to system detailing made well into design development. The input, processes, and output are structured into an overall framework.

1.2.2 The process of the research

The process of the research is described in the following steps:

Step 1. Identify critical issues; propose assessment approaches with the inputs, algorithm analysis, and outputs for decisions related to natural ventilation in the design process.

(1) Literature review

Tools, inputs, procedures, and outputs related to naturally ventilated building design can be identified through extensive literature review. If the tools and analysis algorithms related to some design issues are currently unavailable, the situation will be noted. This is important to the future improvement of the framework.

(2) Study naturally ventilated buildings

Recently constructed examples of naturally ventilated buildings can provide practical information that will impact the development of the framework. Case studies will focus on how the design decisions were made based on the specific projects, the goals and constraints that influenced those decisions, and the lessons that can be gleaned from successful and unsuccessful buildings.

Step 2. Identify related mandates from building codes, standards and regulations.

For example, ASHRAE 62 suggests ventilation standards for maintaining good indoor air quality and ASHRAE 55 offers guidelines for acceptable thermal comfort, while other mandates address acoustics, fire safety, security, and so forth.

Step 3. Identify and/or develop performance prediction and assessment tools that will be included in the assessment procedures in the framework.

Step 4. Develop a framework for the input, processes, and output as a map to the design process.

Step 5. Study the interactions and tradeoffs between performance mandates.

Develop a matrix that summarizes the interactions between inputs and issues of feasibility assessment, constraints**,** and performance assessment. Qualitatively **a**nalyze the interactions and tradeoffs between the performance mandates by tracing their common related inputs. The results are given as design suggestions. The interactions can be quantitatively studied in the future.

Step 6. Adapt the framework to fulfill the sub-objectives.

The sub-objectives of the research are:

(1) The framework should be flexible and open to enhancement

An important concern for the development of the framework is that it is a beginning, not an end, so future work should be easily integrated into the framework. Therefore, the framework should be flexible and have an open structure.

To this end, the framework is designed with a modular structure. It is hierarchical, flexible**,** and extendable. Each component of the framework can be separated and replaced, which is convenient for system updating and patching. When new technologies and tools become available, they can be easily plugged into the framework. Sub-modules and any single modules can be changed or replaced. The structure of the modules is illustrated in Figure 1.2. Each module may include inputs, assessments and outputs.

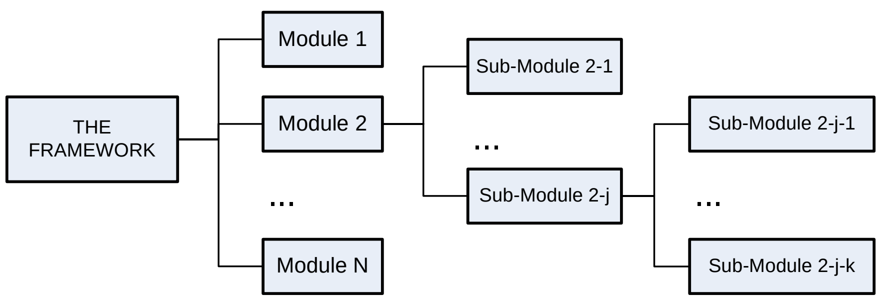


Figure 1.2 The hierarchy of modules

(2) The framework should be easily transformed to a computer-based tool

The framework is developed in such that it can be easily adapted to a computer-based tool.

Firstly, the modular-based structure fits this purpose. In view of the systems design of programming, the decision framework can be translated to an object-oriented style. Modules can be represented as classes and the relationship between them can be modeled by object-oriented techniques. Sub-modules are their own inherent classes. Each inherent class can include some classes that represent a special part of analysis. More classes can be added at each level if needed in the future.

Secondly, the working flow of the framework is illustrated from general to specific, i.e. hierarchically from the whole prospective of the framework to the levels of modules and sub-modules. The computer tool can be developed based on this hierarchy.

(3) The framework should be easy to represent with the graphic language of decision-making

The graphic language of decision-making used in disciplines such as business and engineering can be borrowed to describe the decision process of the framework. Among the basic rules of the language introduced by Clemens [3], influence diagrams can be used to illustrate a decision problem by only including the objects relevant to the problem and their relations.

The rules of influence diagrams are introduced as the following. The elements of the decision process are represented by three nodes: rectangular nodes represent decisions; circular nodes represent chance events and rounded rectangles represent consequences. Arrows pointing into decision nodes are called sequence arcs. Arcs pointing into a chance node or a consequence node are called sequence arcs. These rules are graphically depicted in Figure 1.3.

The relationship between elements in each important module will be illustrated by influence diagrams.

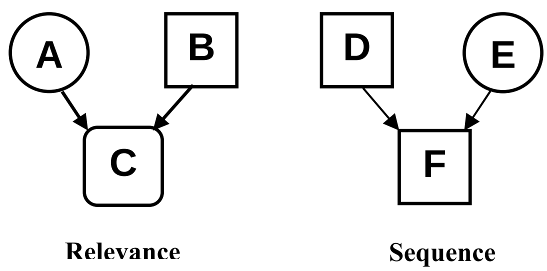


Figure 1.3 The graphic rules of influence diagram

Step 7. Validate the framework

Framework validation is a critical step in the study. Although some of the algorithms used in the modules of the framework might already be validated when published, and some may already be used in practice, the whole framework, including the integration of these algorithms, the procedures, the issues identified, and the design suggestions, need to be validated for necessity, appropriateness, and comprehensiveness.

(1) The strength and weakness of case study as a validation method for this research

As discussed previously, studying constructed building cases has its unique benefit for the framework. Each case may involve many aspects related to the design of natural ventilation. On the other hand, if a case study is used for validating the framework (that is, if the built cases were used to process through and demonstrate the effectiveness of the framework by comparing the outcome with the case itself) then this "inverted" process would produce distinct weakness that would be difficult to avoid for the following reasons:

a. The replication of the benchmark cases and the availability of detailed input information

To be effective for validating the framework, only "successful" cases in terms of the performance of NV system should be used. Those "unsatisfying" cases are only valuable to the extent that they offer lessons for constructing the framework. However, there are only a few "successful" cases available in the U.S. The performance of some cases**,** such as the Chesapeake Bay Foundation Environmental Center**,** are not satisfying [4].

In addition, to be most accurate, the inputs and constraints extracted from the case study should be highly detailed**,** which would require much cooperation and time from designers**;** this is not likely to occur. Given that the number of successful naturally ventilated non-residential buildings in the US is very limited and the designers who have the time to participate are few, the replication of cases is nearly impossible, **so** the direct implementation of the framework toward validation is not feasible at this time.

b. Over-complication

The framework is not a comprehensive design tool but a decision-support tool that will assist in designs with natural ventilation. The actual design process is often non-linear, while the decision-support framework for natural ventilation system design includes a linear, iterative process. Through the iterative process, users may improve their design**s** when natural ventilation is the goal.

Actually, the NV system must be highly integrated with the architectural design as well as with other building systems. Therefore, decisions related to natural ventilation must begin at an early phase. However, it is impossible to include every factor potentially related to the design of NV into the framework. For example, details concerning the building geometry may not be completely known and may be the result of the process itself. During the early phases, the geometry may not be well adjusted with other issues that are indirectly related to the design for natural ventilation but beyond the scope of the framework**.** One such example would be adjusting the building geometry for daylighting or other passive systems. When comparing the outcome of the framework with loosely defined inputs to the predicted performance of the case with the final design, some discrepancy may occur. Accepting the inputs that have been integrated with other systems**,** such as daylighting, the natural ventilation approach is already fixed and the validation process stops. For example, in the case of the Lanchester Library (UK, Case 2-1) the inputs of building geometry integrated with daylighting, i.e. with four light wells, the only available natural ventilation approach was stack ventilation**,** as the designer did not think that wind assistance was reliable.

Therefore, constructed case**s** with highly integrated systems may greatly limit the power of validation.

(2) The alternative approach

An alternative method would be to introduce the framework to experienced professionals and specialists while asking for their comments and suggestions. If most of the practitioners consider the framework to be useful, this will provide a level of acceptance for it.

a. What needs to be validated

An assumption is the algorithms used in the framework are valid, although they may not be perfect. Their appropriateness needs to be validated. In addition, the critical issues, decision procedures, and the design suggestions proposed by the framework also need to be validated.

b. The advantages and disadvantage of the alternative approach

Critical review and comments will be provided by experienced processionals and specialists. This approach will rely on their judgment and has the advantage of integrating their experiences, both successful and unsuccessful, on the design of naturally ventilated buildings. Although the alternative approach cannot provide full validation of the framework, this method potentially covers a more comprehensive and extensive scope than the case-study validation framework. This method also requires less time and effort from both the professionals and the author. The disadvantage is that the reviewers' personal preferences may influence their views and comments on some issues.

c. The process

The framework was sent to three dissertation reviewers with a questionnaire, including questions about the general usefulness of the framework and important details. In addition, the general structure of the framework was commented by journal reviewers. Modifications were based on the reviewers' feedback.

1.3 LIMITATIONS OF THE RESEARCH

The framework focuses mainly on the early phases of design for natural ventilation in non-residential buildings. The framework covers ventilation with natural driving forces and natural ventilation in hybrid ventilation systems.

(1) Early Design Stages

The life cycle of a facility follows a number of stages: project conception, schematic design, design development, construction documents, bidding, construction, and facility management [5]. The proposed framework is intended to assist designers in the project conception and schematic design phases, during which the potential of natural ventilation will be assessed in terms of the building site and the conceptual design proposition. Natural ventilation approaches are selected from alternatives, and the general size and shape of natural ventilation systems and preliminary cost projections will be determined.

(2) Driving Force

While some natural ventilation methods solely use natural driving forces, such as wind or thermal buoyancy, there are two major types of hybrid ventilation approaches that combine both natural and mechanical driving forces. The first type can be described as both a natural and mechanical ventilation system, as it uses different features of the systems at different times of the day or seasons of the year. Known as the "complimentary mixed mode"[6], it can be a system with natural ventilation in intermediate seasons and mechanical ventilation during mid-summer and/or mid-winter. One such system is used in the Chesapeake Bay Foundation Environmental Center in Annapolis, MD. The second type of mixed system is referred to as "zoned mixed mode"[6], which means that different parts of the building use different ventilation modes.

The framework addresses both all natural and hybrid ventilation approaches as described above, but focuses on the decisions involved with natural driving forces and asks when and where mechanical ventilation should be considered as well as when a system needs to switch to the alternative mode.

(3) Variables and Assessment Categories

Because the issues related to the design with natural ventilation are extensive, it is necessary to limit the number of variables and the assessment categories in this research. Limits upon the input of the framework, feasibility analysis, and performance assessment factors considered in the framework are listed in Chapter 3.

1.4 RESEARCH CONTRIBUTION

The research will offer a decision-support framework to assist the design of natural ventilation in non-residential buildings.

The framework is holistic. The assessments and design suggestions involve broad issues and concerns that a designer may meet in the design process, especially in the early design phases.

The framework is flexible and expandable. Future work can be easily added into the framework. The modular structure with working flow illustration makes it easy to develop into a computer-based tool.

1.5 DISSERTATION ORGANIZATION

This dissertation has eleven chapters that are organized in the following way:

Chapter 1 – **Introduction**: Defines the problems in the area of the study, and presents the research objectives and methodology used to accomplish these objectives. Chapter 1 also explains contributions of the research and limitations of this study.

Chapter 2 – **Literature review**: Gives the general review of fundamental knowledge of natural ventilation, current natural and hybrid ventilation approaches, and identification of the critical issues in the decision of design with natural ventilation.

Chapter 3 – **Case studies**: Based on categorized cases of recently built naturally ventilated non-residential buildings, available from literature and design professionals.

Chapter 4 – **Framework overview:** Describes and illustrates the general structure, critical issues, major components, and the general decision process of the framework.

Chapter 5 – **Interactions between performance mandates**: Analyzes the interactions and tradeoffs between performance mandates.

Chapter 6 to Chapter 9 – **Detailed description and illustration of the modules**: Describes and illustrates the two levels of assessments and components of modules (inputs, algorithms**,** and outputs) in detail. These chapters also discuss the use of assessment criteria and algorithms in the framework.

Chapter 6 – **Feasibility assessment**

Chapter 7 – **Constraints**

Chapter 8 – **Design suggestions**, and

Chapter 9 – **Performance assessment**

Chapter 10 –**Critical review and feedback:** The general comments from reviewers**,** as well as response**s** and modification**s** to the framework based upon their suggestions.

Chapter 11 – **Conclusions and future studies**: Presents the results of the research and its contributions to the body of knowledge. The **c**onclusions of this study are given and future research directions are recommended based on this investigation.

CHAPTER 2 LITERATURE REVIEW

This literature review is intended to determine the current state of knowledge in the area of study and to provide a foundation for the grounded theory. It includes a general review of the fundamental principles of natural ventilation, a consideration of current natural and hybrid ventilation approaches**,** and an identification of the critical decision-making issues influencing design**s** with natural ventilation. The detailed results from the literature that impact the components of the decision-support framework will be described in the following chapters.

2.1. THE DRIVING FORCES OF NATURAL VENTILATION

The driving force of natural ventilation is a pressure difference that can be achieved in buildings by the effect**s** of wind and temperature variations.

2.1.1 Wind pressure

2.1.1.1 Flow around buildings

The features of flow around a building that is at 0° to the approaching flow is shown in Figure 2.1.When the approaching flow is normal to the front wall of the building, the flow rolls-up and is separated over the roof, and may reattach to the roof depending on the turbulence intensity and the length of the roof. If the turbulence is low, reattachment may not occur. The size of the recirculation region behind the building**,** where an arch vortex forms, depends on building geometry, orientation, and wind conditions. The wider the building, the longer the size of the recirculation region.

When the approaching flow is not normal to the front wall of the building, the flow rolls-up and generates two vortices. If the wind is at 45° to the building, the two vortices have the same strength; otherwise, one is stronger than the other.

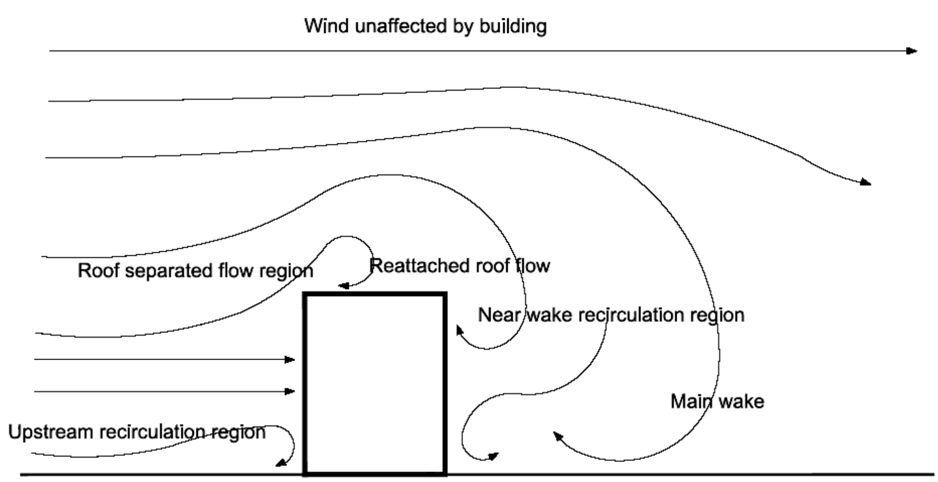


Figure 2.1 Mean streamlines on center of a cuboid normal to the approach flow

2.1.1.2. Pressure caused by wind on the building surfaces

For steady, inviscid, incompressible flow, pressure and velocity are related by Equation 2-1.

$$\frac{P}{\rho} + gz + \frac{v^2}{2} = \text{constant}, \; Nm/kg$$

Equation 2-1

v = velocity of the fluid, m/s

ρ = density of the fluid, kg/m^3

z = elevation, m

g = gravitation acceleration, m/s^2

P = pressure, Pa

This equation is known as the Bernoulli Equation, based on the assumptions that (1) viscous effects are assumed negligible, (2) the flow is steady and incompressible**,** and (3) the equation is applicable along the streamline. The equation shows that along the streamline, where the velocity of a fluid is high, the pressure is low**;** where the velocity is low, the pressure is high.

The time-averaged pressures (p_v) caused by wind on the building surfaces are proportional to the wind velocity pressure:

$$p_v = \frac{1}{2} C_p \rho U_H^2$$

Equation 2-2

U_H = approach wind speed at upwind wall at height H, m/s

ρ = outdoor air density, kg/m^3

C_p = the local wind pressure coefficient for the building surface

Wind-driven ventilation is the flow in the building resulting from the pressure difference of openings caused by wind on the building surfaces.

Since $p_v \propto U_H^2$**,** wind pressure rises significantly as wind speed increases. Variation in wind direction cause various value distribution**s** of C_p on the surfaces of a building. Other factors influencing the distribution are the topography of the building location, the vegetation surrounding the building, obstruction**s** at the site, building geometry**,** and building orientation. Therefore, pressure difference should be assessed in terms of wind speed and direction with respect to the micro-climate and building geometry and the orientation, size, and placement of openings. This can be accomplished by wind tunnel tests or computational fluid dynamics (CFD) simulation, but these approaches are typically not appropriate in the early stages of design. As an alternative, for buildings with approximate rectangular shapes, published data of pressure distribution on building surfaces for varying wind speed and direction are available [7, 8].

2.1.2. Thermal buoyancy

Flow caused by temperature difference is termed buoyancy-driven ventilation. If there is no wind effect, the outdoor and indoor pressures can be expressed as:

$$P_{in} = P_0 - \rho_{out} gh ,$$

Equation 2-3

$$P_{out} = P_0 - \rho_{in} gh$$

Equation 2-4

h = the height of an indoor or outdoor position relative to a reference height, m

P_0 = the outdoor air static pressure at a reference height, pa

P_{out} = the outdoor air pressure at height h, relative to the reference height, pa

P_{in} = the indoor air pressure at height h, relative to the reference height, pa

Therefore, the indoor and outdoor pressure difference at height h is: $\Delta P = (\rho_{out} - \rho_{in})gh$. As shown in Figure 2.2, because the indoor air is heated, its density is lower than that of the outdoor air. Thus, the indoor air pressure is lower than the outdoor air pressure. This means that the outdoor air will enter the building. When a balance is established, outdoor air will keep entering the building at the lower level, while the indoor air will keep leaving the building at the higher level.

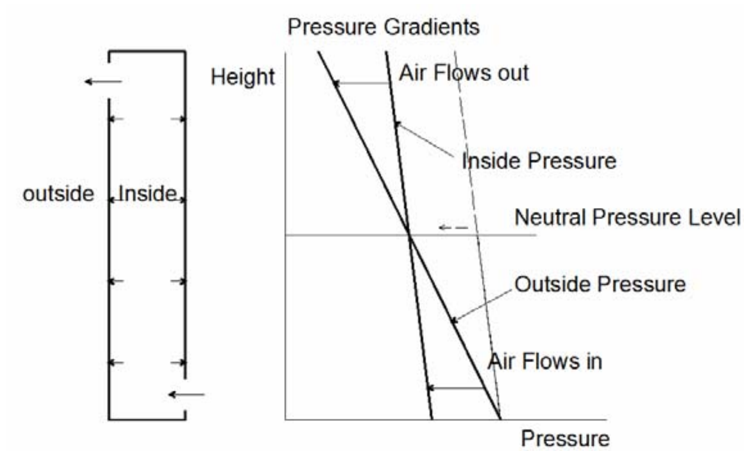


Figure 2.2 Pressure difference caused by thermal buoyancy

2.1.3. Thermal buoyancy and wind pressure

Figure 2.3 shows the inside pressure throughout the building height, combining buoyancy and wind impact with average C_p of each wall and average wind speed (ASHRAE Handbook, Fundamental 2001). Pressure increases on the side with positive $\overline{C}_p$, and decreases on the side with negative $\overline{C}_p$. The higher value of $\Delta\overline{C}_p$ and wind speed $\overline{V}$ results in a larger pressure difference between the two walls and, consequently, greater ventilation driving force.

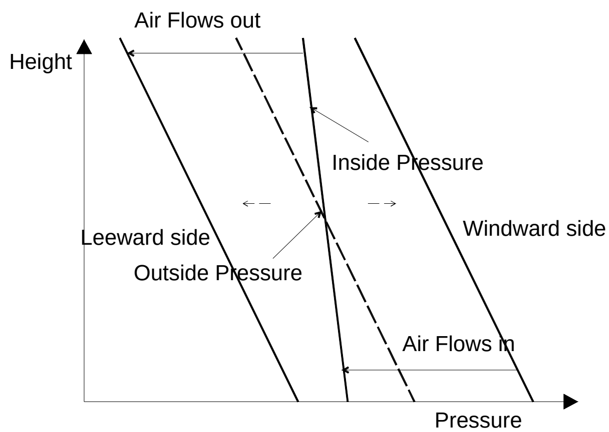


Figure 2.3 Stack effect with wind impact

2.2. NATURAL AND HYBRID VENTILATION STRATEGIES

Natural (passive) ventilation strategies may be categorized as wind-driven ventilation or buoyancy-driven ventilation. Strategies may be further sub-categorized as single-sided, cross flow only, stack ventilation only, cross ventilation with stack effect, and cross ventilation with wind chimney and stack effect. Deciding which approach is most appropriate for a given set of inputs is the purpose of the decision-making process.

2.2.1. Single-sided ventilation

Single-sided ventilation is basically buoyancy-driven ventilation. The window opening size needed for single-side ventilation is typically much larger than for cross ventilation. If the ventilation can only be single-sided, it is preferable to include two openings, one high and one low. The greater the difference of height between the openings, the more influential the stack effect will become. Two openings are typically much more efficient than one single opening. If only single openings can be used, a tall window is better than a horizontal window of the same area, and vertical sliding sash windows can provide good stack ventilation.

2.2.2. Cross ventilation

To draw fresh air through a building, cross ventilation is driven by the pressure difference between high and low pressure zones created by wind, as explained in Section 2.1.1.1 and Section 2.1.1.2. Openings should be located at both the high pressure zone and the low pressure zone in the building envelope to achieve the desired ventilation flow.

2.2.3. Stack ventilation only

In the application of buoyancy-driven stack ventilation, the following concerns should be taken into account.

2.2.3.1. Temperature difference

In peak summer conditions, internal temperatures in occupied areas are typically near the ambient temperature, so the stack pressure will be minimal. In relatively unsheltered sites, wind-driven ventilation provides a moderately high level of thermal comfort while buoyancy-driven ventilation provides little additional benefit. Wind-driven ventilation is likely to be the predominant daytime ventilation driving force. Stack ventilation for night cooling may be very effective because of the larger temperature difference; this would be particularly significant in buildings, such as theatres, that are typically occupied at night.

2.2.3.2. Height of stack above roof

To avoid back draught, for isolated buildings with no local flow interference, the minimum height of the stack above the roof level is given by Equation 2-5: [9]

$$h = \left[0.5 + 0.16(\theta - 23)a\right]$$

Equation 2-5

h = height of shaft above roof level, m

θ = roof pitch, degrees

a = the horizontal distance between the outlet and the highest point of the roof, m

If these relationships cannot be achieved, mechanical assistance should be considered.

2.2.4. Cross ventilation with stack effect

When applying cross ventilation, the stack effect can also be considered, along with wind-driven ventilation, if the two forces are applied in the same direction. In many cases, wind and stack effects are present simultaneously. The interaction between them should be properly utilized.

In narrow plan buildings, cross ventilation is often appropriate. However, when the wind is not favorable, or available, single-side ventilation may be effective. As Gratia suggests, it is best to plan the building layout and depth to serve both single-side and cross ventilation for different wind conditions [10]. For cross ventilation in the absence of wind, the window openings on opposite sides of the building have to be at different heights. In deeper plan buildings, stack-driven cross ventilation with stack effect is often used with elements such as atria or shafts.

In the book "Wind Towers," Battle and McCarthy introduce design strategies for wind towers and wind scoops for naturally ventilated buildings [11]. They suggest that wind towers or wind scoops provide increased reliability and control when compared with simple cross-ventilation. The area of openings can be reduced, while allowing the implementation of night–time cooling in the summer. These structures can also be integrated with mechanical ventilation. Battle and McCarthy further suggest that, during peak summer periods in buildings with high internal heat gains, the return to full mechanical ventilation can be avoided by adopting a hybrid system using both natural and mechanical ventilation. Mechanical displacement ventilation will supply cool air at low levels, allowing the extraction of exhausted via the wind tower. Table 2.1 summarizes the features and applications of wind towers and scoops.

2.2.4.1.Interaction of stack effect with wind effect

If feasible, wind-driven and buoyancy-driven ventilation are more effective when combined; the two forces should be applied in the same direction to avoid cancellation of each other. For example, Gratia et al. simulate a narrow plan multistory office building with a multistory double-skin façade on one side [12]. The building has a typical layout and windows on the corridor walls (Figure 2.4). They demonstrate that the double-envelope works best on the leeward side; in this case, wind effect combines with stack effect (Figure 2.4).

Table 2.1 The features of wind towers and wind scoops

	Wind Tower	Wind Scoop	Wind Tower with Wind Scoop
Special Features	1.Allows building to be oriented regardless of the wind direction 2. Permits a deeper plan than does cross-ventilation	1.Allows building to be oriented regardless of the wind direction 2.Clean, strongly moving air can be collected away from windows, which is good for urban environments	1. Offers both of the features of wind tower and wind scoop. 2. Produces greater pressure difference; a certain degree of duct work can be used; allows smaller-sized openings 3. Better for integration with mechanical ventilation
Restrictions	A certain minimum wind speed is required		
Building Form	Can be aerodynamically shaped to encourage an increased air velocity to improve the drawing effect of the wind tower	Can be shaped to increase positive pressure against the wind scoop	Both
Type of Building	Open plan offices, laboratories, large spaces with high internal heat gain like theaters, auditoriums, and sports halls	Large volume spaces, such as atria and shopping malls	Both large and small spaces like cellular offices are possible with duct work
Height	Sufficiently high to avoid turbulence	The higher above the roof the better	
Position	Windward edge of the roof, or the center of the roof for wind from all directions	A place facing the wind, with cool and clean air source, on the roof or in the ground	
Types, Cap Devices	Leading edge, aerofoil wing (Venturi effect)	Rotatable is better	

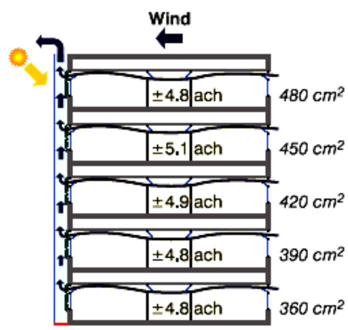


Figure 2.4 The flow pattern when wind effect acts together with stack effect with multistory double-skin façade [12]

If the double-envelope is on the windward side, the pressure driving force of the stack effect is positioned opposite to wind driving forces**.** The stack effect may be lower than the wind effect**,** but would still strong enough so that air would flow to the stack in lower floors and to the offices in the upper floors (Figure 2.5). In this case, contamination may be a problem. Opening the bottom openings of the double-envelope can lower the stack effect.

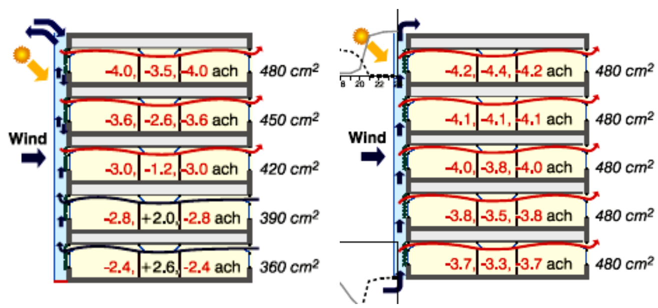


Figure 2.5 The flow patterns when wind effect works against stack effect with multistory double-envelope [12]

If the double-envelope is on the south-facing windward side, the situation is worse. The office is ventilated with the air through the double-skin, where the temperature is higher than the outside temperature due to solar gain.

2.2.4.2.The location of the Neutral Pressure Level (NPL)

As shown in Figure 2.2, the Neutral Pressure Level is the level at which the indoor and outdoor pressures are equal; in this situation**,** no air flow results. The NPL is very important in the design of stack ventilation. The exhaust opening should be placed well above this level.

In situations in which multiple floors sharing the same exhausting stack(s), if the NPL is not high enough, air from the lower floors may enter the upper floors through the stack(s). (Figure 2.5, left) When wind is available, applying the Venturi effect at the stack openings [12] can lift the neutral pressure level and allow natural ventilation to work for all wind directions.

2.2.5. Cross ventilation with wind chimney and stack effect

2.2.5.1 Using the Venturi effect to enhance natural ventilation

Based on Bernoulli's equation, the Venturi effect occurs when an imcompressible and invisid fluid speed is forced smoothly through a narrow or restricted area. The increased speed results in a reduction in pressure. When fluid moves through two different cross-sectional areas, the volumetric flow rate Q remains the same**;** thus**,** the $A \cdot V$ remains constant, i.e. $Q = A_1V_1 = A_2V_2$, thus if $z_1 = z_2$ and $A_1 > A_2$, $\Rightarrow V_1 < V_2$ and $P_1 > P_2$.When V_1, P_1 are known, and $z_1 = z_2$, $V_2 = \frac{A_1}{A_2}V_1$, thus the pressure $P_2 = P_1 - \frac{1}{2}\rho V_1^2\left(1 - \frac{A_1^2}{A_2^2}\right)$, where A_1 and A_2 are the areas of the two cross-sections, z_1 and z_2 are the heights of the two cross-sectional areas, V_1 and V_2 are the flow velocities at the two cross-sections. (Figure 2.6)

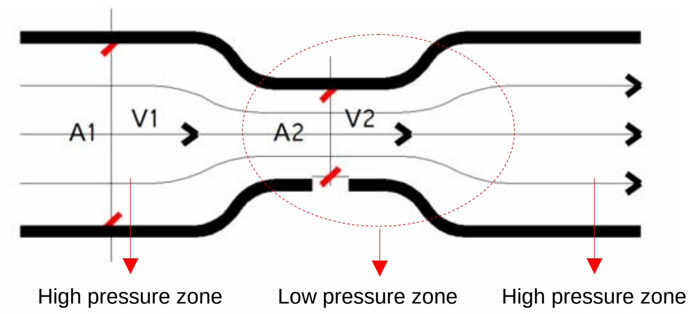


Figure 2.6 Schematic Venturi Flow

In natural ventilation design, the Venturi effect can be used to decrease the pressure at the outlets. As the result, pressure differences between inlets and outlets increase, enhancing the effect of natural ventilation.

Applying the Venturi effect to the openings of atria or air shafts can add a sucking effect whenever wind passes through them. It can also raise the neutral pressure level of a building, as in the case of the RWE Tower, Germany, a convex disc is used to lift the neutral pressure level in stack ventilated shaft with the Venturi effect. (Figure 2.7) In a multi-story building with an atrium, the neutral level is near the middle of the building. Air enters the atrium in the lower region and exit**s** at the region above the neutral level. The upper floors may be exposed to exhaust air from lower levels. Thus**,** a negative pressure at the top of the atrium is needed to raise the NPL above the roof level**.** This can be achieved by applying the Venturi effect with devices constraining air flowing above the atrium openings.

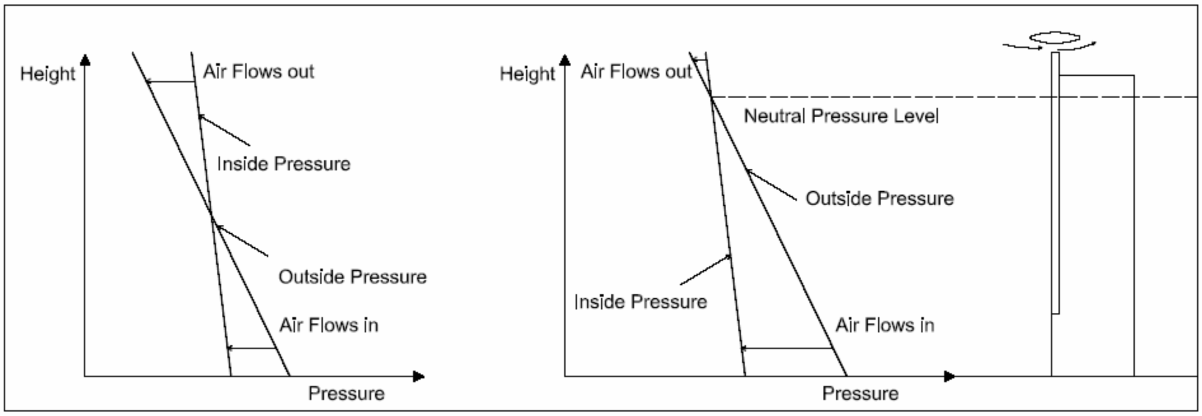


Figure 2.7 Lifting the neutral pressure level by the Venturi Effect

Shaping the building to increase the wind speed near the outlet can lower the pressure at the outlet. When passing a smoothly shaped surface, air speed increases and pressure decreases. A Venturi cap adds constriction as the air moves over the opening, thus lowering the pressure. The device can be designed to work for winds from all directions, such as in the Ionica Headquarters.

2.2.6. Hybrid ventilation strategies

One strategy often used is "complementary mixed mode" ventilation. As defined in the CIBSE Applications Manual AM13, 2000, "complementary mixed mode can be described in simple terms as a combination of natural ventilation and mechanical systems that provides thermal comfort in either passive (natural) or active (mechanical) modes" [6].

The complementary system can have both concurrent operation and changeover operation strategies. In a concurrent operation, background mechanical ventilation operates with natural ventilation. In a changeover operation, natural and mechanical systems work alternately. The most common types are seasonal changeover and night-day changeover.

In the other strategy, "zoned mixed mode," different parts of the building use different ventilation modes. For this, Brown et al. suggest energy zoning for designing naturally ventilated buildings [13]. Spaces that have similar cooling and occupant schedules can employ the same energy efficient design strategies. If these spaces are in the same zone, these strategies can be most efficiently and economically used. In energy zoning, spaces are categorized by allowable temperature range, internal gain, and occupant density. Kosik also suggests clustering high heat gain spaces [14]. If some spaces cannot be cooled with natural ventilation, then they should be located together to allow for efficient distribution of conditioned air.

According to Brown, spaces such as private offices, library book stacks, biology labs, and lobbies that have the characteristics of large temperature swings, low occupant density, and low internal gains are the easiest to night and day ventilate. Spaces such as shared offices, classrooms, and conference rooms that are moderately easy to ventilate typically have a small temperature range, combined with either high internal gain/low density or low gain/high density. They should be located near the source of natural ventilation. The most difficult spaces to naturally ventilate, such as auditoria and data centers, have a tight temperature tolerance, high internal heat gain and high occupant density or obstructions.

Compared to completely naturally ventilated systems, mixed mode systems typically increase the cost of the building. The cost of building with hybrid systems is up to 15% per square meter less than for air conditioning only, and 5% less than “a building with extensive mechanical ventilation” [6]. However, mixed mode systems extend the capability of the natural ventilation system. This includes: (1) permitting deeper and more complex plans with greater flexibility; (2) enhancing the controllability on air quality through filtering, and (3) being able to add humidity control and heat recovery. All these features help meet the needs of ventilating non-residential buildings.

2.2.7. Components of natural ventilation systems

2.2.7.1.Inlets and outlets

Natural ventilation relies on a pressure difference between inlets and outlets. The inlets and outlets can be windows that have multiple integrated functions such as viewing, daylighting and ventilating, and other openings, such as vents, louvers, and transoms. The inlets and outlets can be located in typical building envelope systems, including walls, roofs, in double-skin facades, or in wind scoops, wind towers, and shafts. Double-skin facades can be both air supply and exhausting elements. Double facades can be good for natural ventilation in cases of high exterior noise levels and/or high wind speeds, and are especially good for building renovations. Wind scoops are particularly effective when supplying a large open space in which the ventilation air does not have to be supplied near the occupants.

2.2.7.2.Flow paths

Air flow paths will resist flow and consequently should be carefully considered during the design process. Air may pass through occupied spaces and be directly exhausted. In many cases, to apply stack ventilation or cross ventilation with a wind chimney and stack ventilation, the flow paths should be arranged with a space or building component vertically connecting floors. The building elements that can be used to achieve this include:

(1) Atria
(2) Staircases, such as in the Center for Mathematical Sciences (Cambridge, UK) and the Inland Revenue Headquarters building (Nottingham, UK)
(3) Shafts with extracting towers (wind towers), such as in the Eastgate building (Harare, Zimbabwe)
(4) Multi-story double-skin facades
(5) The roof

In deep-plan low-rise buildings with large ground floor plan dimensions, such as supermarkets, sports halls, exhibition halls, and fair halls, horizontal natural ventilation is often difficult because of the plan depth. For these buildings, the wind driving force is typically not enough to overcome the resistance to flow along the horizontal path, so a vertical path may be the solution. In this case, roof structures can create air extraction paths. In the example shown in Figure 2.8, evenly distributed roof openings and openings at corners and near the center function almost equally well as exhausts [15]. Another example is the Hall 26 building (Hanover Fair, Germany), in which three roof ridges enable even distribution (Figure 2.9).

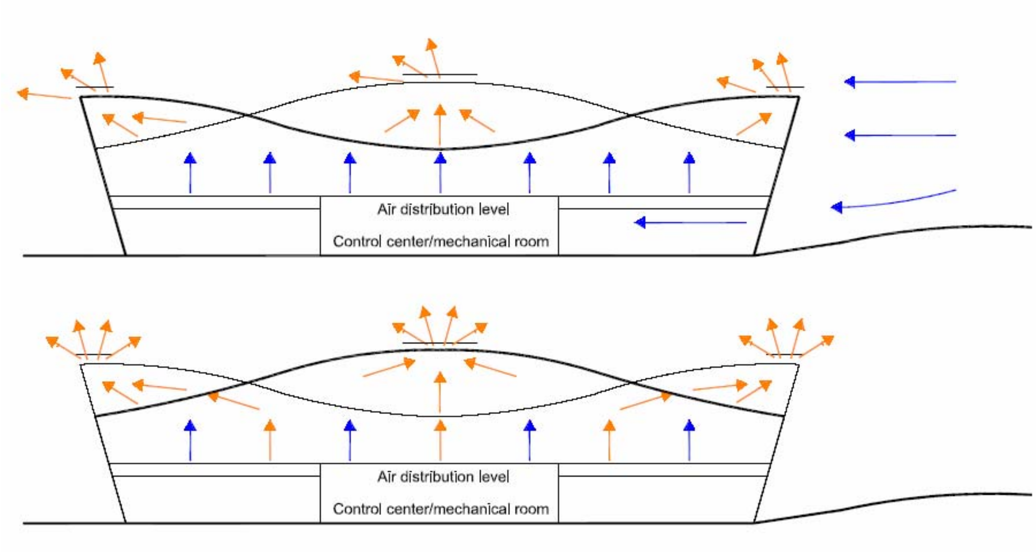


Figure 2.8 Wind-driven and buoyancy-driven air flow

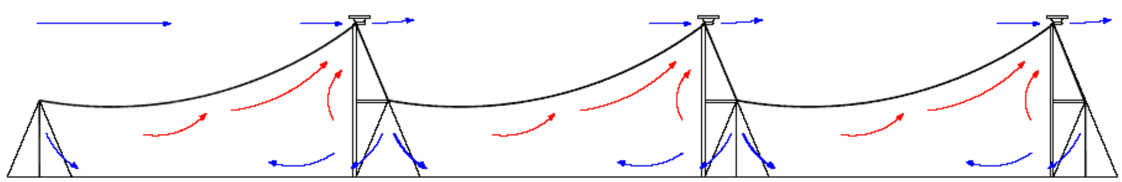


Figure 2.9 The long section of Hall 26, Hanover Fair, Germany

In some cases, ducts, shafts, or under-floor plenum may be used as flow paths, especially when dedicated ventilation is needed for each room.

2.2.7.3.Controls

Control strategies include manual and automatic controls. Manual controls may include operable windows with simple notifying systems such as green/red lights that inform the occupants when the outdoor conditions are good to open the windows. Automatic control systems typically include sensors, actuators and controllers.

Sensors may measure: (1) temperature, (2) CO_2, (3) multiple polluting gasses, (4) wind speed and direction, (5) humidity, and (6) rain. In addition, other sensors that may work with the ventilation system can detect smoke, noise, and intrusions that travel through ventilation openings. The actuators used in buildings mainly include window actuators and dampers that can open or close inlets or outlets for ventilation purposes. Controllers are typically computers installed with controlling software.

The basic control strategies for natural and hybrid ventilation are defined as follows:

(1) Control based on indoor air quality

(2) Control based on indoor and outdoor temperatures

This strategy is used to determine whether ventilation with air at a given outdoor air temperature will provide sufficient cooling. Vents and windows are opened based on the indoor and outdoor air temperature difference and the value of the indoor air temperature.

(3) Integral control strategies taking into account both indoor air quality and temperatures

The following figure shows an example of the flowchart for an integral natural ventilation control strategy, adapted from the example provided by Allard (1998) [16], where T_i is the indoor air temperature, T_o is the outdoor air temperature, $T_{cooling}$ is the indoor cooling set point, and $T_{heating}$ is the indoor heating set point.

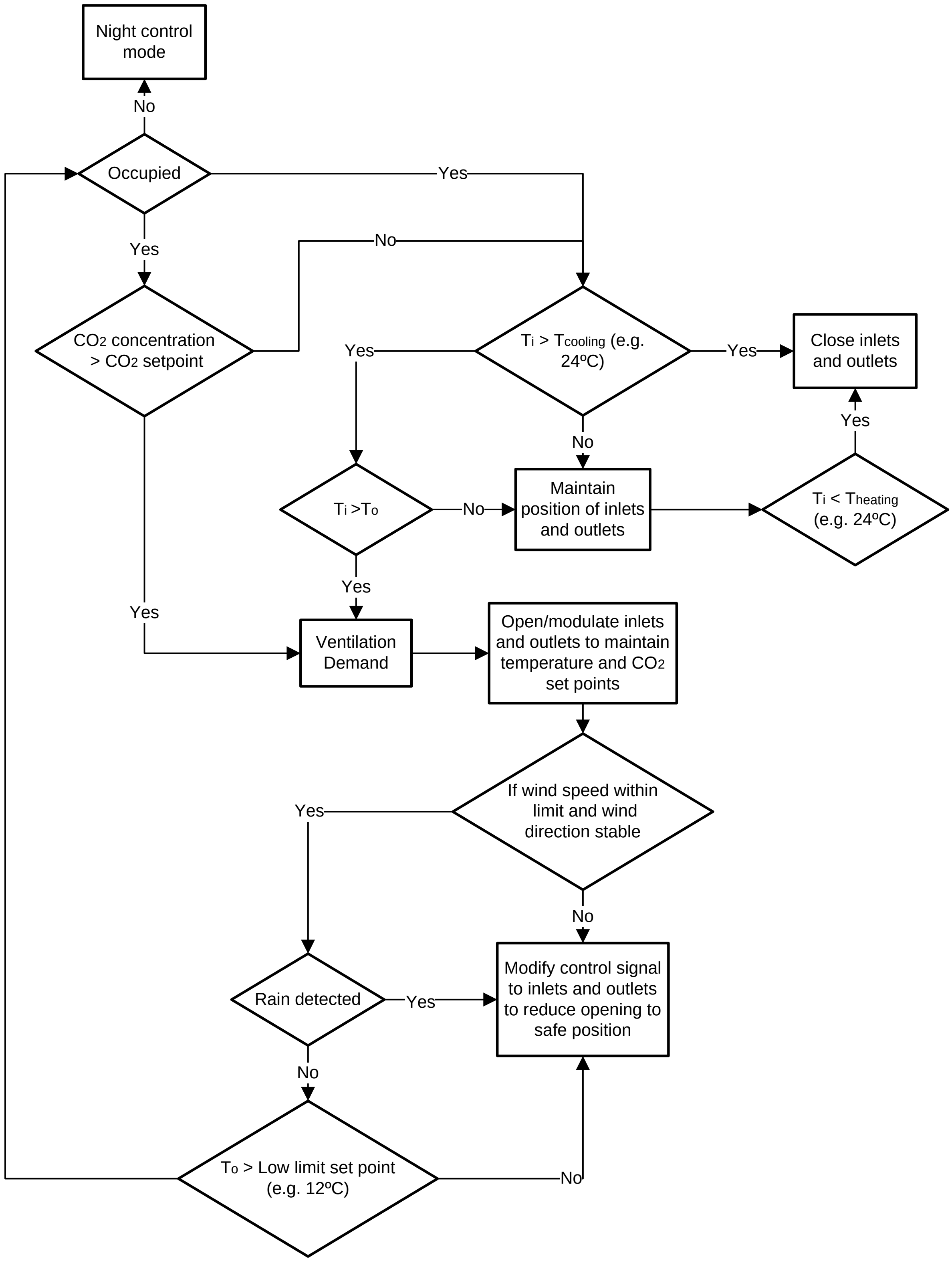


Figure 2.10 An example of integral natural ventilation control strategy

(4) Control for hybrid ventilation systems

When a hybrid ventilation system is applied, the control strategies need to be well developed in order to integrate control of both passive and active ventilation modes. If other approaches, such as night ventilation with thermal mass and earth-to-air heat exchangers, are also used, the control strategies also need to be well developed. These strategies can still be temperature-based or integral based, although the ventilation rates required for cooling are typically much higher than those for indoor air quality.

The ventilation components in the flow path are summarized in Table 2.2.

Table 2.2 Natural ventilation strategies, ventilation components in the flow path

	Flow path			
	Supply (Natural/Mechanical)		Exhaust (Natural/Mechanical)	
Strategies	Inlets	(Possibly Through) Ventilation components and building elements	(Possibly Through) Ventilation components and building elements	Outlets
Single-sided ventilation Cross flow only Stack ventilation only Cross ventilation with stack effect Cross ventilation with wind chimney and stack effect	Windows, Wind Scoops or Vents, with Manual/Automatic control	Vertically: Atria, Shafts Horizontally: Double-skin facades, Ducts, Corridors, Underneath floor supply plenum	Vertically: Atria, Stair cases, Shafts, Wind towers, Double-skin facades Horizontally: Corridors, ducts	Windows, Vents, with Manual/ Automatic control

2.3. CRITICAL ISSUES IN NATURAL VENTILATION DESIGNS

Through literature it was found that differences exist when applying natural ventilation to residential or non-residential buildings. Fundamentally, the differences may be based on the following reasons:

(1) Multiple room functions

Non-residential buildings often have many room functions. For example, classrooms, copy rooms, or offices typically have much higher heat gain rates than residential buildings, making it more difficult to maintain comfortable conditions with natural ventilation. Also, unlike residential buildings, rooms may have different comfort, air quality, acoustic, safety and security, and zoning requirements. These differences must be accounted for.

(2) Larger plan-depth and building volumes

Pressure loss and restricted air flow caused by large plan-depth may limit the use of natural ventilation in non-residential buildings. In addition, these buildings often have rooms of various volumes. Ventilating small interior rooms in a deep plan building can be difficult.

2.3.1 Barriers to implementation

An issue often discussed in the literature is that a successful naturally ventilated building should overcome potential "barriers." These barriers are often associated with broad issues that are "unrelated to thermal performance" [16]. Table 2.3 lists the barriers summarized by Allard. Most of these "barriers" for building operation need to be considered in the design process.

Table 2.3 "Barriers" in the design for an successful naturally ventilated building

Barriers during building operation	Barriers during building design	Other Barriers
Safety	Fire regulations	Architectural impact
Noise	Acoustic regulations	Lack of suitable standards
Air pollution	Type of building use	Increased risk for designer
Shading	Controls	Fee structure for design
Draught	Lack of suitable design tools	User ignorance
User ignorance		

2.3.2 Selection Criteria

The Chartered Institution of Building Services Engineers (CIBSE) proposed criteria influencing the selection of natural ventilation systems (CIBSE, 1997). These criteria include: (1) robustness, (2) cost, (3) user preference, (4) internal comfort conditions, (5) humidity control, (6) noise, (7) air quality, (8) flexibility and adaptability, (9) heat recovery, (10) security, and (11) rain [9]. Their importance will be discussed in the next section.

The barriers and the selection criteria can be translated as constraints and performance mandates. Constraints are those issues, such as fire regulations, that can limit design solutions, but can still probably be solved. Performance mandates are the issues by which the success of the system will be measured. The performance mandates and constraints are discussed as follows.

2.3.3 Performance mandates and constraints

The performance mandates include:

- **Energy Savings**

Saving energy is a primary goal when considering natural ventilation. Energy cost reduction is one of the strongest arguments for natural ventilation.

In order to optimize energy savings in natural ventilation applications, there are some barriers to overcome. For example, ventilation heat loss is a concern. To decrease the ventilation heat loss, the exhaust from the heat recovery systems that are often used in mechanically ventilated buildings can preheat the incoming air. This technique is difficult to apply in natural ventilation systems as it typically uses duct components. Even if heat recovery is used, however, high efficiency is difficult to achieve with natural driving forces because the pressure loss is usually high.

- **Thermal comfort**

Thermal comfort is another major issue when evaluating the success of a natural ventilation system. Temperature, humidity, and draft are the most important variables for thermal comfort. First, when indoor and outdoor air temperatures are very close, comfort may be difficult to achieve through natural ventilation. Second, when the wind is rapidly fluctuating, the large openings used for natural ventilation may result in uncomfortable drafts indoors. The draft issue can be critical in windy climates and in high-rise buildings. In addition, drafts are a particular concern in the winter. Therefore, preventing drafts is a performance goal in the design of naturally ventilated buildings. Third, because natural ventilation can directly bring outdoor humidity inside the building, it is difficult to apply humidity controls. Outdoor humidity directly affects indoor humidity and, in turn, influences thermal comfort.

- **Indoor air quality**

As natural ventilation uses outdoor air to cool the building, when the outdoor air is clean, the indoor air quality will tend to be high. However, "the use of natural ventilation typically means that it is more difficult to clean the air entering the building" [9] than with mechanical ventilation. If the air is not clean, pollutants, dust, bugs, pollen, and airborne seeds can enter the building. If there are indoor pollutant sources, the natural ventilation system should effectively remove these pollutants. This, however, can be difficult and a constraint on the design solution.

Indoor air quality is a critical performance mandate for natural ventilation systems.

- **Acoustics and background noise**

Natural ventilation systems typically produce little noise when compared to mechanical ventilation systems. However, natural ventilation can allow noise from the outside of the building to enter the interior. It also allows noises inside the building to transmit to other areas through ventilation openings. Noise control is important and sometimes critical for determining the feasibility of natural ventilation.

- **Cost**

Cost can be a critical concern when selecting a natural ventilation approach. According to CIBSE, the following features are among the factors that may increase the capital cost of a naturally ventilated building.

(1) Envelope improvements, such as shading, operable windows, double envelopes, and additional noise absorbent materials.

(2) Narrow plan width may be less economic due to a decreased ratio between the net use area and the gross area.

(3) The use of thermal mass structures may increase the construction cost.

(4) Additional spaces for the plant room and ducts may be reserved for the future adaptability

Other major costs are energy consumption, maintenance cost, and replacement costs. Typically, (1) the capital cost of a naturally ventilated high quality building can be equal to that of an air-conditioned basic quality building [9]; (2) the energy cost of a naturally ventilated building can be 40% less than that of an air conditioned building; (3) the maintenance cost of a naturally ventilated building is generally lower than an air-conditioned building. The simpler the natural ventilation system, the lower the likely maintenance costs. The cleaning cost could be higher due to the unfiltered air that proceeds directly indoors.

The constraints and barriers include:

- **The designer and client's goal and preference**

The designer and client's goals and preferences determine the choice of natural ventilation elements and the expression of natural ventilation systems.

- **Safety and security**

The barriers of safety and security include the following aspects: (1) fire regulations, (2) unauthorized intrusion, and (3) blast or contaminant release.

Natural ventilation often incorporates open floor plans, large openings and building elements, such as atria and shafts, which connect floors. These elements organize and promote air flow with decreased resistance. Since air movement is an important means of fire propagation, fire compartmentalization is required by many fire regulations. That has two potential influences on natural ventilation design. First, the area of naturally ventilated floors may exceed the limit of fire compartments, which may significantly influence the design of natural ventilation zoning and flow paths. For example, in the IVEG building in Belgium, the upper floor had to be separated from the lower floors to meet fire regulations; thus, one exhausting tower is designed for each zone (Figure 2.11) [17]. In the Lanchester Library, Coventry, UK, adding the compartment wall could significantly impair the architectural quality of the building. Sprinkler systems can extend the area limit but also increase the cost. Secondly, the opening at the exterior envelope and internal subdivisions, such as floors and walls should not exceed certain sizes, and the distance between them should not also be lower than a minimum requirement. In addition, the openings are often required to be closed and protected in case of fire to prevent fire propagation, which also adds cost.

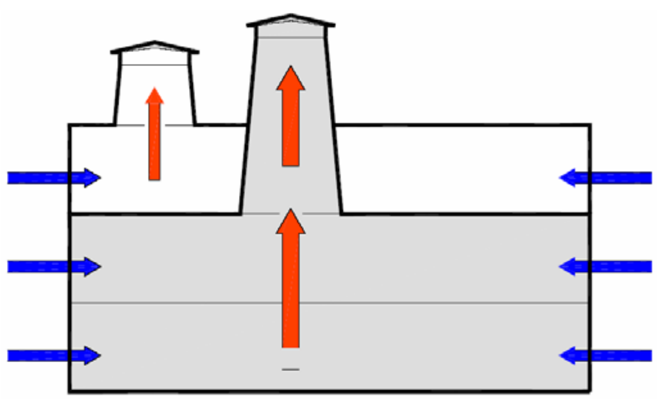


Figure 2.11 Zoning of natural ventilation in the IVEG Building

Security standards vary with building type and may preclude natural ventilation from certain types of buildings or certain building spaces. For most buildings with an ordinary protection level, unauthorized intrusion is the major concern, especially when night ventilation is planned. If the protection level is high, for example, when protecting against blast and/or external or internal contaminant release are required, a natural ventilation system may not be suitable because positive pressure control may be required and it may not be possible to install windows at lower levels.

- **Pressure loss in the ventilation path**

Pressure loss caused by large plan-depths, or flow paths in many non-residential buildings may influence the effectiveness of natural ventilation. This, in turn, would constrain the design of natural ventilation.

- **Site constraints**

Zoning requirements may potentially influence the layout of the building on a site. This can influence the microclimate of the site, including the outdoor air flow conditions, available sunlight and shading, the plan-depth, and the shape of the building. These directly influence the design for natural ventilation.

- **Rain**

Rain prevention should be considered since openings can let rainwater enter the building. In addition, in a rainy environment, since the building is operated under negative pressure, moisture will more easily infiltrate the building, potentially causing problems.

- **Controllability**

Natural ventilation systems are believed to be a robust solution because they typically have "fewer failure modes due to the reduction in the number of components that are susceptible to malfunction" [9]. However, since outdoor conditions (wind, temperature, humidity, air quality, noise, etc.) and indoor conditions (occupancy, temperature, fire, noise, etc.) are always changing, proper control is crucial to the success of natural ventilation systems.

- **Flexibility**

Clients and designers may prefer that buildings with natural ventilation systems incorporate flexibility for the future. For example, since it is common that a building can last more than 50 years, dealing with climate change and occupancy change by adding additional service systems is practical. Therefore, the design must allow the easy attachment of additional service systems.

The barriers influencing the designer's practice, such as the lack of design tools, and the fee structure for design, are beyond the scope of this study.

All the issues briefly discussed above can be major constraints or the performance mandates in the framework. Their relations to the decision-making in the natural ventilation design process and their interactions with the design inputs will be discussed in detail in the following chapters.

CHAPTER 3 CASE STUDIES

3.1 CASE STUDY AS ANOTHER FOUNDATION TO THE GROUNDED THEORY

Using a grounded theory methodology, knowledge related to design decisions for natural ventilation may be acquired from literature and studies of selected recently constructed buildings that incorporate natural ventilation. Knowledge related to design discussions can be acquired through case studies of naturally ventilated buildings. According to Groat and Wang, as a research method, the strengths of case studies include: (1) a focus on cases in their contexts, (2) the capacity to explain causality, (3) the development of theory, (4) the ability to use multiple sources of evidence, and (5) the power to generalize to theory (Groat and Wang, 356). As introduced in chapter 1, the case study is one of the methods used for the development of the framework. In particular, case studies will examine how the design decisions were made, based on specific project goals and constraints, and will verify if the critical issues identified from the literature review were applied.

For this purpose, multiple-case design is advantageous because it provides breadth to the inquiry and can be tested by replication. In other words, "every case severs a specific purpose with the overall scope of inquiry" (Groat and Wang, 356). For the case studies, a combination of a literal and theoretical replication was used. As Groat and Wang point out, "A literal replication is a case study that tests the same outcomes, principles, or predictions established by the initial case study. In contrast, a theoretical replication is a case study that produces contrasting results but for predictable reasons" (357). For some groups of naturally ventilated non-residential buildings categorized by their functions, several exemplars were selected. Each functional group serves a theoretical replication, while the exemplars within each group are literal replications.

In contrast to its strength, Groat and Wang summarized the weaknesses of case studies as a research method; these are shown in the following table [18]. To limit the potential over-complication, which is the major weakness of case studies, and to achieve the goals stated above, the case studies are focused on a few key issues: site and climate conditions, the client's requirement and constraints, the client and designer's goals, ventilation and control strategies, the design process, building performance, and lessons learned. Due to literature limits, not all categorical information is available for all case studies, as will be shown. These case studies are limited to the sources available from literature and design professionals, and will only use relatively recently constructed exemplars.

Table 3.1 The strength and weakness of case study as a research method

STRENGTH	WEAKNESS
1. Focus on the embeddedness of the case in its context	1. Potential for over-complication
2. Capacity to explain causal links	2. “causality” likely to be multi-faceted and complex
3. Richness of multiple data sources	3, challenge of integrating many data sources in a coherent way
3. Ability to generalize to theory	3. Replication required in other cases
4. Compelling and convincing when done well	4. Difficult to do well; fewer established rules and procedures than other research designs

3.2 NATURALLY VENTILATED OFFICE BUILDINGS

3.2.1. Philip Merrill Environmental Center (Case 1-1)

3.2.1.1 *Building description*

The Philip Merrill Environmental Center was completed in December 2000 and is located in a suburban area of Annapolis, MD. It is a 2-story office building and an interpretive center. The total building area is 32,000 square feet (2,970 square meters). Its plan depth is 60 feet (18.3 meters).

3.2.1.2 *Site and Climate Condition*

The building is located in Annapolis near the Chesapeake Bay. According to the designer, the summer breezes are from the south and east, and the winter wind is typically from southwest. This helped for the sitting of the building and placement of inlets and outlets.

3.2.1.3 *Client’s Requirement: N/A*

3.2.1.4 *Constraints and Solutions: N/A*

3.2.1.5. *Design Strategy - Cross ventilation, complementary mixed mode*

The building has an open plan office, orientated for the summer breezes, natural ventilation, daylighting, and passive solar heating (Figure 3.1). Louvers along the south façade accept sunlight in the winter and block it in the summer. The building uses operable windows and a geometry that was designed to take advantage of the breezes off the bay for natural ventilation. The outlet area was larger than the inlet area, which was designed to produce higher air velocities, increasing the cooling effect. The natural ventilation includes fan assistance, if necessary, when the outdoor temperature is between 68°F to 77°F and relative humidity between 20% and 70%.

3.2.1.6 *Control*

The control for comfort includes the following design strategies: low and mid-height windows on the south side are operated with hand cranks. “Red light/green light” in the offices notifies occupants when conditions are optimal for natural ventilation. When occupants open windows, the system control turns off the air conditioning equipment. (Figure 3.2) Windows located high on the north side are controlled by the building’s

EMS based on the sensor data for interior temperatures, interior humidity, and outdoor temperature.

The control for rain intake prevention was achieved with sensors detecting moisture at the north façade. When it is raining, the windows automatically close.

3.2.1.7 *Estimation/Design Verification*

The design airflow rate for natural ventilation was based on the peak cooling load in October. Window size and placement were determined using empirical formulas and engineering judgment. No simulation was done for air flow.

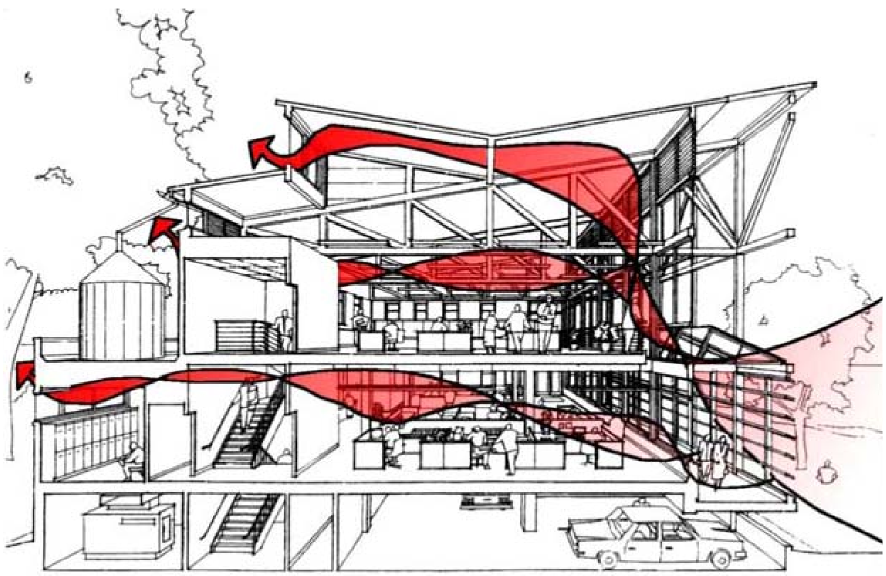


Figure 3.1 Designed air flow path of Philip Merrill Environmental Center [4]

Figure 3.2 Red light notifies occupants when conditions are optimal for natural ventilation to open the manually operated windows

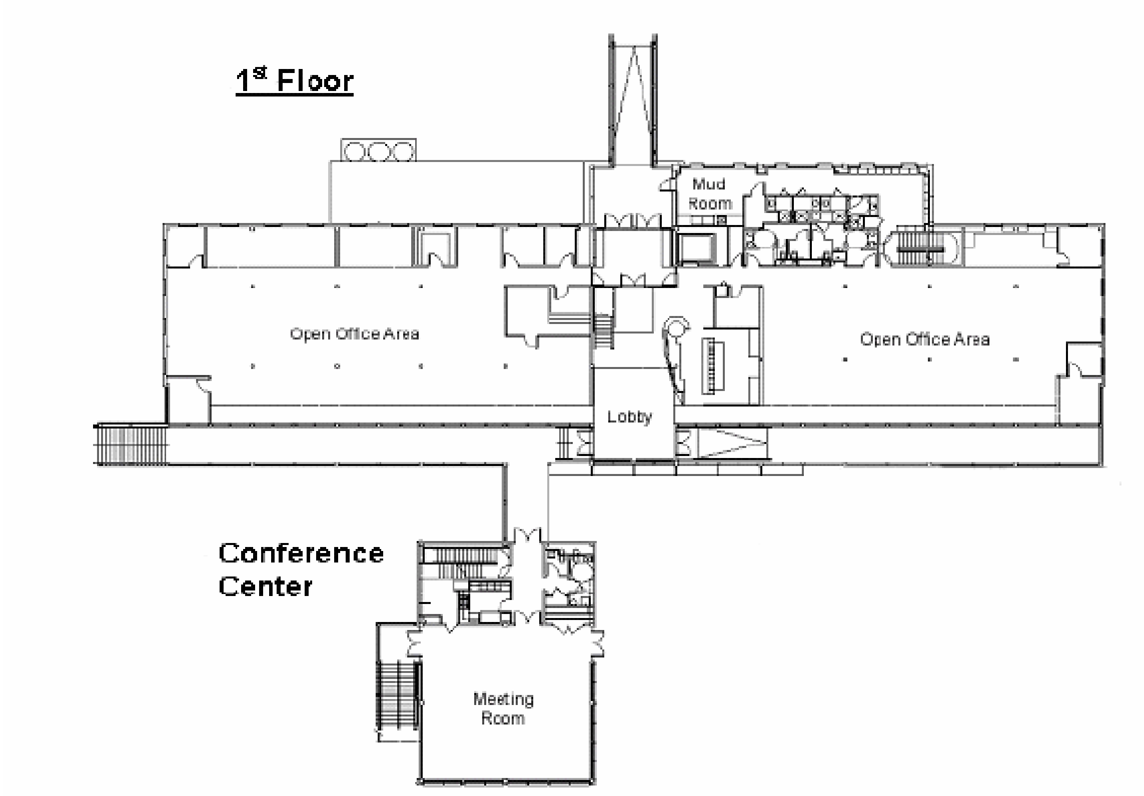


Figure 3.3 First Floor Plan of Philip Merrill Environmental Center [4]

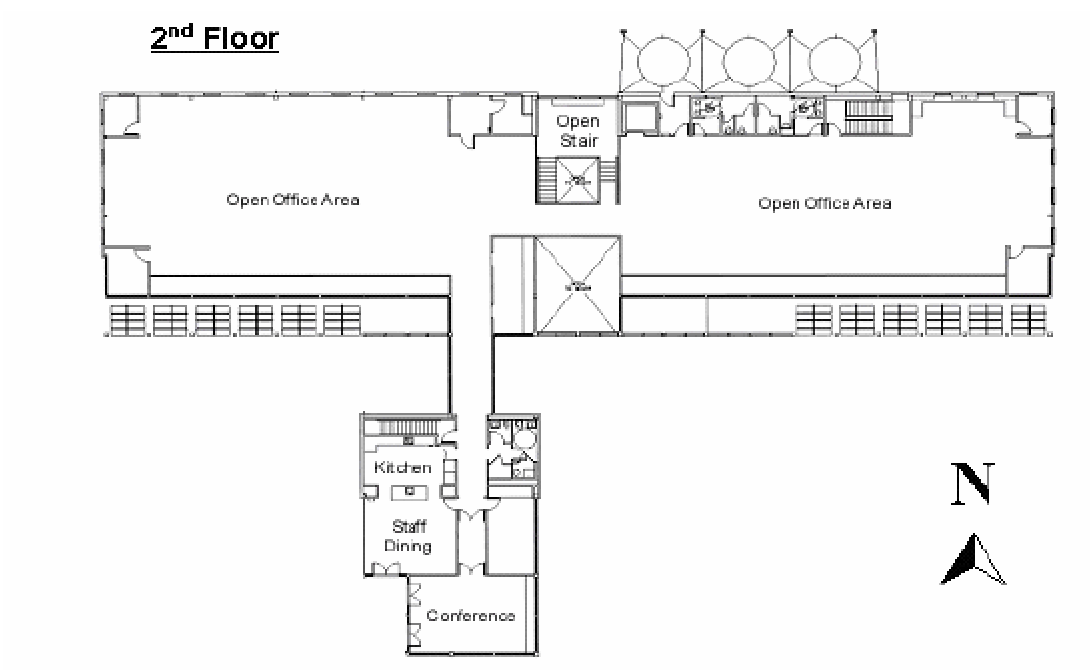


Figure 3.4 Second Floor Plan of Philip Merrill Environmental Center [4]

3.2.1.8 *Interactions and Solutions: N/A*

3.2.1.9 Performance Monitoring Results

The performance of the building was monitored and analyzed by Chang and the National Renewable Energy Laboratory. The results show that occupants were content with the natural ventilation. From May 16, 2001 to December 31, 2001, natural ventilation was used 34% of weekday working hours. However, the fans were used more often than planned to assist natural ventilation. The original design called for natural ventilation when outdoor temperatures were below 77°F (25°C), but this was found to be too high [4]. The major cause was thought to be that wind directions at the building site are different from those factored into the design assumptions.

The building was designed to take advantage of winds that flow from south to north, but the on-site measurements done by the National Renewable Energy Laboratory indicate that winds flow from the northwest when outdoor conditions are good for natural ventilation. They also come from the east as often as from the south [4]. The analysis team concluded that designers should not have assumed that the winds come from the south (off the bay) for natural ventilation cooling, but should have done on-site observation before designing.

3.2.1.10 *Lessons Learned*

First, it is clear that on-site measurements were necessary for this project. The recorded climate data should have been confirmed with site conditions before use.

The wind direction anticipated during the design phase differs from the actual prevailing winds at the building site. This may be because local wind data were not available, and the design was based on the archived data of a nearby weather station. The prevailing wind direction also conflicts with the rule-of-thumb that breezes blow off the water toward the land during the day; in this case, southeast or easterly winds should be more common. In addition, the design of the building's natural ventilation airflow path was based on a single wind direction. Therefore, confirming the wind conditions at the building site is very important for an effective design. Alternatively, the following strategies may help:

(1) make the natural ventilation strategy work for more than one wind direction, or,

(2) design for multiple airflow paths, as suggested by Griffith et. al (2005), or

(3) utilize stack forces rather than wind.

Second, as this project demonstrates, control is important for the successful operation of this building.

Third, energy saving and thermal comfort were the primary goals for using natural ventilation in this project. However, since the airflow in the building was less than predicted, fans are used more often than intended. This compromises the success of the natural ventilation strategy. Griffith et al. (2005) indicate that designers should be aware of the energy consumed by fans.

3.2.2. The New San Francisco Federal Building (Case 1-2)

3.2.2.1 Building description

The new San Francisco Federal Building is located in an urban area of San Francisco, CA. It is an 18-story office building with total building area of 575,000 square feet (53,420 square meters). Construction was expected to be completed in 2006.

3.2.2.2 Site and Climate Condition

For this project, the potential for the use of natural ventilation was determined based on the monthly mean maximum temperature of 75°F for September, the hottest month, and the strong prevailing winds from the west-northwest. Temperature, wind speed and direction at the site were found to be similar to the nearby airport data. Thus the TMY2 data of San Francisco International airport were used for simulation to select alternative natural ventilation approaches.

The typical daily maximum dew point in summer is about 12°C. Thus high humidity is not an important concern for natural ventilation for this location.

3.2.2.3 Client's requirement: N/A

3.2.2.4 Constraints and Solutions

(1) Safety and security

Since this is a federal office building, an impenetrable perimeter at the base of the building was required. All outside air intakes into the building are "removed from easy access"[19]. The lower floors were sealed with full air conditioning systems. Natural ventilation is used in levels 6-18.

According to the requirements in the Uniform Building Code and the US National Fire Code, automatic windows must be automatically closed with the emergency power in the event of fire; this pressurizes adjacent zones and extracts smoke from the floor. However, this requirement presented challenges for the natural ventilation strategy.

(2) Plan depth

The plan depth is about 62.3 feet (19m). Zoned mixed mode ventilation is used. The open-plan perimeter area is naturally ventilated, while the enclosed rooms, stairwells, elevators, and bathrooms located in the center spine of the floor are mechanically ventilated. The depth of the perimeter area was determined to allow for single sided ventilation. In addition, "California's Energy Code allows a space to be considered naturally ventilated only if every part of the space is within 6m (20 feet) of an operable element in the facade"[19].

3.2.2.5 Design Strategy: Wind-driven cross ventilation; exposed thermal mass with night ventilation; zoned mixed mode

Zoned mixed-mode ventilation is used, i.e. the open-plan perimeter area is naturally ventilated while the enclosed rooms, stairwells, elevators and bathrooms located in the center spine of the floor are mechanical ventilated. The depth of the perimeter area is limited by the depth for single sided ventilation. In addition, "California's Energy Code allows a space to be considered naturally ventilated only if every part of the space is within 20 feet (6m) of an operable element in the facade". [19]

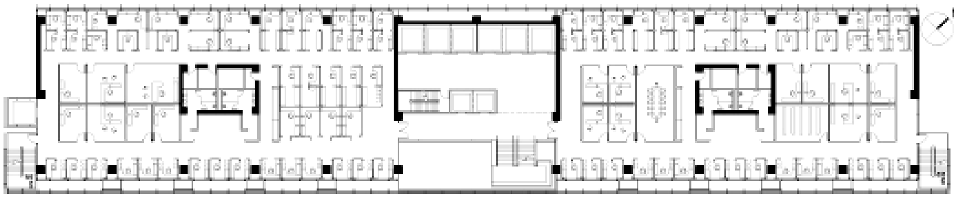


Figure 3.5 Typical floor plan of the new San Francisco Federal Building [19]

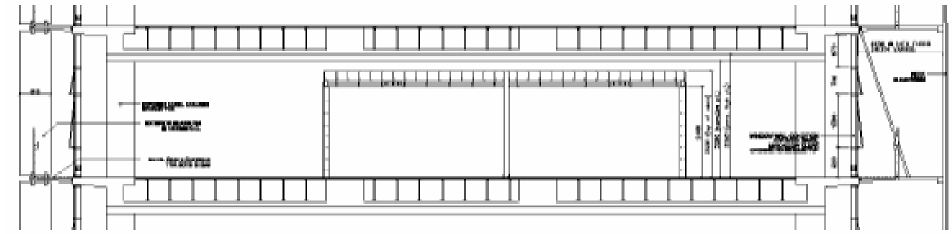


Figure 3.6 Section of a typical floor of the new San Francisco Federal Building [19]

3.2.2.6 *Control: N/A*.

3.2.2.7 Estimation/Design Verification

The natural ventilation approach was selected from alternatives based on the ability to meet thermal comfort performance issues.

This project uses the adaptive comfort model with 80% acceptability range (ASHRAE Standard 55-2004) as a criteria for evaluating indoor thermal comfort conditions. To evaluate several natural ventilation strategies and placement of openings for the thermal comfort conditions, the designers employed simulations with EnergyPlus and COMIS. The simulation sought to determine if buoyancy effects could supplement the wind effects, or if additional buoyancy from an external façade could help achieve desired indoor thermal comfort conditions. [20]

In the simulation, pressure coefficients were obtained from the ASHRAE Handbook Fundamentals 2001. The flow rate Q through the opening of area A is: $Q = C_d A \sqrt{2 \Delta P / \rho}$. The discharge coefficient of openings C_d is set to 0.5, which was thought to be conservative.

The alternative approaches considered were wind only, utilizing inlets and outlets on opposite sides and at the same level; internal stack effect, utilizing inlet openings at floor height and outlets at opposite sides and at the ceiling level; internal and external stack, with inlet openings at floor height and outlets at opposite sides and at the ceiling level, plus a 3-story high double-façade chimney; internal stack with wind; and internal and external stack with wind.

The simulation results suggested that the wind-only approach was the most effective when comparing the estimated indoor air temperatures. Wind-driven ventilation, combined with internal stack, had only marginal improvement. The effect of an external stack was counterproductive since it increased flow resistance. [20]

Ventilation effectiveness and the size of openings and control strategies were adjusted using computational fluid dynamics (CFD) software.

3.2.2.8 Interactions and Solutions

(1) Solar gains impact the utilization of thermal mass, so shading devices are added to the building envelope.
(2) Down-stand beams attached to the exposed ceiling may prevent airflow and block daylighting. Consequently, the interaction of airflow with exposed thermal mass, as well as the daylighting condition, are improved by the use of upstand-beams and an under-floor plenum.

3.2.2.9 Performance Monitoring Results

The building is under construction. No information is available.

3.2.2.10 Lessons Learned

First, before being used, the nearby airport wind data were compared with on-site measurements.

Second, using climate data, the feasibility of natural ventilation was briefly assessed at the beginning of the design process.

Third, safety and security were confirmed as important constraint issues for applying natural ventilation.

Fourth, the plan depth was related to pressure loss and airflow resistance, and was therefore viewed as a potential constraint for applying natural ventilation. If the plan was too deep, the pressure loss would impair the ventilation system's effectiveness. The designers acknowledged that this was a design consideration.

Fifth, local building codes were recognized as an important design issue. In this case, California's Energy Code's requirements for natural ventilation are more stringent than those in the ASHRAE Standard 62 and therefore had to be considered during the design process.

Finally, alternatives were compared based on the critical performance mandates of thermal comfort, energy saving, and indoor air quality. Thermal-network models were used in the early design stages to compare alternatives. The cost of the analysis was shown to be minimal.

3.2.3. Anglia Polytechnic University (APU) Learning Resource Center (Case 1-3)

3.2.3.1 *Building description*

The APU learning resource center, which was completed in September 1994, is located in Chelmsford, Essex, UK. It functions as a library, office, and education facility with a total area of 64,584 square feet (6000 square meters). The building is completely naturally ventilated with the plan depth of 98.5 feet (30 meters).

3.2.3.2 *Site and Climate Conditions: N/A*

3.2.3.3 *Client's requirement*

The client required simple systems, minimum maintenance, daylighting, and low capital and operating cost.

3.2.3.4 *Constraints and Solutions* [21]

For security, no manually controlled windows were installed in low level floors. Clerestory windows were controlled by the Building Management System (BMS) with local room temperature sensors.

Since the building has two atria, fire safety was a potential constraint for ventilation. In this design, the essential objective was to use a passive fire protection system to eliminate any need for mechanical smoke extraction, sprinklers, a standby power supply, and any barriers between each storey and the atrium. Complete natural ventilation throughout the atrium areas was achieved, which also reduced energy consumption and maintenance costs.

3.2.3.5 *Design Strategy: Stack ventilation, exposed thermal mass with night ventilation*

Inlet openings include automatic windows and vents. Exhaust airflow was directed through a pitched roof atrium. The pitched roof increased the drawing effect.

Concerns from using this strategy were, first, that the exhaust air may exit via the top floor windows, rather than through the atrium. The solution include reducing the number of operable windows on each floor in proportion to the increased stack height, while using negative pressure at the top of the atrium to increase the drawing force. A second concern was reducing wind disturbance in the occupied zone. The solution was to open leeward atrium vents and close windward vents controlled by local temperature sensors. Finally, designers were concerned with ensuring good indoor air quality in winter, so they used trickle ventilation. Air is exhausted via the atrium, as controlled by the BMS with atrium CO_2 sensors.

Thermal mass works with the stack effect for peak summer cooling, while the stack effect drives nighttime ventilation. During the day, excess heat is stored in the thermal mass, and temperature sensors are used to control when the nighttime cooling starts, to avoid over-cooling the thermal mass.

3.2.3.6 *Interactions and Solutions: N/A*

3.2.3.7 *Control*

The flow rate of natural ventilation was controlled by balancing the free area of the atrium vents in proportion to the free area of the clerestory windows on each floor. The opening and closing of the clerestory windows and the roof vents were controlled by the Building Energy Management System (BEMS) via mechanical actuators, although some of the clerestory windows can be operated manually. When most windows are shut during the winter, background ventilation is maintained via trickle ventilators hidden behind the heating elements.

3.2.3.8 *Estimation/Design Verification: N/A*

3.2.3.9 *Performance Monitoring Results: N/A*

3.2.3.10 *Lessons learned*

First, it is clear that cost can be a critical performance mandate and a major client's goal. This project shows that natural ventilation was achieved with modest cost by applying relatively simple solutions.

Second, security issues imposed constraints that influenced the design and control strategies. Fire safety was a particularly critical issue. It was solved innovatively and cost-effectively in this case through the use of an atrium design strategy.

Third, thermal comfort, indoor air quality, energy saving, and cost were the most critical performance goals.

Fourth, controls were essential to achieve the desired operation.

3.2.4. AVAX Building (Case 1-4)

3.2.4.1 *Building description*

The AVAX building is located in an urban area of Athens, Greece. It is an office building with three basement levels, four floors, and a penthouse. The useable floor area is 32830 square feet (3.050 square meters).

3.2.4.2. *Site and Climate Condition*

The site is confined; only the east façade faces open air. In addition, noise and pollution were concerns for natural ventilation, suggesting control for closing openings. The summer climate in Athens has the potential for overheating, so natural ventilation may need to be supplemented with mechanical ventilation during peak summer periods.

3.2.4.3 *Client's Requirement: N/A*

3.2.4.4 *Constraints and Solutions: N/A*

3.2.4.5 *Design Strategy: Single sided and cross ventilation, assisted by fan if windows have to be closed* [21]

A single-sided ventilation strategy was used, as it can work well when wind speeds and temperature differences between the interior and exterior are low. Offices are located at the east side and the staircase is located on the west. Ceiling fans are used to extend the comfort zone. In addition, the thermal mass of the exposed concrete ceiling, automatic night ventilation, and automatic external shading were used to reduce heat gain.The mean indoor temperature varies from 70.7 °F (21.5 °C) during winter to 83.3 °F (28.5 °C) during the summer period.

3.2.4.6 *Interactions and Solutions: N/A*

3.2.4.7 *Control: N/A*

3.2.4.8 *Estimation/Design Verification:*

To ensure that the natural ventilation design works efficiently, an airflow simulation tool Passport–Air was used.

3.2.4.9 *Performance Monitoring Results*

Occupants' rating is excellent for the built environment. Less than 3% of the occupants complained about discomfort and most occupants were able to work efficiently (Table 3.2).

Table 3.2 Occupant rating results for the AVAX Building (The range of the rating is from -3 to +3, bad to good. The table is developed based on the figure from [22])

Temperature in summer	1.6
Temperature in winter	2
Air in summer	1.75
Air in winter	2
Noise	2
Comfort	2.3
Health	1.8
Productivity	1.8
Overall user acceptance	1.9

3.2.4.10 *Lessons Learned*

First, the climate, noise and pollution condition of the building site must be evaluated at the beginning of the design process.

Second, the site can influence the natural ventilation design by limiting the shape of the building. This case shows that, if properly designed, this problem may be solved. Thus, natural ventilation can be used in buildings within confined sites.

3.2.5. Leeds city office park, UK (Case 1-5)

3.2.5.1 *Building description*

Leeds city office park is a 3-story 69965 square feet (6500 square meter) office building, located in an urban setting.

3.2.5.2 *Site and Climate Conditions*

Intensive traffic near the site causes pollution and noise, so it is not practical to supply air through the façade at all times.

3.2.5.3 *Client's Requirement: N/A*

3.2.5.4 *Constraints and Solutions*

Smoke ventilation was achieved passively with natural ventilation through the atrium, assisted by mechanical ventilation through the Building Management Systems (BMS).

3.2.5.5 Design Strategy: A complementary system with mechanical supply and passive exhaust, and natural and mechanical night cooling. [21]

The designers' goal was to create a low energy building that would have a comfortable internal environment all year round. Fresh air is mechanically taken through the roof, transported through an under-floor plenum and supplied to the occupied spaces. In the occupied zones, air rises to the ceiling and is extracted through the grilles at the central atrium. Heat recovery is combined with exhaust in winter.

3.2.5.6 *Interactions and Solutions: N/A*

3.2.5.7 *Control: N/A*

3.2.5.8 *Estimation/Design Verification: N/A*

CFD study was used to optimize the effectiveness of the design, such as determining the number and distribution of the inlets and outlets.

3.2.5.9 *Performance Monitoring Results: N/A*

3.2.5.10 *Lessons Learned*

First, concerns for noise and pollution conditions at the building site were critical for the feasibility assessment for natural ventilation. In this case, only a hybrid solution with a mechanical supply was found to be feasible.

Second, as with Case 1-4, fire safety was an important constraint that was solved with passive ventilation.

Third, energy savings and thermal comfort were the designers' primary performance mandates. Indoor air quality and acoustics were also identified as mandates in this case.

Fourth, CFD was shown to be a useful tool in optimizing the design for ventilation effectiveness.

Fifth, control was found to be essential for achieving the performance goals, including comfort, indoor air quality, and fire safety.

3.2.6. Telus William Farrell Building (Case 1-6)

3.2.6.1 *Building description*

Telus William Farrell building is an office and retail building. This is a renovation project.

3.2.6.2 *Site and Climate Condition*

The building is located in downtown Vancouver, British Columbia.

3.2.6.3 *Client's Requirement: N/A*

3.2.6.4 *Constraints and Solutions: N/A*

3.2.6.5 *Design Strategy: Seasonal mix-mode ventilation*

The office tower, which is more than 50 years old, was built with cast-in place concrete and exterior walls of brick with single pane windows. Cooling was provided from a central chilled water system, while heating was accomplished by a central steam system. The renovation included a new double façade with a tensile steel system supporting the glazing that envelopes the walls with a cavity width of 35.4 inches (900mm). The project integrates natural ventilation, PV panels and light shelves. The steam-heating system was replaced with a heat-recovery system that uses waste heat from the cooling process. [23]

In winter, the double-envelope is closed and acts as a buffer and sun-space. In summer, the dampers at the bottom and top of the double-envelop are open, and warm air from the plenum is exhausted with the stack effect, which can be assisted by PV-powered fans at the top of the plenum. The cooled air is supplied through the raised floor plenum of the offices. The double-envelope is multiple-story, with operable windows at each floor level. During mid-season, occupants can control the operable windows on the old shell and the new skin. Warmed air from both the plenum and the occupied spaces is exhausted through the top of the plenum.

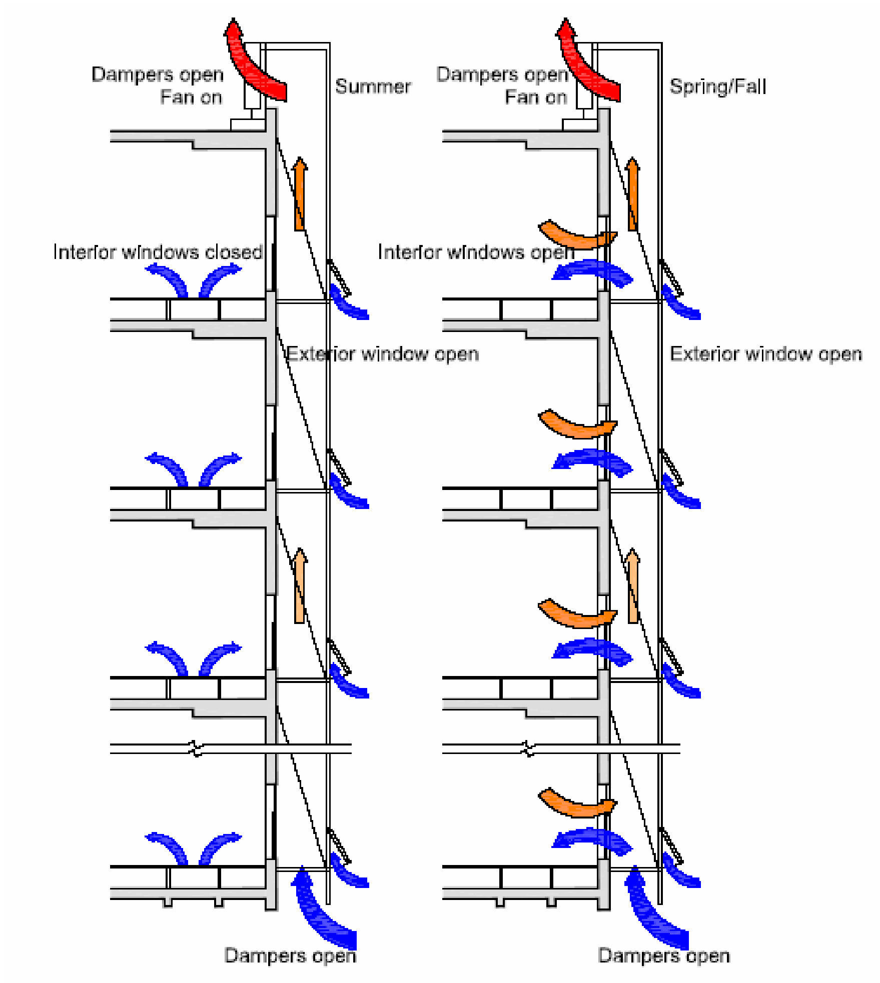


Figure 3.7 Ventilation themes in summer and spring/autumn

3.2.6.6 *Interactions and Solutions: N/A*

3.2.6.7 *Control: N/A*

3.2.6.8 *Estimation/Design Verification: N/A*

3.2.6.9 *Performance Monitoring Results: N/A*

3.2.6.10 *Lessons Learned*

First, thermal comfort, indoor air quality, and energy savings were identified as the major performance goals of this project. Although the literature did not show that pollution control was an issue, it is typically important when a project is located in a downtown setting.

Second, double-skin facades can integrate multiple functions, such as ventilation, noise reduction, and daylighting. This was found to be a good solution for a renovation project.

3.3 NATURALLY VENTILATED ACADEMIC AND RESEARCH FACILITIES

3.3.1 Lanchester Library, University of Coventry (Case 2-1)

3.3.1.1 *Building description*

The Lanchester Library is located in the University of Coventry, UK. It is a four-story building with 164 feet × 164 feet (50m × 50m) plan-depth. The floor-to-ceiling height is 13 feet (4 meters). The building was completed in August 2000.

3.3.1.2 *Site and Climate Condition*

Since the building is located in an urban setting, the temperature rise caused by the heat island effect in urban settings was considered in the design. There was a restriction on the overall building height.

Figure 3.8 The exterior view of the building [25]

3.3.1.3 *Client's Requirement*

The client requires: (1) an open plan, or maintaining clear view; (2) flexibility of internal space; (3) security of the stock; (4) some cellular offices; (5) learning resource centers

For these requirements, partitions need to be flexible, which is a concern for the use of thermal mass. Cellular offices often make it difficult to apply natural ventilation. Also, learning resource centers contain clusters of computers, which can contribute to high heat gain.

3.3.1.4 *Design Strategy*: *Stack Ventilation, wholly naturally ventilated and passively cooled except the 260m^2 computer lab and small computer server room*

An orthogonal floor plan was designed for flexibility: "each quadrant of the library footprint is punctured by a light well that admits fresh air and daylight into the building" [24]. Fresh air is supplied from a 5 ft (1.5m)-high plenum below the first floor, distributed to each floor by 4 light wells. Air is exhausted through central light wells and stacks at the perimeter.

The location of light wells and stacks allow larger teaching spaces that span from the light wells to the stacks, "providing dedicated, but controlled, ventilation for these areas".[24] Cellular offices are grouped directly to air supply (light wells) or exhaust (stacks) areas. Concrete ceilings are used as thermal mass.

Figure 3.9 The light wells of Lanchester Library [25]

A Building Management System (BMS) is used for comfort control. If the outdoor temperature is higher than 75.2 °F (24°C), inlet louvers are adjusted to maintain a minimum ventilation rate to keep the indoor temperature lower than ambient by utilizing thermal mass.

3.3.1.5 *Constraints and Solutions: Fire and Smoke Ventilation* [26]

The design team thought it was "desirable, efficient and economic to use day-to-day natural ventilation systems to vent heat" by exploiting the stack effect.

A single floor plate of the building is 24000 ft^2 (2230 m^2). Five light wells puncture and connect the four floors. The building above the upper ground floor is a single fire compartment whose area and volume greatly exceeds the "Approved Document Part B" of the UK building regulations, which requires 8610 ft^2 (800 m^2) maximum compartment size confined to a single floor level.

In the early design process, the cost of the approach to maintain compliance with the 8610 ft^2 (800 m^2) maximum compartment size requirement was found nearly the same as the conventional mechanical scheme. This approach includes fire compartment walls for each floor, fire doors, fire dampers, seals, 60 minute fire-rated glazing on all light well/atria side walls, and automatic controls. The scheme includes a full sprinkler system on all floors, a full mechanical smoke ventilation system, stand-by power, a generator, plant rooms, sprinkler pumps, and so forth. The designer stated that the cost "would negate a viable natural ventilation strategy," and "a mechanical scheme would be difficult to avoid" [26].

Through CFD modeling of fire scenarios and negotiation, it was assumed that the occupants would be students and faculty members who are familiar with the layout of the library. In this case, the strategy was set as follows: (1) the atria can be partly open, not fire rated but smoke retardant; (2) it was necessary to have fire and smoke detection; (3) the top story of the atria forms a smoke reservoir; (4) the day-to-day natural ventilation scheme is used to extract smoke, and (5) no sprinkler systems was planned.

The sprinkler system is claimed to have the following drawbacks: (1) By cooling the smoke and imposing downward momentum on it, the water spray slows the buoyancy-driven clearance of smoke. This makes the smoke layer deeper. Thus, the sprinkler system would (2) have little impact on escape times and would (3) damage the book stock.

3.3.1.6 *Estimation/Design Verification*

A CFD analysis was applied to assess the risk that back flow from exhaust stacks to the top floor may cause inadequate stack force. The analysis found that there was risk if the upper floor shared the same outflow routes as the lower floors. Therefore, dedicated exhaust stacks were added to the top floor. Fire scenarios were also modeled with CFD to show the effectiveness of the passive smoke ventilation system.

3.3.1.7 *Performance Monitoring Results: N/A*

3.3.1.8 *Lessons Learned*

First, the local climate was influenced by the heat island effect, which was considered in the feasibility assessment phase of design.

Second, the client's goals and preferences can be an important constraint. In this case, the open plan and the desire for flexibility influenced the conceptual design.

Third, control is an important and necessary measure to achieve comfort and fire prevention. Again, fire prevention is an important constraint for a multistory building with open floors connected by an atrium. Compliance with fire regulations may significantly change the initial design intention.

Fourth, cost can be a critical performance mandate. In the early stages of design, the natural ventilation strategy may be rejected due to the program and budget constraints. Compliance with fire regulations may make the capital cost of the natural approach nearly the same as the conventional mechanical approach.

Fifth, to ensure the performance mandates of thermal comfort and indoor air quality, CFD can be a good tool. In this case, it helped to find that, when using the stack effect to ventilate multiple-story buildings, attention should be paid to the effect of backflow. However, CFD was used later in the design process.

Sixth, although a plan depth can be a constraint for natural ventilation, this building demonstrates a good solution for natural ventilation and passive cooling in a deep plan building.

3.3.2 School of Slavonic and East European Studies, UCL (Case 2-2)

3.3.2.1 *Building description*

The building is located in London, UK. It functions as a five-story library, academic and research facility with total building area 37,670 square feet (3,500 square meters). It was completed in October 2005.

3.3.2.2 *Site and Climate Condition*

The temperature rise due to the heat island effect in urban settings was considered during the design. Since the site is "tight," the building is very near the surrounding buildings. In this case, the fire spread between adjacent buildings was considered. Thus the opening area in the building façade was limited. In addition, because the wind-driven pressures are typically weaker at locations between buildings, the ventilation effectiveness may be adversely impacted. Some cellular offices were required.

3.3.2.3 *Client's Requirement: N/A*

3.3.2.4 *Design Strategy: Naturally ventilated all year and passively cooled through the summer months with downdraught evaporative cooling.*

Fresh air is supplied through a center light well and exhausted through a double envelope and stacks at the front elevation and at the back of the building. The stacks have transparent elements to provide daylighting. The building is zoned into an open-planned core zone that surrounds the center light well, and a perimeter zone with cellular offices that are connected to the ventilation stacks.

The seasonal ventilation modes are as follows: (1) In the winter, fresh air is preheated by heating coils. The air is taken in from the plenum under the center lightwell and exhausted through the stacks. The top of the lightwell is closed. (2) During mid-season, fresh air is taken in from both the plenum and the top of the lightwell and exhausted through the stacks. (3) During the summer, fresh air is taken from the top of the light well, and cooled by chilled water in cooling coils. As the cool air falls, it is taken into each floor through bottom-hung windows, then exhausted through the stacks.

3.3.2.5 *Constraints and Solutions: Fire and Smoke Ventilation*

Since the floor plate areas are between 2100 ft^2 ($195m^2$) and 7060 ft^2 ($656m^2$), there is no need to compartmentalize the building; however, the floors should be compartmentalized from each other. Thus the fire resistance of the glazed wall of the atrium should be 1 hour. Together with a sprinkler system, plant rooms, full fire-rated damper or ducts, and a mechanical ventilation system, the cost for fire prevention becomes significant, and the full mechanical smoke-extract system "undermines the case for investing in a parallel full natural ventilation system" [26]. Thus the building was proposed with natural ventilation for fire and smoke ventilation. Through analysis and simulation, the building was approved, based on the assumption that the majority of occupants would be familiar with the layout. Thus the building was configured as a single, naturally smoke ventilated compartment without a sprinkle system.

3.3.2.6 *Interactions and Solutions: N/A*

3.3.2.7 *Control*

A Building Management System (BMS) was used for control. The fire alarm is connected to the building management system (BMS). Eleven zones of control allow the smoke ventilation to act only in the affected area by opening the inlets and outlets and closing the openings to other zones.

3.3.2.8 *Estimation/Design Verification*

This is the first known application of downdraught evaporative cooling in a city center in the world [24]. Computer thermal modeling using Esp-r and physical modeling in a water tank were used to test the strategy. The analysis found:

(1) Possible backflow from the stack to the forth floor.

(2) Air is possibly drawn down the double envelope and out through the ventilation stacks.

(3) If the occupied space is cooler than the outside, the temperature of the exhausting air may be lower than the ambient temperature, especially in summer when the downdraught evaporative cooling is used. As a result, the ventilation may stop on 72 occupied hours in a year.

The improvements were:

(1) Addition of a dedicated exhaust stack and dampers that restrict the direction of air movement.

(2) Partitioning the front of each floor from the rear.

(3) Increasing the buoyancy of the air in stacks by warming the stack with the heat from the mechanical cooling process, or opening the BMS-controlled dampers at the bottom of the stacks.

3.3.2.9 *Performance Monitoring Results: N/A*

3.3.2.10 *Lessons Learned*

In this project, thermal comfort, indoor air quality, energy saving and cost were the primary performance mandates for the natural ventilation design. Fire regulation and site conditions were major constraints. Local climate conditions relative to wind should be known at the beginning of the design process.

To fulfill the major performance goals, CFD was used to help assess the performance of alternative ventilation approaches and detect design problems. In this case, it was found that air movement in an undesirable direction may occur when multiple stacks are used in multiple story buildings. Controlling the direction of flow is important for the success of the natural ventilation strategy. The designer states that "controls optimize its performance so that its eventual energy consumption is barely higher than that of a completely unassisted building, like the Lanchester Library"[27].

3.4 NATURALLY VENTILATED ASSEMBLY BUILDINGS

3.4.1 The Contact Theatre (Case 3-1)

3.4.1.1. *Building description*

The Contact Theater is located in an urban area of Manchester, UK. It has a floor area of 40,353 square feet (37,532 square meter) with 380 seats. The building was originally built in 1963, and the renovation was completed in 1999.

3.4.1.2 *Site and climate conditions*

The building is near busy roads, therefore sound transmission was a design issue.

3.4.1.3 *Client's Requirements*

Because the air conditioning system was old and inefficient with high maintenance and energy costs, the original mechanical system was replaced with a natural stack ventilation system utilizing extract fans.

The design comfort criteria agreed to by the client was that the temperature in seated areas was not to exceed the outside summer peak temperature by more than 5.4°F (3°C). The heat gain rate of the building was assumed to be 630 Btu/h·ft^2 (200W/m^2).

3.4.1.4 *Constraints and Solutions: N/A*

3.4.1.5 *Design Strategy: Stack ventilation*

The air intake was located at ground level in a back yard away from traffic, with "approximately 60-70 dBA background noise, 3 feet (1 meter) from the air inlet grilles"[28]. Air goes through attenuators and is cooled by passing over concrete walls of high thermal mass, then supplied under the seats. Fans help increase air flow: "Five extract stacks were built on the roof, each containing a slow-speed axial fan designed to operate automatically to increase ventilation flow in conditions of high temperature and to cool the structure at night" [28]. The extract stacks also contain acoustic splitters, selected for low-pressure drop.

Figure 3.10 The exterior view of Contact Theatre [25]

3.4.1.6 *Interactions and Solutions: N/A*

3.4.1.7 *Control: N/A*

3.4.1.8 *Estimation/Design Verification:*

Wind tunnel tests and CFD simulation were done to estimate the indoor air-flow and thermal conditions. Acoustical performance was also studied.

3.4.1.9 *Performance Monitoring Results: N/A*

Monitored data suggested that evening temperatures were approximately 3.6 °F (2°C) below to 1.8 °F (1°C) above the external peak depending on the location in the theatre, which met the previously set criterion.[29]

3.4.1.10 *Lessons Learned*

Since acoustics is a critical performance mandate for a theatre, site noise should be evaluated at the beginning of the design process. Thermal comfort, cost reduction and energy saving are other critical performance mandates; the latter two are required by the client.

Designer preference for a particular natural ventilation system was a major constraint. The designer wanted to avoid wind-induced ventilation because it was thought to be less controllable than stack-induced flow.

This is a good example of integrated design by which interactions between the performance mandates are solved.

3.4.2 General

Natural displacement ventilation with thermal mass utilization was shown to be successful in a series of auditoria and theatres in the UK. For example, the Queens Building at De Montfort University (Leicester, UK), the Contact Theatre (Manchester, UK) and the Garrick Theatre (Lichfield, UK) all successfully use natural ventilation.

The main challenges of the design are:

- The need for large inlet and outlet areas;
- The need to manage acoustic attenuation;
- The need to carefully configure the building management system;
- The need to ensure that stratification of warm, stale air forms above the breathing zone in theatres with raked seating; and
- The need to avoid airflow imbalances generated by wind pressures.

For acoustic attenuation, inlets are better located away from obvious sources of noise. Noise dampers at inlets and absorbing materials in plenums and exhaust ducts can be used. As exposed concrete is sound-reflective, there is a tradeoff between the exposed thermal mass and sound attenuation. The designer suggested that, if possible, plenums should be used for locating thermal mass to assist the thermal performance, since acoustic requirements are likely to limit the use of exposed mass in the occupied space. However, the volume of the auditorium, in part, depends on seating capacity and required reverberation time. According to Short et al., since a considerable height is required to ensure that the displaced warm layer remains above head height, the overall height or volume of the building often exceeds the desired volume for reverberation. Thus, extra absorption is needed.

In this building, the ventilation strategy does not rely on wind-driven pressures, since solutions using wind effect were considered to be less robust and more complex. Thus, inlets were placed away from negative pressure areas at the building surface.

The occupancy patterns of auditoria and theatres are intermittent, so demand controlled ventilation, i.e. monitoring CO_2 concentration, is appropriate for comfort,.

Cases with similar ventilation approaches include the Garrick Theatre (Lichfield, UK), the Lecture Theatre at the University of Bulawayo (Zimbabwe), and the Oliver Theatre at the Bedales School (UK). The floor area of the Garrick Theatre, completed in 2003, is approximately 40,000 ft^2. These theatres switched to natural ventilation for similar reasons: "the existing mechanical ventilation was too noisy and too expensive to operate and so the existing spaces were acutely uncomfortable." [30] The design goals of the Lecture Theatre at the University of Bulawayo were to provide light-tightness, soundproofing, and thermal comfort. Stack ventilation was also used. Because the single roof slab created reverberation problems in the larger spaces, double brickwork skins with a ventilation cavity were designed such that the ventilation of the building fabric was separated from the ventilation of the interior. The envelope screens "create a particular pleasing quality of light and keep the sun off the inner skin" [30].

3.5 NATURALLY VENTILATED EXHIBITION BUILDINGS

3.5.1 General

Many large, deep plan buildings, such as exhibition pavilions and air terminals, are "little more than protection from the weather and provision of a large lit enclosed space"[31]. This type of building has large horizontal dimensions with major clear-span spaces, often mixed with some small spaces. Exhausting air through the roof by wind chimneys utilizing thermal buoyancy was shown to be a successful solution for natural ventilation, in the David L Lawrence Convention Center (Pittsburgh, US) and Hall 26 of the Hanover Fair (Germany).

3.5.2 David Lawrence Convention Center (Case 4-1)

3.5.1.1 *Building description*

The 1,486,000 square feet (138,050 square meters) David Lawrence Convention Center building is located in Pittsburgh, Pennsylvania. It was completed in September 2003.

3.5.1.2 *Site and Climate Condition*

The building is located in downtown Pittsburgh, PA, by the Allegheny River, on a former brownfield site.

3.5.1.3 *Client's Requirement: N/A*

3.5.1.4 *Constraints and Solutions: N/A*

3.5.1.5 *Design Strategy*

The design strategy included wind assisted stack ventilation with night ventilation in warmer periods.

In this building, the driving force is the chimney effect created by the sweeping shape of the roof and the convection currents that develop from the river: “The roof profile, whose pitch increases as it rises from the terrace towards the masts, creates convection currents that naturally ventilate the exhibition hall by drawing cool air from the Allegheny River and venting warm air at the top.” Vents in the building’s north and south facades allow outside air to flow through the building without requiring fans or other mechanical systems. Cool air is also distributed to meeting rooms.

Natural ventilation is used in mid-season and provides effective air circulation when outdoor temperatures are between 45°F and 65°F (7°C and 18°C), about one-third of the time in Pittsburgh. It also is especially appropriate when convention displays are installed and dismantled, since little heat is generated during these times and comfort needs are less stringent. The building has a weather station near the roof to measure outdoor air temperature, humidity, and wind speed and direction. When conditions are right, the 20 air-handling units serving the exhibit halls shut off, the vents open, and outside air flows into the exhibit area. [32]

3.5.1.6 *Interactions and Solutions: N/A*

3.5.1.7 *Control: N/A*

3.5.1.8 *Estimation/Design Verification*

Extensive computer modeling was used to verify the design.

3.5.1.9 *Performance Monitoring Results*

Combined with other features to minimize energy usage, the building achieves an annual energy savings of about 35 percent when compared to a conventionally designed building.

3.5.1.10 *Lessons Learned*

Energy saving and thermal comfort were the critical performance mandates for this building.

3.6 NATURAL VENTILATION IN SHOPPING MALLS

3.6.1 General

Shopping malls are generally similar to atria with large open spaces between shops. In these spaces, air quality is typically not as much of a concern because of their large volume. Malls are very similar to exhibition halls and other large buildings. Fire and smoke control are important concerns [31]. The atria are often used as smoke reservoirs and for smoke ventilation, with stack ventilation using mechanical assistance and a low level supply of fresh air.

In the Bluewater shopping mall, Battle McCarthy use rotating wind scoops to catch wind and supply fresh air.

3.6.2 Bluewater Shopping Mall, Kent, UK (Case 5-1)

3.6.2.1 *Site and Climate Condition: N/A*

3.6.2.2 *Client's Requirement: N/A*
To create a naturally ventilated and day lit "internal avenue" of the mall while filtering noise and pollution.

3.6.2.3 *Constraints and Solutions: N/A*

3.6.2.4 *Design Strategy*

Wind scoops were believed to be particularly effective when supplying large open spaces because air does not have to be supplied adjacent to the occupants.[11] The specific strategies included:

(1) 6.6 ft (2 m) high conical wind scoops were mounted on the roof to allow cool air to drop and mix within the space. The wind scoops "owe their form to the influence of traditional Kent coast houses" [33]. They are spaced at 49 ft (15 m) intervals along the centre line of the mall.

(2) The scoops were designed to rotate into the wind.

(3) In the event of fire, the scoops can be rotated away from the wind and act as wind towers to extract smoke out of the building.

3.7 NATURAL VENTILATION IN FACTORIES AND WAREHOUSES

3.7.1 General

In warehouses, humidity control is often a concern, while in factories, local pollution extraction is often important [31]. According to the technical notes of the Architects' Journal [34], natural ventilation is usually acceptable in industrial buildings, except for those with (1) high occupancy, (2) high heat gain rates, (3) a high concentration of pollutants, and where (4) a clean environment is required for the industrial process.

3.7.2 Greyston Bakery (Case 6-1)

The Greyston Bakery is located in Yonkers, NY. The bakery produces brownies and other baked products. Completed in November 2003, the total building area is 23,100 square feet (2,140 square meters).

3.7.2.1 *Site and Climate Condition: N/A*

3.7.2.2 *Client's Requirement: N/A*

3.7.2.3 *Constraints and Solutions: N/A*

3.7.2.4 *Design Strategy: Mechanically assisted stack ventilation*

A two-story atrium separates the offices from the bakery. A three-level light shaft allows natural light into the interior of the bakery. Both the light shaft and the atrium allow for natural airflow through the bakery, which eliminates excess heat from the ovens in the summer and supplements the primary ventilation system: "The passive ventilation within the bakery is supplemented by a mechanical fresh-air make-up system that filters 99% of particulates from the air. Baked products are partially cooled by ambient outside air."[35] In this bakery, the oven is well insulated to reduce heat transmission to the space.

Daylighting and efficient metal-halide lamps are used throughout the bakery to reduce energy consumption.

3.7.2.5 *Interactions and Solutions: N/A*

3.7.2.6 *Control: N/A*

3.7.2 7 *Estimation/Design Verification: N/A*

3.7.2.8 *Performance Monitoring Results: N/A*

3.7.2.9 *Lessons Learned*

According to the designer, natural ventilation helps to save energy and ensure thermal comfort by removing the excess heat from the oven.

3.8 NATURAL VENTILATION IN SCHOOLS

3.8.1 General

Schools often have single or multiple floors and are designed to utilize daylighting Their plans are typically not very deep, about 30 to 90 feet, so wind-driven cross ventilation and buoyancy-driven ventilation are common approaches. These strategies are applied in the Jubilee School (London, UK), the Haute Vallée School (UK), the Clarkamas High School (Oregon, US) and the Dalles middle school (Oregon, US).

School classrooms are occupied intermittently, and the major source of heat gain is from lighting and occupants. Demand control ventilation can be used and achieved either by monitoring the carbon dioxide concentration in the extracted air to control fresh air flow rates or, more simply, by using occupancy sensors. In the Dalles middle school, a green/red light system was used to let teachers know when to open windows based on indoor and outdoor conditions. The school uses wind turbine vents for ventilation, with a back-up conventional fan system. When outside weather is moderate (55°F to 75°F), "a green light in the classrooms lets the teachers know that the wind turbine vent system can be engaged to harness the Columbia Gorge region's abundant wind for natural ventilation" [36].

In schools, indoor air quality, thermal comfort, acoustics, and energy saving were identified as important performance mandates.

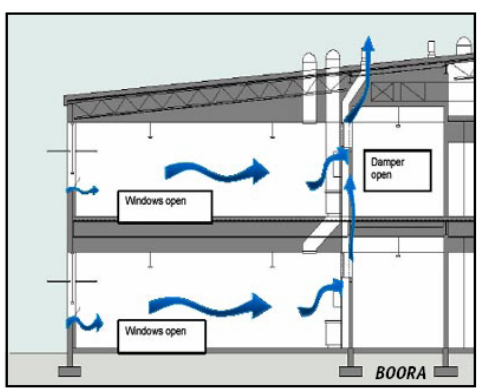


Figure 3.11 Ventilation flow paths of the Dalles Middle School (Source: http://oregon.gov/ENERGY/CONS/school/docs/thedalles.pdf)

3.9 NATURAL VENTILATION IN OTHER TYPES OF BUILDINGS

3.9.1 General

Examples of natural ventilation in healthcare facilities and laboratories are few. Mechanical ventilation is often needed to achieve the desired pressure gradients to control airflows between areas and clean the air. Currently, the issues of air quality and infection control may be the reasons precluding the use of natural ventilation in hospitals, even in temperate climates. One of the major energy demands in hospitals is for air treatment. In a few cases, "non-clinical" areas were adaptable for natural ventilation. For example, in St. Vincent University Hospital (Dublin), the atrium is naturally ventilated while other parts of the building are mechanically ventilated or air conditioned [37]. Similar to laboratory buildings, the spaces can be zoned first, so that the areas requiring mechanical ventilation or air conditioning are divided from other less critical areas.

3.10 CONCLUSION

Through interpretation from the case studies, conclusions related to the design process can be made in the following aspects:

First, we can conclude that, with proper design, natural and hybrid ventilation strategies can be effectively used in various types of non-residential buildings under certain weather conditions.

Second, the case studies confirm the decision-making issues in the design of natural ventilation that were identified through literature review, although some of the constraints, barriers, and performance mandates were not identified for all cases. Table 3.3 summarizes the lessons learned from the case studies.

Third, these cases offer a good general process for determining ventilation approaches to achieve thermal comfort, reach a good IAQ, and save energy. The process was generally grounded in a suitability analysis for the climate and site conditions, a consideration of the client's requirements, and an analysis of the features of the building. The case studies suggested that constraint issues such as cost, acoustics, safety, and security limited the decision making process. Applying a grounded theory approach from this, a decision-support framework can be developed to assist the design process of natural ventilation in most non-residential buildings. It is also found that the importance of each critical issue varies for each project, which suggests the need for weighting these issues in the decision-making process.

Fourth, estimating and verifying the performance of alternative approaches was shown to be an effective procedure for adopting a better design. This can also be incorporated into the decision process.

Fifth, the case studies also demonstrate that controls and building management systems are very important considerations for the success of naturally or hybrid ventilated buildings.

In addition, the detailed solutions found in the case study can be a good source for design suggestions in the framework.

Table 3.3 Identification of critical design issues from the case studies

(Note: Those cells left blank represent that no such issues are considered or no such measures are done, or no information is available.)

	Office						Academic/research		Assembly	Exhibition	Shopping mall	Factory	School
Case No.	1-1	1-2	1-3	1-4	1-5	1-6	2-1	2-2	3-1	4-1	5-1	6-1	
Performance mandates													
Thermal comfort	●	●	●	●	●	●	●	●	●	●	●	●	●
Energy Saving	●	●	●	●	●	●	●	●	●	●	●	●	●
Indoor air quality	●	●	●	●	●	●	●	●	●				●
Acoustics					●	●			●	●			
Cost	●		●	●			●	●	●	●			
Other issues													
Control	●	●	●				●	●	●				●
Heat recovery					●								
Constraints and barriers													
Client and designer's intention			●				●		●	●			
Fire regulation			●		●		●	●					
Security		●	●										
Zoning				●			●	●					
Rains													
Local standards, regulations		●											
Pressure loss		●					●						
Design process													
Site condition input estimation or on-site measurement, and site analysis for the suitability for natural ventilation	●	●		●	●	●	●	●		●			
Approach comparison		●											
Performance assessment in design process		●			●		●	●	●	●			
Post-occupation monitoring	●			●						●			

CHAPTER 4 FRAMEWORK OVERVIEW

4.1 INTRODUCTION

The decision-support framework is developed from three main concerns: (1) the necessary inputs, (2) the assessment procedures and (3) the structure of the output. The input was determined by identifying the critical design issues when the integration of natural ventilation is a goal. These issues were identified from the literature review and case studies of exemplars.

The assessment procedures link the input to the output and provide the foundation for comparative analysis and recommendations from the framework. The assessment procedures were also developed from literature review, case studies, and interviews.

The framework must convey understandable information for its intended users. For this, the type of information and its format must be carefully considered. It is important to decide which format is most appropriate for each output category. The framework begins with this overall structure.

4.2 CRITICAL ISSUES AND INPUT TO THE FRAMEWORK

Critical decision-making issues and input were identified through a review of the related literature and case studies of naturally ventilated buildings. The critical issues include:

- Energy saving potential
- Indoor air quality
- Thermal comfort
- Acoustics and background noise
- Safety and security
- Cost
- The designer and client's goals and preferences
- Pressure loss in the ventilation path
- Controllability
- Site constraints
- Rain penetration
- Flexibility and adaptability

These issues are identified from the major performance mandates or constraints in the design of a naturally ventilated building.

To address these issues, the input may be categorized as: (1) those associated with the owner's and designer's goals and objectives; (2) those associated with the design proposition; (3) those associated with site and climate, and (4) the designer's and owner's relative level of concern for each performance mandate, representing how the designer weighs the importance of each module in a given project. These four categories condense the critical input related to the design of a naturally ventilated project.

Typically, for a given project, the performance mandates may not have equal importance for decision-making. Therefore the relative level of concern for each of the performance mandates (energy, thermal comfort, IAQ, etc.) must be inputted and used as part of a decision-weighting process. These relative levels become normalized weights in the decision-making process, as described later.

4.3 INPUT TRANSFORMATIONS AND ADJUSTMENTS

Through case studies, it was found that, in addition to capturing the owner's and architect's design intentions, information concerning the site and climate are also needed. Among the site and climate data are the temperature and humidity, prevailing wind speed and direction, solar radiation, and noise and pollution sources. Most likely, the available data are not on-site measurements. To be useful in the support framework, this input must often be predicted, transformed, or adjusted for local effects, or compared with on-site sampling measurements. For example, the following input processing may take place.

(1) Wind at the building location

Wind velocity from meteorological stations available in typical meteorological yearly archival files can be transformed and modified for micro-climate effects for the terrain and height corrections at the building location [7]. While it would be most desirable to determine these transformations using wind tunnel studies or computational fluid dynamic (CFD) simulations, this is time, space, and/or cost intensive. Therefore, for the proposed decision-support framework, prediction models for some typical scenarios are included.

(2) Temperature and humidity

Information concerning the ambient temperature is needed to assess potential energy savings, heat gain to the building, and thermal comfort. In lieu of on-site monitoring, the TMY data should be adjusted for local effects such as evaporative cooling by nearby bodies of water, transpirative cooling by vegetation, or warming of the air due to the heat island effect. Currently, no immediately useful methods are available for these adjustments. Research is needed and is beginning in these areas.

(3) Noise Intensity Levels (IL)

Noise intensity levels at the building site can be obtained from on-site measurement and translated to noise contour maps. When this is not feasible, some standards and guidance can help to predict the exterior noise environment. These sources provide an approach to estimate the noise Intensity Levels for the proposed building site.

(4) Outdoor air quality

Some air quality databases in the US provide regional ambient air quality information. There are also algorithms that estimate the amount of pollution caused by traffic or nearby emissions.

Section 6.2 describes these input transformations and prediction modules in detail.

4.4 ASSESSMENT

The decision-support input and output are related by a series of both sequential and parallel assessment procedures. These assessment procedures may be Boolean or arithmetic, with outcomes that may be categorized as:

(1) Binary (Yes or No)

For example, feasibility assessment provides the result that natural ventilation is feasible or not.

(2) Scalar

For example, performance assessment for energy savings potential can rate the estimated savings as low, medium or high, or in a numeric scale, such as 1(very low) to 10 (very high).

(3) Categorical

Such assessment provides categorized results, such as the ranking of alternative natural ventilation approaches and categorized design suggestions.

The proposed decision-support framework has two primary assessment algorithms. The first evaluates the feasibility of applying natural ventilation for the given input. If feasibility is suggested, then the relative performance of alternative natural ventilation approaches is evaluated, ranked, and compared. The results of these assessment procedures are then presented as recommendations.

4.4.1. Assessment Level 1: Feasibility

Modules assess the feasibility of natural ventilation for the given input by analyzing the interaction of the adjusted critical site and climate information with the design proposition. The algorithms in the modules are identified and developed from technical publications that are referred in the following sections. In the proposed framework, the feasibility assessment consists of four sub-modules:

(1) Outdoor temperature and humidity assessment

(2) Wind assessment

(3) Site noise assessment

(4) Pollution assessment

If the outcome from any of the four modules concludes that natural ventilation is not feasible, no further assessment is made, although certain remedial solutions may be suggested. Chapter 6 describes and illustrates these modules in detail.

For these sub-modules, feasibility is assessed for the following performance mandates as identified from the literature review and case studies: thermal comfort, noise, energy, and indoor air quality.

4.4.2. Assessment Level 2: Comparison of Alternative Natural Ventilation Approaches

If the result from any one of these four feasibility assessment modules suggests that natural ventilation is not viable, then redesign strategies are suggested, but detailed performance assessment is not carried out. If, however, natural ventilation is determined to be feasible, then assessment proceeds to a more detailed comparative analysis.

Natural ventilation strategies may be categorized as wind-driven ventilation or buoyancy-driven (stack effect) ventilation. Strategies may be further sub-categorized as single-sided, cross flow only, stack ventilation only, cross ventilation with stack effect, and cross ventilation with wind chimney and stack effect. Which approach is most appropriate for a given set of inputs is a concern for the decision-making process. Comparison of these alternatives should consider inputs such as building geometry and prevailing wind speed and direction. Therefore, the decision-support framework should allow for comparison of these alternatives for the given inputs and constraints by evaluating the performance mandates.

4.4.2.1 Application of Constraint Functions

All of the possible natural ventilation approaches and system designs are assessed by first applying constraints functions to each of the alternatives. The scope of the constraints in the framework is introduced as follows.

(1) Architect's and client's preferences regarding natural ventilation options
(2) Safety and security
(3) Site constraints
(4) Pressure loss in the ventilation path

Chapter 7 describes and illustrates the constraints in detail.

4.4.2.2 Performance Mandates

The comparison of alternative approaches to natural ventilation continues by assessing the critical performance mandates. These include:

(1) Energy Savings
(2) Thermal Comfort
(3) Acoustic Control
(4) Indoor Air Quality
(5) Cost

Chapter 9 describes and illustrates the assessment modules and sub-modules in detail.

Less critical issues such as control and flexibility will be discussed in design suggestions in Chapter 8.

4.4.2.3 Weighting

Before comparisons amongst the alternatives can be made, two additional decision making steps are necessary. These are: obtaining a normalization scale to each performance mandate outcome and weighting the relative importance of each performance mandate. For example, if the building is a library, when comparing natural ventilation alternatives, the acoustic performance may have higher relative importance.

4.4.2.4 *Ranking*

Because the ranking of design requires the examination of several performance factors, the multi-purpose optimization method is used to assess the performance of alternative natural ventilation system design approaches. For alternative i (i =1, ...i) and factor j (j = 1, ... j), the performance of alternative i on factor j is defined by P_{ij}. With a set of normalized weightings ω_j ($\sum_{j=1}^{k} \omega_j = 1$), the overall performance score of an alternative i is $P_i = \sum_{1}^{j} \omega_j p_{ij}$. Thus, the design alternatives can be ranked.

4.5 OUTPUT

The users of the framework are architects and engineers involved in the process of natural ventilation design. The usefulness of assessment algorithms and the levels of detail of the outputs must be appropriate for the early phases of design.

Each decision-making module includes input, process (algorithms), and output. The output can be feasibility assessment or ranking of alternatives, natural ventilation approaches, and design suggestions. Suggestions include the design and sizing recommendation for the natural ventilation system's features and control strategies. The final output of the framework is a ranking of alternatives.

4.6 THE GENERAL PROCESS, THE SCOPE OF DECISION-MAKING ISSUES, AND THE ASSESSMENTS OF THE FRAMEWORK

In summary, the general structure and process of the decision-support framework is illustrated in Figure 4.1. The scope of decision-making issues and the assessments of the framework are illustrated in Figure 4.2.

The general decision-making process presented in this chapter is developed in detail in subsequent chapters.

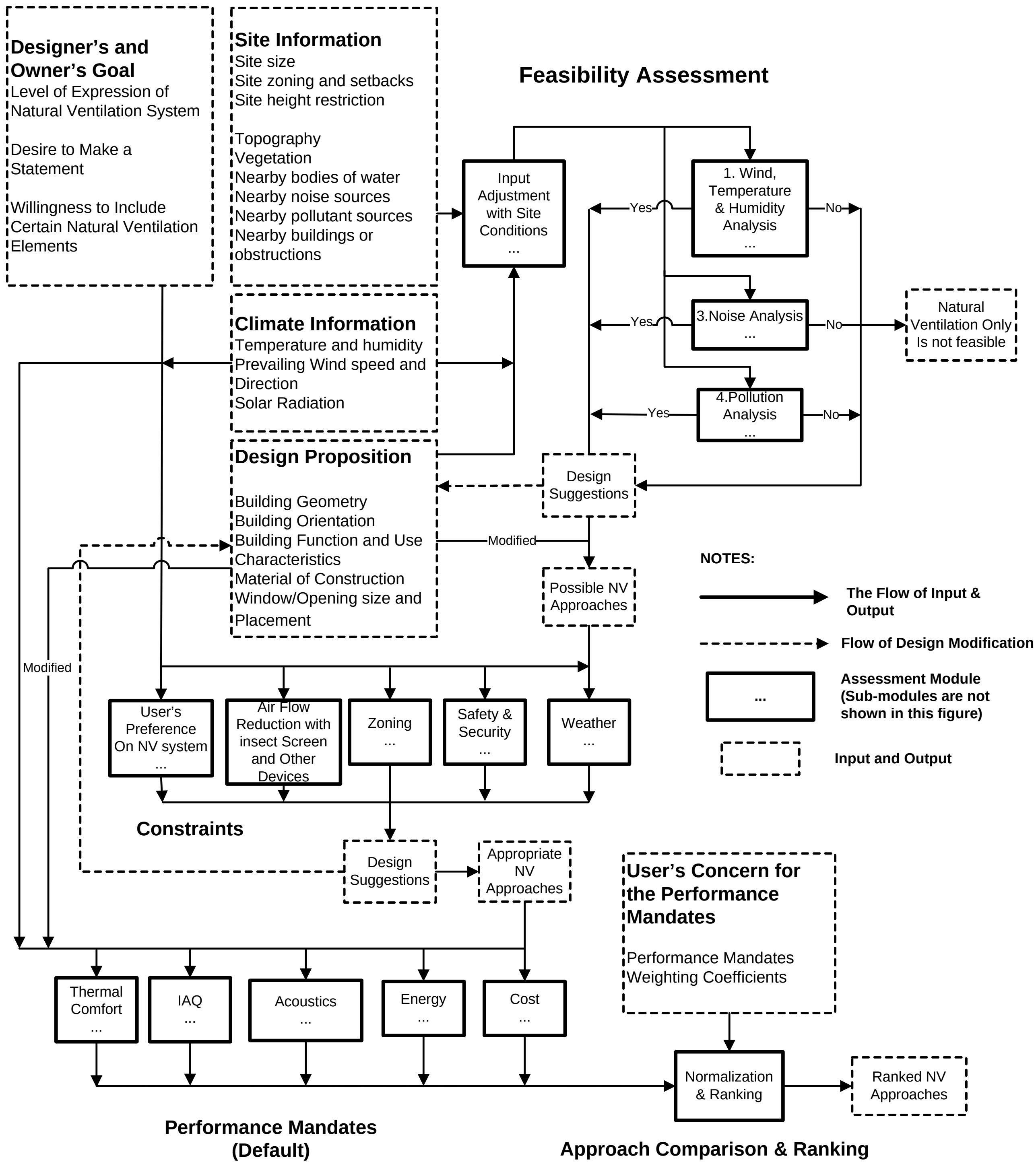


Figure 4.1 General structure and process of the decision-support framework

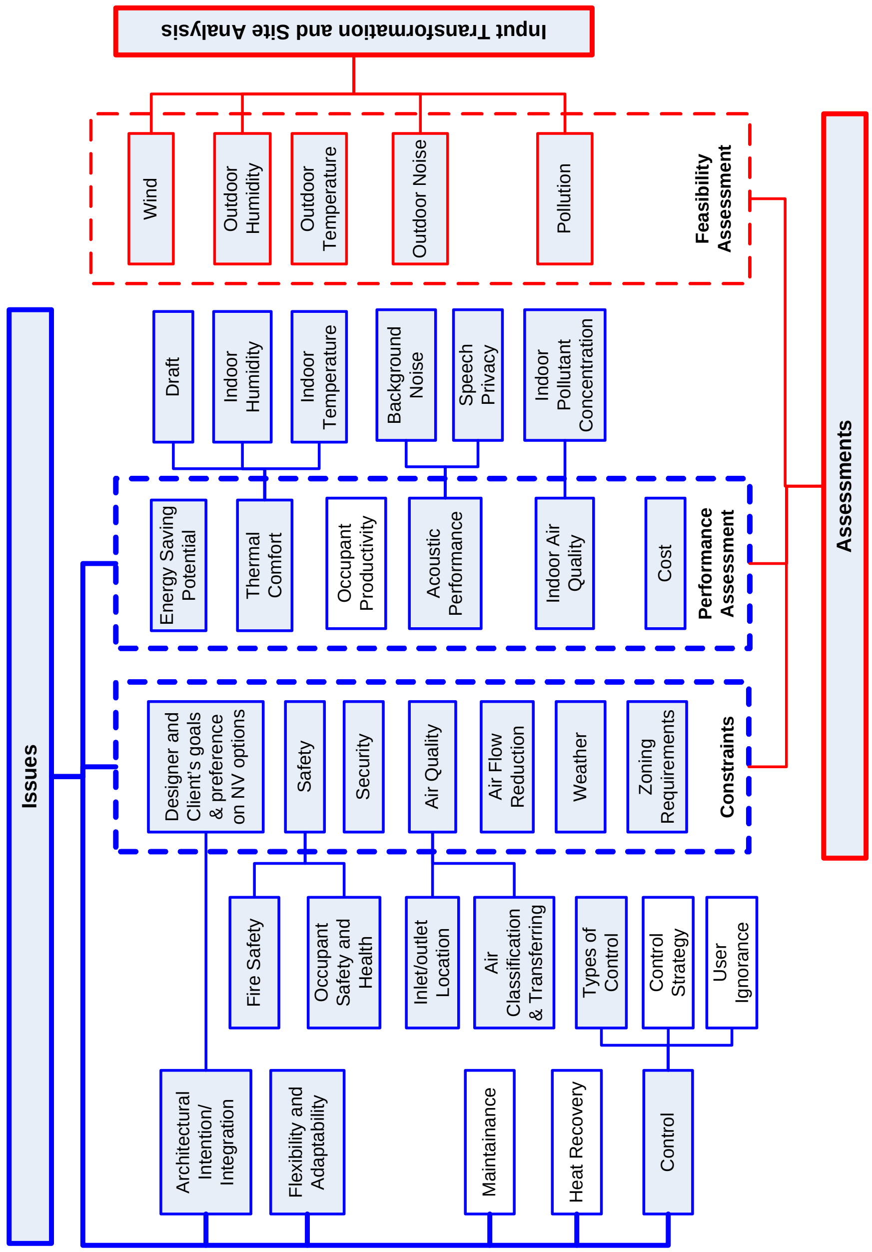


Figure 4.2 The scope of decision-making issues and the assessments of the framework

Indicates issues to be addressed through this work

Indicates issues not addressed but identified for future development

CHAPTER 5 INTERACTION AMONG PERFORMANCE MANDATES

5.1. METHODOLOGY

This chapter explores the interactions among performance mandates for natural ventilation designs. The literature review and case studies identify the five critical performance issues as, Energy Savings, Thermal Comfort, Indoor Air Quality, Acoustic Performance, and Cost.

Table 5.2 summarizes the interactions between data input and issues of constraints and performance mandates. In this framework, the interactions and tradeoffs among the performance mandates are qualitatively analyzed by tracing their common related inputs or common intermediate results in the table. The results of this interaction analysis are given as design suggestions. The interactions can be quantitatively studied in the future.

The interactions among the five critical performance mandates are explored by studying the interaction between any pair of two mandates. Therefore, there are a total of 10 combinations, listed in the Table 5.1

Table 5.1 The ten pairwise combinations of interactions of the five critical performance mandates

	Energy saving				
Thermal Comfort	●	Thermal Comfort			
IAQ	●	●	IAQ		
Acoustics	●	●	●	Acoustics	
Cost	●	●	●	●	Cost

The interactions are explored in the following ways:

- Find the common inputs of the two performance mandates in the matrix in Table 5.2. For example, Figure 5.1 illustrates that common inputs are needed for evaluating interactive issues such as Thermal Comfort and Acoustical Performance.
- Study the influence of these inputs on the performance of each combination pair for the design of natural ventilation.

Table 5.2 The interactions between inputs and issues of constraints and performance mandates

INPUTS	(1) OWNER AND DESIGNER'S GOALS AND OBJECTIVES			Important Intermediate Results					CONSTRAINTS					PERFORMANCE MANDATES				
	Levels of Expression of NV systems	Willingness to include natural ventilation elements	Desire to Make a Statement	**Building Heat Gain Rate**	**Pressure Difference**	**Indoor Air Pollutant**	**Air Flow Rate**	**Indoor Temperature**	**Architect's and Client's Preference on NV Options**	**Fire Safety**	**Security**	**Zoning Requirement**	**Vector Prevention**	**Thermal Comfort**	**IAQ**	**Acoustic Performance**	**Energy savings**	**Cost**
																		●
														●			●	
								●					●	●	●		●	
INPUTS							●								●			
(2) DESIGN PROPOSITION							●											
Building Geometry							●	●						●			●	
Building Geometry	●		●	●	●					●		●						●
Room/Space Geometry	●		●				●			●						●		●
Ventilation Components (Fans, ducts, dampers, etc.)/Building Ventilation Elements (Atria, Shaft, Wind Tower, Double-envelope, etc)	●	●	●		●		●		●	●	●	●			●	●		●
Building Orientation				●	●							●						
Building Function and Use																		
Space Function				●		●				●	●					●		
Schedule of Use				●		●				●	●					●		●
Ventilation Zones and Flow Paths					●					●						●		●
Fire Compartment	●									●								●
Equipment & Lighting Fixtures				●														●
Materials/Construction																		
Envelope Materials/Construction				●						●						●		●
Interior Materials/Construction				●		●		●		●						●		●
Window/Opening Size and Placement																		
Exterior Openings(Location, geometry, construction)	●		●	●	●		●			●	●	●				●		
Interior Ventilation Openings (Location, geometry, construction)	●				●		●			●	●					●		
Solar Radiation				●														
Prevailing Wind Speed and Direction					●		●											
Outdoor Temperature & Humidity				●			●	●						●			●	
Nearby Noise Sources																●		
Nearby Pollution Sources															●			
Site Plan layout												●						
Site Zoning and setbacks												●						
Site Height Restrictions												●						
Topography				***(4) DESIGNER'S AND OWNER'S RELATIVE LEVEL OF CONCERN FOR PERFORMANCE MANDATES-- WEIGHTS (DEFAULT)***										●	●	●	●	●
Vegetation																		
Nearby Body of water																		
Nearby Building/Obstruction																		
(3) CRITICAL SITE AND CLIMATE INFORMATION																		

Note:

1. A note of "●" at each interaction means the input is related to the intermittent result, constraint, or assessment.
2. If the influence of an input on a performance mandate is through an important intermediate result, no "●" is shown at the intersection of the input and the performance mandate; instead, it is shown at both the intersection between the input and the intermediate result, and between the intermediate result and the performance mandates.

The interaction analysis does not consider the relative importance of each of the performance mandates. Because the relative importance varies in different buildings, the tradeoffs among these performance mandates need to be treated differently.

5.2. INTERACTIONS

5.2.1. Thermal Comfort – Acoustical Performance

(1) Room geometry

Thermal comfort and acoustical effects can be improved or affected by building and room geometry. Room geometry may influence the air distribution in the room, and thus may influence the ventilation effectiveness of the occupied area and the temperature distribution of the space. For example, with other conditions unchanged, a higher ceiling can make warmer air stay above the occupied zone. If air is exhausted at higher level openings, and the stratification layer is above head level, then occupants may feel cooler than in a room with a lower ceiling level.

Acoustical effects of a room also relate to its geometry. The rate of decay of sound in a room is related to the sound absorbance of the room surfaces and the volume of the room and is expressed as the reverberation time in Equation 5.1.

$$RT = 0.161V/A$$

Equation 5-1

RT = Reverberation time, s
V= cubic volume of the room, m^3
A= total sound absorption, m^2, of the surfaces of the room and loss due to the air

INPUTS	(1) OWNER AND DESIGNER'S GOALS AND OBJECTIVES			Important Intermediate Results					CONSTRAINTS					PERFORMANC E MANDATES				
	Levels of Expression of NV systems	Willingness to include natural ventilation elements	Desire to Make a Statement	**Building Heat Gain Rate**	**Pressure Difference**	**Indoor Air Pollutant**	**Air Flow Rate**	**Indoor Temperature**	**Architect's and Client's Preference on NV Options**	**Fire Safety**	**Security**	**Zoning Requirement**	**Vector Prevention**	**Thermal Comfort**	**IAQ**	**Acoustic Performance**	**Energy savings**	**Cost**
																		●
														●			●	
								●					●	●	●		●	
INPUTS							●								●			
(2) DESIGN PROPOSITION							●											
Building Geometry							●	●						●			●	
Building Geometry	●		●	●	●					●		●						●
Room/Space Geometry	●		●			●	●			●						●		●
Ventilation Components (Fans, ducts, dampers, etc.)/Building Ventilation Elements (Atria, Shaft, Wind Tower, Double-envelope, etc)	●	●	●		●		●		●	●	●	●			●	●		●
Building Orientation				●	●							●						
Building Function and Use																		
Space Function				●		●				●	●					●		
Schedule of Use				●		●				●	●					●		●
Ventilation Zones and Flow Paths					●					●						●		●
Fire Compartment	●									●								●
Equipment & Lighting Fixtures				●														●
Materials/Construction																		
Envelope Materials/Construction				●						●						●		●
Interior Materials/Construction				●		●		●		●						●		●
Window/Opening Size and Placement																		
Exterior Openings (Location, geometry, construction)	●		●	●	●		●			●	●	●				●		
Interior Ventilation Openings (Location, geometry, construction)	●				●		●			●	●					●		
Solar Radiation				●														
Prevailing Wind Speed and Direction					●		●											
Outdoor Temperature & Humidity				●			●	●						●			●	
Nearby Noise Sources																●		
Nearby Pollution Sources															●			
Site Plan layout												●						
Site Zoning and setbacks												●						
Site Height Restrictions												●						
Topography				***(4) DESIGNER'S AND OWNER'S RELATIVE LEVEL OF CONCERN FOR PERFORMANCE MANDATES-- WEIGHTS (DEFAULT)***										●	●	●	●	●
Vegetation																		
Nearby Body of water																		
Nearby Building/Obstruction																		
(3) CRITICAL SITE AND CLIMATE INFORMATION																		

Figure 5.1 The common inputs found for Thermal Comfort and Acoustical Performance

(2) Ventilation components, external openings

Ventilation components greatly influence air flow rate and flow pattern, and consequently affect thermal comfort. These components also affect the indoor sonic environment. Increasing opening size may increase the flow rate, resulting in comfort, but may also increase the noise level of the room if external noise is allowed to enter the building. Generally, choosing a direct ventilation flow path with less pressure loss is desirable to promote greater air flow. However, to reduce noise transmission, using building components to provide sound buffering such as double-envelopes, shafts, plenums, atria, acoustic louvers, acoustical attachments, and insulation may induce air flow resistance. The tradeoff between the air flow rate and noise reduction should be evaluated in each particular case. Computer simulation or analytical techniques are useful in investigating the effect of pressure drops. As an alternative, intermittent ventilation with automatic controls can be used when the outdoor noise is variable.

(3) Space occupancy

Space occupancy partially determines the building's internal heat gain rate and the desired acoustical criteria. According to Table 5.3 and Table 5.4 (the heat gain rate and recommended background noise revels of typical occupancies), buildings or spaces that have both high heat gain rates and strict requirements on background noise include concert halls, auditoriums, theatres, recording studios, and places of worship. Since ventilating spaces with higher heat gain rates may need larger openings while the acoustical constraints suggest small or no openings, a conflict may exist. As discussed above (5.3 (2)), a balance should be made. In projects designed by Short and Associates, the conflict is solved with stack displacement ventilation by introducing fresh air from the plenums under the auditorium, and exhausting through shafts. Noise absorbing treatment is added in the plenum and shafts. Thermal mass walls act as heat sinks and the plenum acts as a sound barrier.

(4) Schedule of use

Shifting the schedule of use may avoid both hot hours and noise in the day from nearby traffic and facilities.

(5) Envelope materials/construction

In principle, envelope materials of both high thermal insulation and high acoustical insulation or absorbance can improve thermal comfort and lower indoor background noise. However, because the sound Transmission Loss of an envelope component drops significantly if an opening is added, the improvement of the envelope may have only a marginal effect on the overall acoustic performance. For example, if the Transmission Loss of the wall is 30 dB, the TL of the opening is 0 dB, and the total area occupied by the opening is 5%, the composite TL of the wall is 9dB. If the TL of the wall is increased to 50 dB, the composite TL remains about 9dB.

Table 5.3. Internal heat gain of some typical occupancies with day light factor at 40 degrees latitude

(Developed based on (1) Table 1, Representative rates at which heat and moisture are given off by human beings in different states of activity, ASHRAE Handbook, Fundamentals, 29.4, (2) Occupant Density, Sun, Wind & Light, pp.40, (3)Heat gain totals, Part A, Internal heat sources-people and equipment, Sun, Wind & Light, pp.63 and (4) Heat gain totals, Part B, Internal heat sources-electric lighting, Sun, Wind & Light, pp.64-65)

Occupancy type	**Sensible heat gain rate from occupants,W/m^2**		**Equipment gain, W/m^2**	**Lighting gain with 3<DF<5, Latitude 40**	**Lighting gain with DF<1.5**	**Total (Low)** (Average occupancy+ efficient equip.+ low lighting gain)	**Total (Maximum)** (Peak occupancy+ high equip.+ high lighting gain)
	Average	Max					
Retail building	6	24	10-17	5-15	11-36	21	77
General office	2.8	5.6	10-17	6-7	14-16	26.8	38.6
Office with computer			<47				
Computer areas			237-552				
Assembly				4-6	9-15		
Auditorium space	94.5	105.7	3			101.5	123.7
Conference rooms		37.8	10-17				69.8
Education			13-23	5-9	13-20		
Classroom		37.8	10-13				70.8
Laboratory		25	13-23				68
Libraries		16	10-13				49
Grocery stores	6.75	16.5	24-42	5-11	12-25	35.75	83.5
Gymnasium		67.2	3-6				
Ball room		97.2	3-6				
Warehouse	0	6	8-13	0-4	0.3-3.1	8	22.1

Table 5.4 Recommended classification and suggested noise criteria range for steady background noise

Type of Space	NC curve	Approximate dBA
Concert halls, opera houses and recital halls (for listening to faint musical sounds)	10-20	20-30
Broadcast and recording studios (distant microphone pickup used)	15-20	25-30
Large auditoriums, large drama theatres and houses of worship (for excellent listening conditions)	20-25	30-35
Broadcast, television and recording studios (close microphone pickup only)	20-25	30-35
Small auditoriums, small theatres, small churches, music rehearsal rooms, large meeting and conference rooms (for good listening), or executive office and conference rooms for 50 people (no amplification)	25-30	35-40
Bedrooms, sleeping quarters, hospitals, residences, apartments, hotels, motels, and so forth (for sleeping, resting, relaxing)	25-35	35-45
Private or separate offices, small conference rooms, classrooms, library, and so forth (for good listening conditions)	30-35	40-45
Living rooms and similar spaces in dwellings (for conversing or listen to radio or TV)	35-45	45-55
Large office, reception areas, retail shop and stores, cafeterias, restaurants, and so forth (for moderately good listening conditions)	35-50	45-60
Lobbies, laboratory work spaces, drafting and engineering rooms, general secretarial areas (for fair listening conditions)	40-45	50-55
Light maintenance shop, office and computer equipment rooms, kitchens and laundries (for moderately fair listening conditions)	45-60	55-70
Shops, garages, power-plant control rooms, and so forth (for just acceptable speech and telephone communication). Levels above PNC-60 are not recommended for \any office or communication situation.	-	-
For work spaces where speech or telephone communication is not required, but where there must be no risk of hearing damage	-	-

(6) Interior materials/construction

Thermal mass, such as exposed concrete with night ventilation, can be used to lower energy consumption. However, structural concrete is much less effective as thermal mass when it is covered with a sound absorbing material. An exposed roof deck reflects sound off the slab, possibly causing specular reflections and increased reverberation. Specular reflection is typically undesirable between adjacent cubicles in open plan offices when ceiling heights are less than 15 feet. Noise from distant sources may reflect and annoy occupants. In this case, using ceiling clouds or hanging baffles in sensitive areas in the spaces may be effective. Since these issues have been overlooked in many recently built “green buildings,” acoustician M. Noble argues the necessity for an acoustician to be a member of the design team [38].

(7) Interior openings

Interior openings for ventilation may also transmit sound from adjacent rooms.

5.2.2. Thermal Comfort – IAQ

Air flow can dilute contaminants and remove heat and moisture produced in the space. When properly designed, natural ventilation can ensure both thermal comfort and good indoor air quality.

(1) Exterior openings

Typically, natural ventilation is not a feasible thermal comfort solution if outdoor contaminant levels are high. In addition to pollutants, natural ventilation openings can allow bugs and leaves into the building. Screens can be used to prevent this, but they induce a pressure loss whose value depends on the open area ratio, the material, and the texture of the screen. For vector prevention, rough screens can reduce air flow more than 60 percent, and smooth screens reduce the air flow by 35 percent on average [39]. Sometimes it is not practical to compensate for this loss by increasing the opening areas, so mechanical assistance may be needed.

(2) Humidity

According to ASHRAE Standard 55-2004, humidity limits are only applicable when there is a system designed to control humidity. According to this standard, for naturally vented situations, higher relative humidity limits can be thermally acceptable. However, if a building is naturally ventilated and high relative humidity results, then IAQ may be adversely impacted. This is because microbial growth tends to increase in high humidity conditions. For molds, the growth of xerophilic species begins at an RH of 75% to 80%. If outdoor humidity is equal or higher than that level, natural ventilation will probably not be appropriate.

(3) Air flow rate, building heat gain, and indoor pollutants

The air flow rate should meet the minimum requirement for IAQ (ASHRAE Standard 62), and be sufficient to remove heat. Increasing the air flow rate may improve both thermal comfort and IAQ. However, the pollutant removal rate may be limited even when the ventilation rate is very high (Figure 5.5), while high ventilation rates can cause draft. In cooler weather, ventilating to improve IAQ may also cause drafts. Preheating the air at inlets or making air pass a buffer space to mix with indoor air can reduce or eliminate this problem.

(4) Ventilation zone and flow paths

Increasing the ventilation effectiveness can improve both thermal comfort and IAQ with lower air flow rates by improving distribution and flow patterns.

Displacement ventilation is a strategy for providing good air quality in occupied spaces. It uses density differences or supply momentum to form unidirectional vertical flow, which displaces the contaminated air vertically. The contaminant removal effectiveness is expressed by Equation 5-2:

$$\varepsilon_c = \frac{c_e - c_s}{c_{oz} - c_s}$$

Equation 5-2

Where C_e is the contaminant concentration in the exhaust air, C_s is the contaminant concentration in the supply air stream, and C_{oz} is the mean contaminant concentration in the occupied zone. Therefore, the value of ε_c for displacement ventilation can be much higher than 1. According to E. Mundt et al.[40], displacement ventilation is preferable when contaminants are warmer and/or lighter, and in tall rooms, such as in classrooms, theaters, and supermarkets.

Changing the flow pattern may significantly change the effectiveness of natural ventilation. As shown in Figure 5.2, for stack ventilation, supplying air under the seats and extracting at the ceiling is preferred to using only one inlet at the lower part of the room. In the latter case, neither the thermal comfort nor the air quality of the people seated in the upper part of the room is good.

Attention should be paid to the pressure distribution with stack ventilation

- In multi-floor buildings, make sure that the exhausted air from lower floors does not contaminate upper floors;
- In buildings with multiple stacks, some shafts may draw the air from other exhausting stacks;
- In cases where stack effects interact with wind, such as the example shown in Figures 5.3 and 5.4, with a double-envelope located to the south side and wind also coming from the south, neither thermal comfort nor IAQ conditions in the rooms are satisfying.

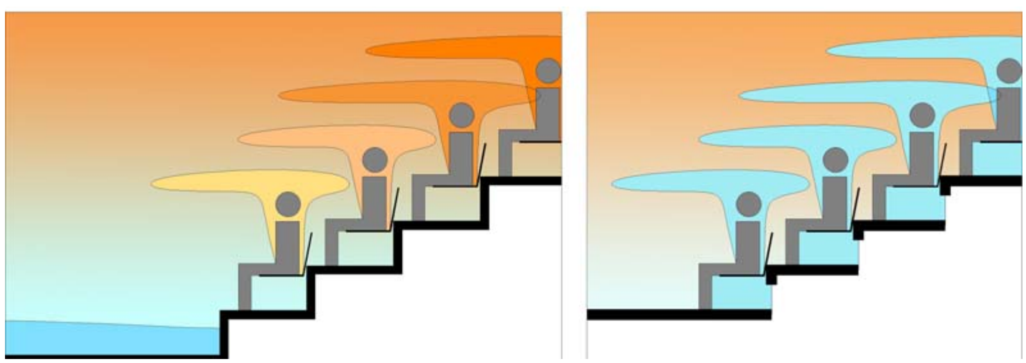


Figure 5.2 Comparing the temperature and air flow pattern of two different supplying methods

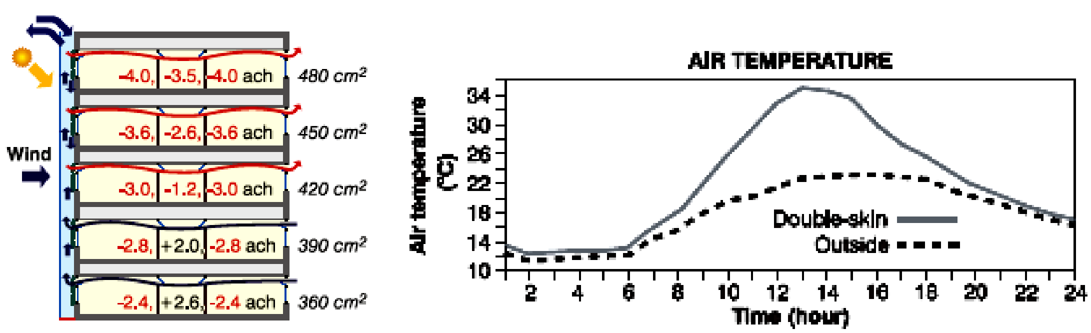


Figure 5.3 Temperature in the south double-skin and flow pattern with top window opened [12]

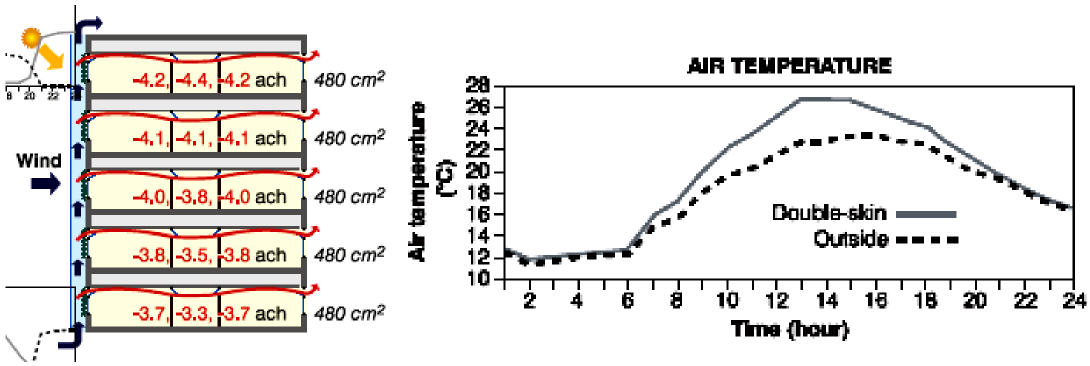


Figure 5.4 Temperature in the south double-skin and flow pattern with top and down windows opened [12]

During design development, it is better to check the concentration and temperature using computer simulations such as CFD to determine the success of the proposed flow pattern. Design decisions can be made based on comparisons with regulatory requirements for the minimum air flow rate, contaminant concentration, and temperature.

(5) Interior materials

Interior materials can influence comfort and may be the source of indoor air pollutants. For example, condensation may occur if the thermal mass is pre-cooled below the dew point. That may cause local discomfort and the potential growth of microorganisms.

5.2.3. Thermal Comfort – Energy Saving

Natural ventilation can result in comfortable indoor conditions and reduce energy consumption. However, under certain conditions, these two objectives may compete. Cost analyses in office buildings in Western countries suggest that personnel costs account for about 80 percent of total expenses, and energy consumption accounts for less than 3 percent [41]. Thus Ghiaus et al. claim that, since comfort directly influences the occupants' productivity, reducing energy consumption should not be a goal if thermal comfort is adversely affected [41].

(1) Indoor temperature and humidity

Extending the thermal comfort zone can save energy. Temperature limits for thermal comfort can be established from ASHRAE Standard 55-2004. However, for natural ventilation, recent studies suggest that, when occupants are given control of an operable window or other devices, the boundary of the thermal comfort zone can be extended both to warmer and cooler temperatures. ASHRAE Standard 55-2004 also provides useful tables that indicate the interactions between temperature, air speed, and thermal comfort. These tables can be applied to the decision-support framework. An adaptive model can be used to estimate what percentage of occupants would express satisfaction corresponding to a range of indoor conditions.

(2) Air flow rate

When the driving forces for natural ventilation are not sufficient to achieve thermal comfort, using a well-designed mixed-mode ventilation approach can extend the limits of natural ventilation and reduce energy consumption. However, simply using fan assistance to achieve comfort may not be economical if this operating mode happens often. For example, according to the post-occupancy study done for the Philip Merrill Center, the building is often operated as a hybrid system with the aid of exhaust fans. This is because of the prevailing wind directions were different than expected. This system essentially acts as an economizer, but could be designed more efficiently [4]. CIBSE states that the most important aspect of mixed mode design is to minimize the energy use by fans [6]. That usage depends on the air change rate, fan power, and hours of use of the system. Minimizing the hours of use with good design, avoiding poor operation of the systems, and using low power fans can help.

(3) Building heat gain rate

It is difficult to cool buildings with high heat gain using only natural ventilation. Minimizing the building heat gain rate is an important step for maintaining thermal comfort and achieving energy savings. The measures include:

- Reducing solar heat gain.
- Removing excess heat during the day by night ventilation with thermal mass, reducing or eliminating the need for mechanical cooling during the day.
- Using daylight effectively.
- Selecting efficient equipment and lighting.
- Successful operation of the natural ventilation system depends on the control system with sensors for indoor and outdoor temperature, contaminant levels, humidity, solar incident angles, wind directions and speed, openings, and so forth.

(4) Ventilation zone and flow path

To reduce energy consumption, spaces can be grouped by similar allowable temperature range, internal heat gain, and occupant density to form ventilation zones. Long or indirect flow paths in each zone should be avoided because mechanical assistance may be needed to compensate for the pressure loss.

5.2.4. Energy Saving – IAQ

If the outdoor pollutant level is unacceptably high, then natural ventilation may not be applicable. The limited application of natural ventilation may lead to increased energy consumption. As previously discussed, since costs associated with the occupants' health and productivity are much larger than energy costs, it is unwise to sacrifice the indoor air quality to reduce energy consumption.

(1) Indoor pollutants

To maintain good IAQ and lower energy consumption, designers can reduce indoor pollutants by minimizing the source strength or providing local air exhaust.

Indoor air quality depends on the contamination level of the supply air and the ability to remove internally generated pollutants through the exhaust. Natural ventilation systems use 100% fresh outside air, resulting in an improved supply air quality (assuming the outdoor air is clean). If the emission characteristics of the source are known, the ventilation rate needed to reduce the concentration to the required concentration can be calculated. Assuming a well-mixed condition [7], the steady state indoor pollutant concentration can be calculated with Equation 5-3:

$$C_i = C_o + S / Q$$

Equation 5-3

C_i = steady state indoor concentration, μg/m^3,

C_o = outdoor concentration, μg/m^3,

S = total pollutant source strength, μg/s,

Q = the ventilation rate, m^3/s.

Considering the removal effectiveness ε, $C_i = C_o + S / \varepsilon Q$, the higher the ventilation effectiveness, the lower the contaminant concentration will be in the occupant breathing zone. Thus, improving ventilation effectiveness is the key to improving IAQ and energy savings. Since the ventilation rate can be calculated by $Q = \frac{S}{\varepsilon(C_i - C_o)}$, as shown in Figure 5.5, the pollution removal becomes less effective as the air flow rate increases beyond an optimum flow rate.

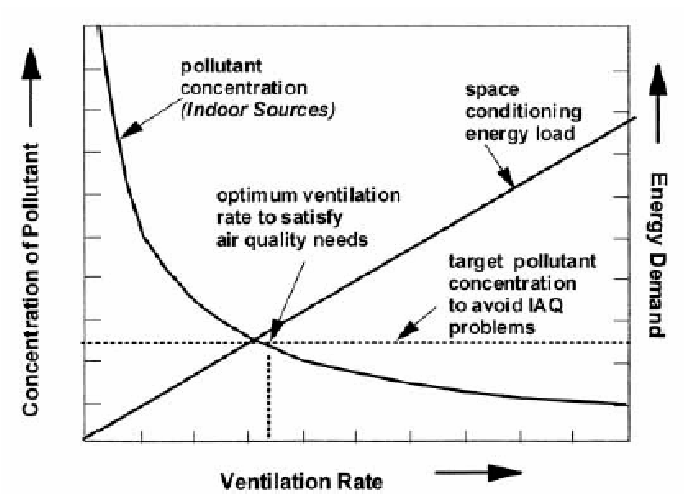


Figure 5.5 Characteristics of dilution ventilation [42]

5.2.5. Acoustics – Energy Saving

The need to control sound transmission and background noise, while reducing energy consumption, can be challenging with natural ventilation. The following are interactive issues and strategies to consider when trying to address these performance mandates.

(1) Position inlet and outlet apertures away from direct outdoor noise sources.

(2) If outdoor noise levels are high, introduction of a indirect sound path might be considered. This can be accomplished by use of a double envelope, shafts, towers, or plenums. These elements would typically be lined with sound absorbing materials. This may have the interactive effect of increasing the resistance to air

flow; consequently fan assistance may be needed. This increases energy consumption.

5.2.6. IAQ – Acoustics

(1) *Exterior openings*

Exterior openings should be kept away from direct exposure to exterior pollution sources. For example, traffic exhaust, smoke stacks, and trash bins are potential pollutant sources to the building. ASHRAE Standard 62 recommends the minimum distance from outdoor intakes to these pollution sources, and the minimum separation distance between intakes and exhaust outlets (see Section 7.5, Module 3-3). At the same time, the location of exterior openings should take into account nearby noise sources. The noise intensity level at a ventilation opening can be calculated if the distance to the source(s), the sound intensity level, and the site conditions are known.

(2) *Air flow rate and air exchange rate*

If intermittent ventilation is used, the air exchange rate must meet the minimum requirement of ASHRAE Standard 62 for acceptable indoor air quality.

(3) *Ventilation zone and air flow path through interior openings*

Within the same ventilation zone, to ensure good indoor air quality, airflow should not pass from a space with a lower air class to the space with a higher air class (see Section 7.5.3, Module 3-3-3). Caution should also be used if spaces with higher background noise requirements or acoustical privacy are connected to other spaces through ventilation openings. For spaces with stringent requirements for both IAQ and background noise, it may be necessary to design a dedicated ventilation system with separate inlets and exhausts.

(4) *Interior materials and indoor pollutant*

Some materials used for acoustical purposes can be sources of indoor pollutants or provide a habitat for microbial organisms. For example, evidence suggests that carpeting may contribute to an increase in respiratory problems, asthma, and dust-mite allergens; on the other hand, carpeting may improve the acoustics characters of a space by minimizing impact noise and reducing reverberating sounds and background noise. There are similar concerns for porous materials that are used as sound attenuation.

5.2.7. Thermal Comfort – Cost

To achieve thermal comfort with natural ventilation, in large non-residential buildings with deep floor plans, design elements such as atria, shafts, wind scopes, wind towers, and double-envelopes may be desirable. These building elements may increase the capital and operating cost of the building by adding additional floor area, non-programmatic components, and maintenance tasks. As the complexity of the system increases, proper control systems are also needed, which also adds to the capital and operating costs. For example, sensors monitoring temperature, humidity, wind speed, and direction to control the openings and fans may be needed, thus increasing the cost. However, some integrated features such as atria or double envelopes also improve the indoor environment with daylight, views, and other amenities; the value of these factors is difficult to quantify. Additionally, according to the CIBSE, natural and hybrid ventilation increase the return on investment in the building fabric, and reduce the shorter-lived and energy-consuming building services. An iterative design process can find an optimum range for cost by balancing the passive and active features. ([6], p30, Figure 5.1)

If natural ventilation cannot completely dilute the pollution concentration to acceptable levels then mechanical ventilation may be needed. That could possibly raise the costs of the building. Identifying low-cost, low off-gassing material choices can help lower the indoor pollution concentration; thus, it may be easier to dilute pollutants by using natural ventilation.

5.2.8. Acoustics – Cost

When outdoor noise levels are extremely high, mechanical ventilation may be the only alternative. If noise can be controlled, acoustical treatment may increase the capital and operating costs.

Because low frequency noise is typically more difficult to reduce, an acoustical treatment at the envelope can be cost effective.

Optimizing and integrating acoustical treatments with architectural design may be a good solution, for example, locating the openings away from direct noise sources, using integrated multi-function building components or space, such as the design of the Contact Theatre.

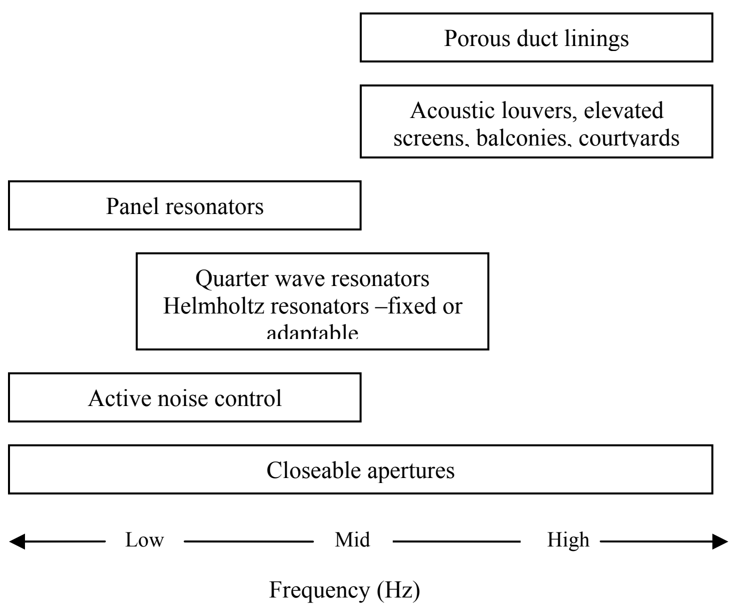


Figure 5.6 The frequency of noise reduction of different treatment and devices [43]

5.2.9. Energy Saving – Cost

The percentage of operating costs to total costs varies with occupancy. For commercial buildings, salary and other business costs are typically near 100 times higher than energy costs. In schools, energy related costs account for about 2.2 % of total expenditures. Of this, the cooling and ventilating energy use is less than 15% of the energy used in temperate climate zones in the U.S. For other occupancies, the percentage can be higher. For example, "the ratio for performing arts venues of construction cost compared with maintenance/operating cost to business operation cost has been estimated as 1:2:7." [29]. Therefore, the importance of energy savings for different types of buildings should be weighed differently.

In some types of buildings, energy consumption only represents a small percentage of the total costs, so it is one of the expenses that can be effectively decreased without adversely affecting the building performance and indoor environment.

To evaluate all of the tradeoffs related to the cost of the natural ventilation system and relative components in the design, a life cycle cost analysis should be performed. Then the concerns for the relative importance of different performance mandates should be involved in the evaluation. A decision can be made after several possible alternatives are compared.

5.3. CONCLUSION

In this chapter, with Table 5.2, the interactions between the five critical performance mandates are studied in pairs and qualitatively. The interaction of any three or more performance mandates or other issues can be studied with the same method.

The interactions can be studied quantitatively in the future. For example, sensitivity analysis can be done to explore the influence of the parameters on the performance mandates for each interaction.

CHAPTER 6 FEASIBILITY ASSESSMENT

6.1 INTRODUCTION

One problem with natural ventilation is the lack of a well-defined feasibility assessment approach. The feasibility of natural ventilation is determined by analyzing the interactions between (1) site conditions, (2) the design proposition and (3) climate information. For the proposed decision-support structure, inputs, analysis algorithms and outputs are identified through literature, and case studies of naturally ventilated buildings. The list of inputs and the scope of interactions are shown in Table 6.1.

Table 6.1 The scope of interactions between inputs, intermediate results, and assessment in the framework

Nearby Building/Obstruction	Nearby Body of water	Vegetation	Topography	INPUTS	Inlet-outlet Pressure Difference	Heat gain rate	Balance Temperature	Air flow rate	Indoor pollutant	WIND	TEMP. & HUMID.	NOISE	POLLUTION
				Indoor pollutant									•
				Air flow rate						•			
				Balance Temperature							•		
				Heat gain rate			•	•		•	•		
				Inlet-outlet Pressure Difference				•		•			
				Building Geometry									
				Building Geometry	•	•							
				Room/Space Geometry								•	
				Ventilation Components (Fans, ducts, dampers, etc.)/Building Ventilation Elements (Atria, Shaft, Wind Tower, Double-envelope, etc)				•				•	
				Building Orientation	•	•							
				Building Function/Use									
				Space Function		•			•			•	
				Schedule of Use		•							
				Ventilation Zones and Flow Paths								•	
				Equipment & Lighting Fixtures		•							
				Materials/Construction									
				Envelope Materials/Construction		•	•	•	•			•	
				Interior Materials/Construction								•	
				Window/Opening Size and Placement	•	•		•		•			
				Solar Radiation		•							
•			•	**Prevailing Wind Speed and Direction**	•			•					
•			•	**Outdoor Temperature & Humidity**		•					•		
•	•	•	•	**Nearby Noise Sources**								•	
				Nearby Pollution Sources									•

6.2 INPUT TRANSFORMATIONS (MODULE 1)

The decision-making process begins by making any necessary transformations to the inputs and then assessing feasibility for the proposed design.

Among the site and climate data inputs are the temperature and humidity, prevailing wind speed and direction, solar radiation, and noise and pollution sources at or near the site. For these inputs, the available data, most likely, are not taken from the on-site measurements. To be useful in the decision-making process, these inputs must often be predicted, transformed or adjusted for local effects. Generally, the following input processing may take place (Figure 6.1).

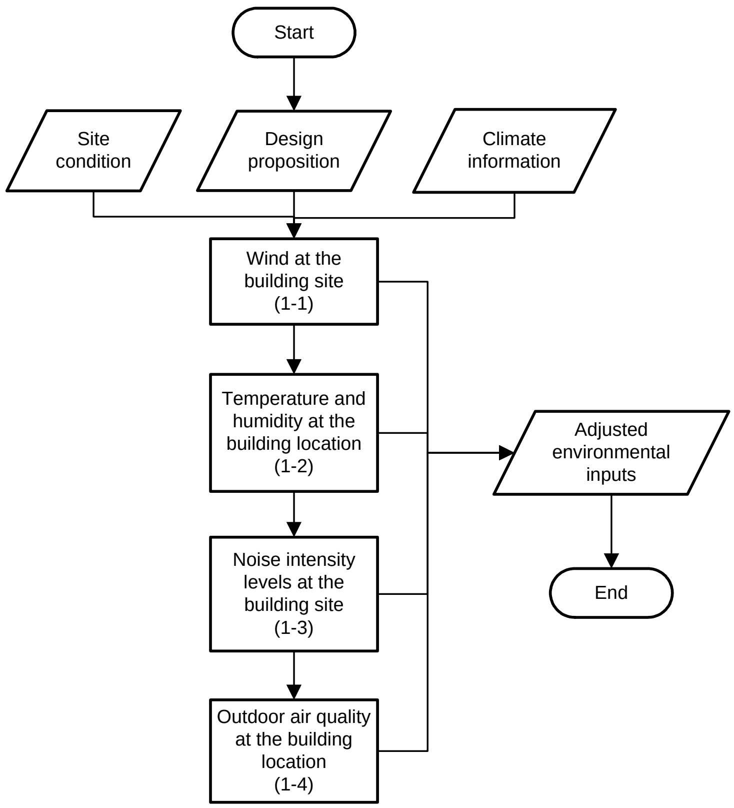


Figure 6.1 Flow chart for the general process of the input transformation module

6.2.1. Wind at the Building Site (Module 1-1)

Wind velocity from meteorological stations available in typical meteorological year (TMY) archival files can be transformed and modified for micro-climate effects for the terrain and height corrections at the building location [7] (Module 1-1-A, Appendix B). Prediction models for some typical site scenarios are available. For example, algorithms calculating winds in an urban street canyon by Ghiaus et al.[44] (Module 1-1-B, Appendix B) and the approximate prediction of wind speed reduction by trees [45] in a suburban or rural setting or other obstructions (Module 1-1-C, Appendix B) can be used. Corrections for wind direction may refer to the air movement principles relating to typical topographies (Module 1-1-D, Appendix B). The flow chart illustrating the decision process of Module 1-1 is shown in Figure 6.2. Detailed description of the sub-modules is listed in Appendix B.

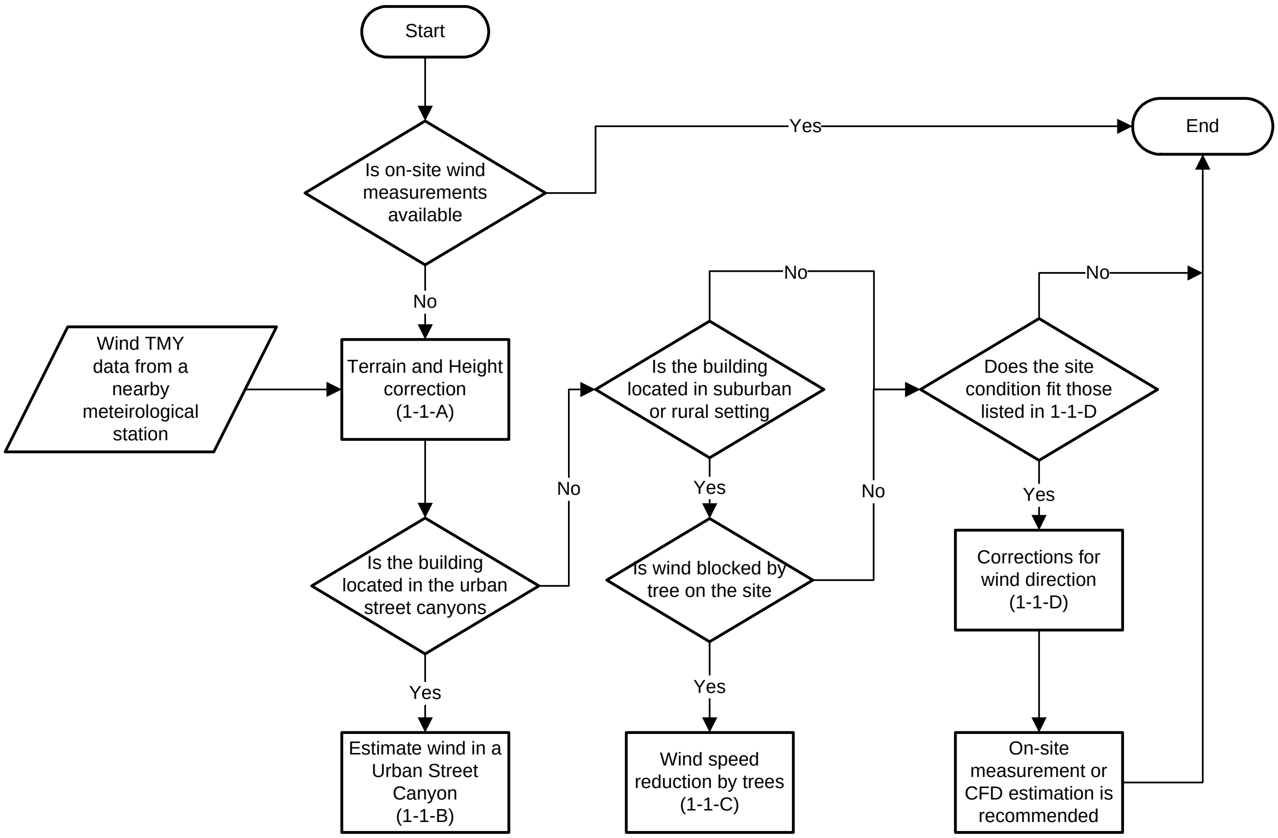


Figure 6.2 Flow chart for the Module 1-1: wind assessment

6.2.2. Temperature and Humidity (Module 1-2)

Information concerning the ambient temperature is needed to assess the potential cooling benefits from natural ventilation. In lieu of on-site monitoring the TMY data should be adjusted for local effects such as evaporative cooling by nearby bodies of water, transpirative cooling by vegetation, or warming of the air due to the heat island effect. Currently, no directly useful methods are found for these adjustments. Research is needed and is beginning in these areas. For example, data concerning the heat island effects on temperature change in London was recently measured [46, 47] (Appendix A). Data such as this may be translatable to the framework input processing procedures.

6.2.3. Noise Intensity Levels (IL) (Module 1-3)

Noise intensity levels at the building site can be obtained from on-site measurement. When this is not feasible, some sources provide standards and guidance to predict the exterior noise environment, such as Federal Transit Administration (FTA) noise impact assessment guidelines for transit and rail projects (Module 1-3-A), the Highway Traffic Noise Model (HTNM) from the Federal Highway Administration (FHWA) (Module 1-3-B1) and the Integrated Noise Model (INM) for aircraft noise from the Federal Aviation Administration (FAA) (Module 1-3-C). The British standard method for road traffic noise calculation [48] (Module 1-3-B2, see Appendix A), GIS tools with integrated noise prediction models that consider the local topography [49], and the calculation for industrial noise attenuation are sources that can be incorporated into the proposed framework for general and easier estimation. Some rules-of thumb including estimating background noise levels (1-3-F) and noise in street canyons (1-3-G) could be useful in the initial stage of design. These sources provide approaches with different levels of required details and accuracy to estimate the noise Intensity Levels for the proposed building site. The flow chart illustrating the decision process of Module 1-3 is shown in Figure 6.3. Detailed description of the sub-modules is listed in Appendix B.

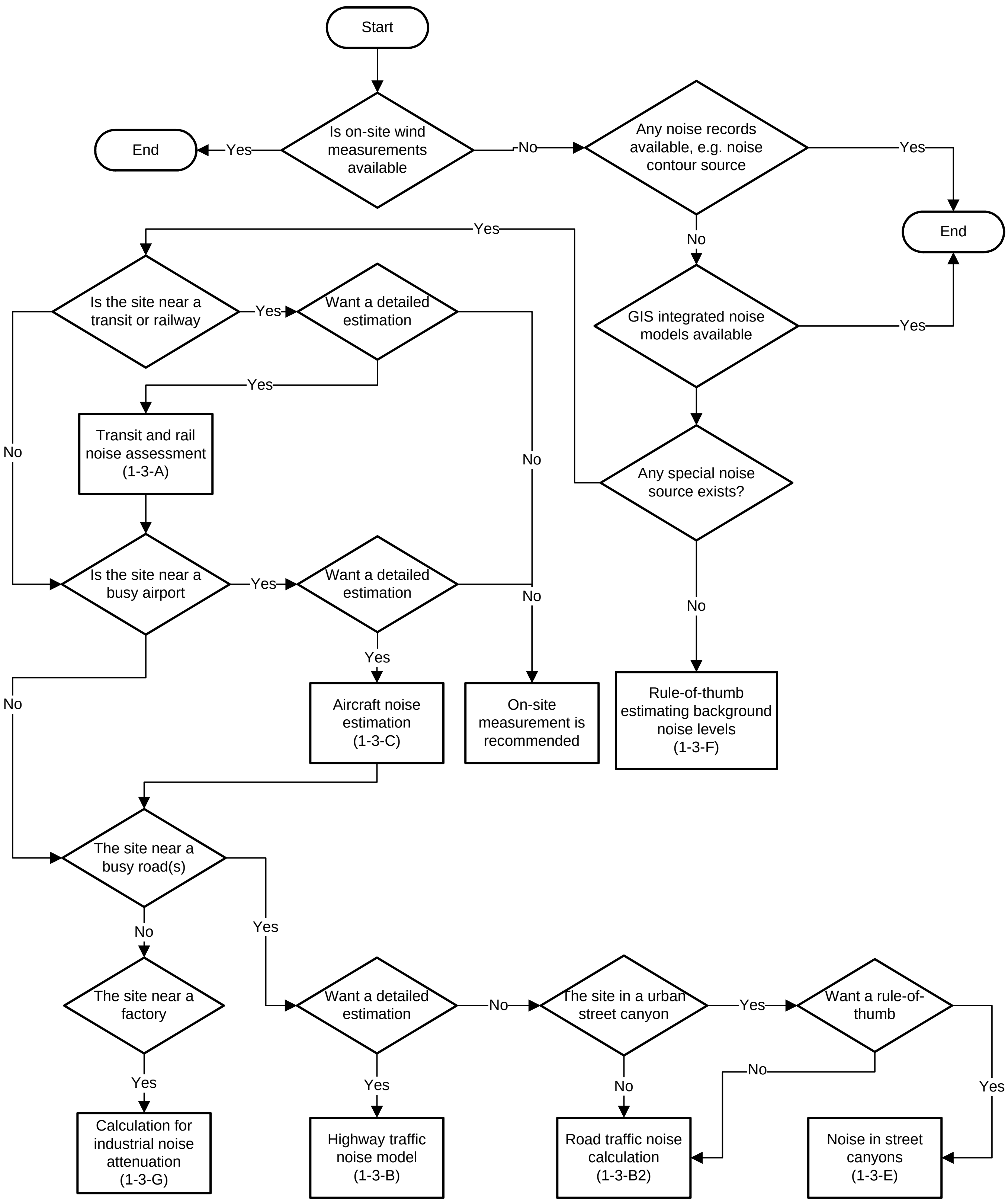


Figure 6.3 Flow chart for the Module 1-3: noise intensity

6.2.4. Outdoor Air Quality (Module 1-4)

The regional outdoor air quality compliance status for the United States as found in the Air Quality System (AQS) Database from the US Environmental Protection Agency (EPA) website is useful for determining the ambient air quality. Local outdoor air quality investigation is required by ASHRAE Standard 62.1-2004. "An observational survey of the building site and its immediate surroundings shall be conducted during hours the building is expected to be normally occupied to identify local contaminants from surrounding facilities that may be of concern if allowed to enter the building." As required by ASHRAE Standard 62, which includes:

- Date of observations
- Time of observations
- Area surveyed
- Description of nearby facilities
- Observation of odors or irritants
- Description of visible plumes or air contaminants
- Description of nearby sources of vehicle exhaust
- Direction of prevailing winds
- Conclusions regarding the acceptability of outdoor air quality

The level of outdoor air pollutants as the results of the local outdoor air quality investigation should be used to determine the viability of natural ventilation.

Algorithms estimating the amount of pollution caused by traffic or nearby emissions are available. For example, pollution down wind from a point source such as a smoke stack (Module 1-4-A), and a line source such as a busy highway [50] (Module 1-4-B), and pollution in a street canyon within certain range of the height to width ratio can be estimated from existing models [51] (Module 1-4-C). The flow chart illustrating the decision process of Module 1-4 is shown in Figure 6.4. Detailed description of the sub-modules above is listed in Appendix B.

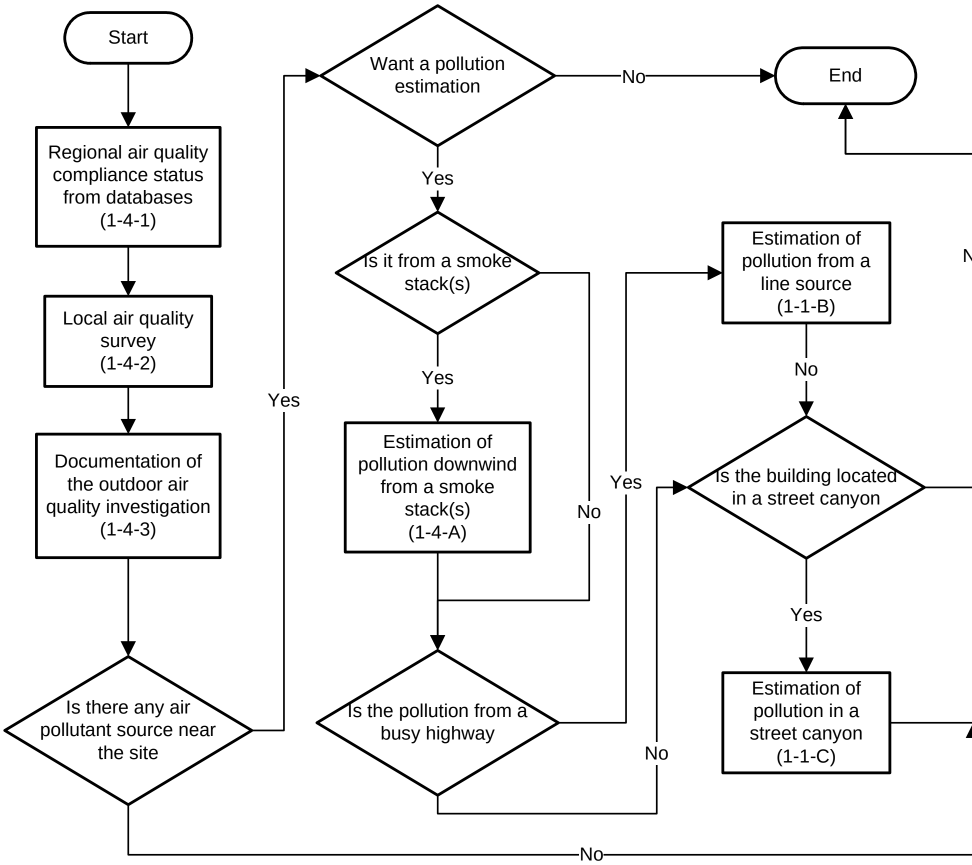


Figure 6.4 Flow chart for the Module 1-4: outdoor air quality

6.3 FEASIBILITY ASSESSMENT (MODULE 2)

Following input processing the feasibility of natural ventilation is assessed for the proposed design.

The algorithms in the feasibility assessment modules are identified and developed from technical publications that are referred in the following sections. In the proposed framework, following the previously described input processing, the feasibility assessment consists of three sub-modules:

(1) Outdoor temperature, humidity and wind assessment

(2) Site noise assessment

(3) Pollution assessment

If the outcome from any of the three modules concludes that natural ventilation is not feasible, no further assessment is made, although certain remedial solutions may be suggested. Figure 6.5 illustrates the general process of the feasibility assessment module.

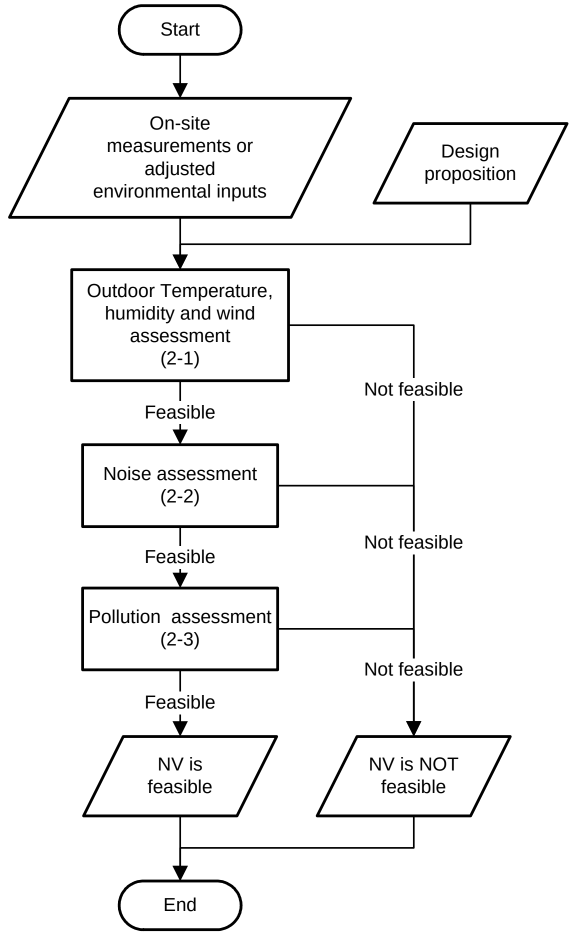


Figure 6.5 Flow chart of the general process of the feasibility assessment module

6.3.1. Module 2-1: Outdoor Temperature, Humidity and Wind Assessment

6.3.1.1. Temperature limits and temperature assessment (Module 2-1-B)

Temperature limits for thermal comfort can be established from ASHRAE Standard 55-2004. However, for natural ventilation recent studies suggest that when occupants are given control of an operable window for ventilation, the boundary of the thermal comfort zone can be extended both to warmer and cooler temperatures. ASHRAE Standard 55-2004 also provides useful tables that indicate the interactions between temperature, air speed and thermal comfort. Using TMY climate data, hourly values for outdoor air temperature, and wind speed can be compared to the limits of the extended comfort zone and the annual number of hours in or near the comfort zone can be determined. The summation of the number of these hours of occurrence can then be compared to a target value to assess feasibility relative to thermal comfort. This is similar to procedures of analysis used in Climate Consultant [52].

However, to cool buildings with higher internal heat gain with only natural ventilation, the outdoor temperature limits may vary.

6.3.1.2. Humidity limits and humidity assessment (Module 2-1-A)

Humidity limits for naturally ventilated buildings may not be restricted to that required by ASHRAE 55-2004. According to section 5.22 of this standard, humidity limits are only applicable when there is a system designed to control humidity. Higher relative humidity is claimed thermally acceptable [53]. However, if a building is naturally ventilated and high relative humidity results, then IAQ may be adversely impacted. This is because microbial growth tends to increase in high humidity conditions. For molds, the growth of xerophilic species begins at an RH of 75% to 80%. Mold growth curves for different species as presented by Clarke et. al show all curves range between RH 75% to RH 100% for a minimum growth requirement [54] (Figure 6.6).

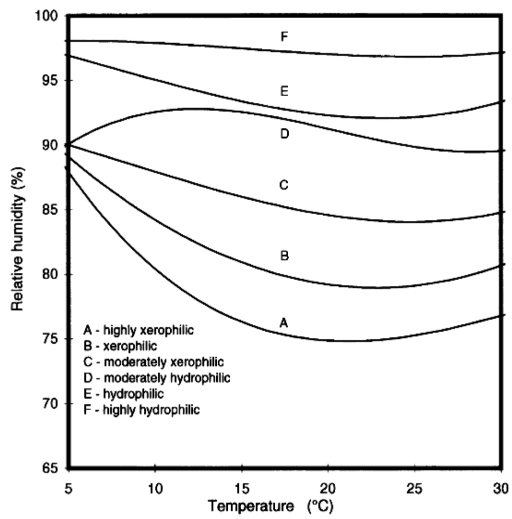


Figure 6.6 Limiting growth curves for six mould growth categories

To avoid concerns for condensation and microbiological growth, the upper limit of humidity for natural ventilation should be set to 70% relative humidity or 0.012 humidity ratio (whichever is higher).

6.3.1.3. Wind assessment (2-1-C)

The feasibility of natural ventilation must also be assessed in terms of wind speed and direction with respect to the micro-climate, building geometry and orientation, and size and placement of openings. After adjusting TMY wind speed and direction data for topography and micro-climate conditions, the module analyzes the pressure distribution on the building surfaces. Ideally, this would be accomplished by wind tunnel tests or CFD simulation, but these approaches are typically not appropriate in the early stages of design. As an alternative, for buildings with approximate rectangular shapes, published data of pressure distribution on building surfaces for varying wind speed and direction are available [7, 8]. For buildings with irregular shapes, adjustments must be made. Exactly how to adjust is not available in the literature and further study is needed.

Air flow rate is calculated based on the pressure difference between the inlet and outlet. The air flow rate V_w through the opening of equivalent area A can be calculated by

$$V_w = C_D A\sqrt{2\Delta P / \rho}$$

Equation 6-1

where $\Delta P = \frac{1}{2}\rho V_{ref}^2 (C_{p-in} - C_{p-out})$

Equation 6-2

To cool the building, the heat removed by the air flow should be equal to the building heat gain rate Q_t to the space. Thus the limit of effective outdoor air temperature is:

$$T_o = T_i - \frac{Q_t}{CV_w}$$

Equation 6-3

where

C = specific heat of air, kJ/kgK

ρ = density of air, kg/m^3

V_{ref} = wind speed at referenced height, m/s

C_{p-in}, C_{p-out} = wind pressure coefficient at inlet and outlet

C_D = Discharge coefficient

T_o = Outdoor air tempersture, °C

T_i = Indoor air temperature, °C

Q_t = Building heat gain rate, W/ m^2

V_w = Air flow rate, m^3/s

Therefore, in this module, the sufficiency of available wind is evaluated by the effective outdoor temperature.

If the wind speeds are too low, the following design suggestions are given.

- Changing orientation

Orientate the building within 30 degree normal to the prevailing wind. If this is not applicable, use wing walls, or apply a wind chimney through the roof with the outlets in all directions or use rotatable wind catchers.

- Modifying building geometry

Changing the building geometry can improve the pressure distribution on building surfaces. For example, Kindangen et al. found that a two-slope roof is the most favorable to improve indoor airflow except for the wind flowing parallel to the building; a vaulted roof has good overall performance for all wind directions [55] (Figure 6.7 and Figure 6.8).

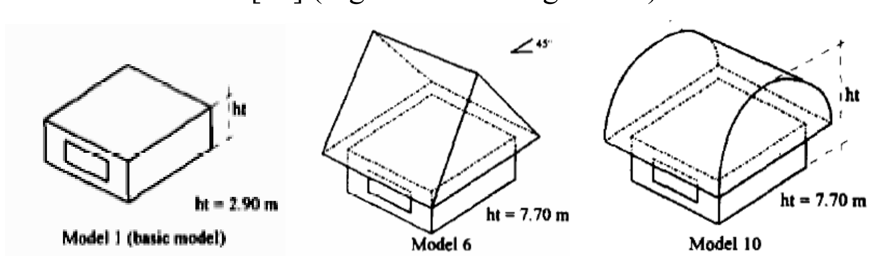


Figure 6.7 building models with different roofs

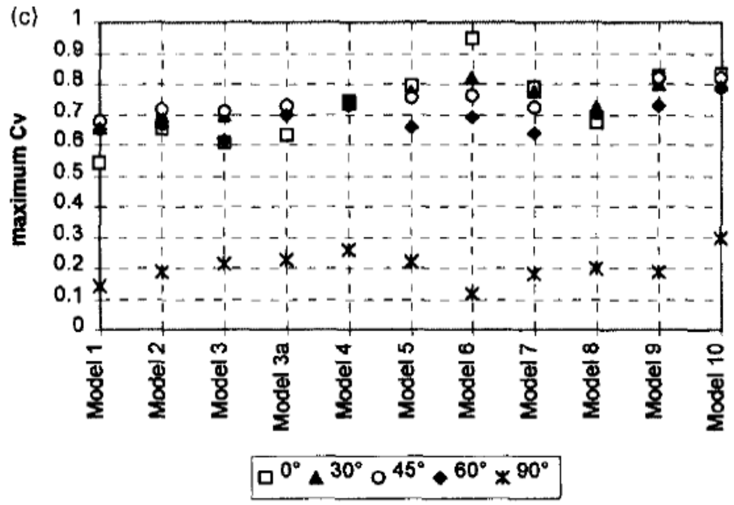


Figure 6.8 Maximum C_v

6.3.1.4. Stack ventilation (Module 2-1-E)

The utilization of natural ventilation can be extended by combining wind and buoyancy driven pressures. The total air flow rate can be found by

$$V_T = \sqrt{V_w^2 + V_s^2}$$

Equation 6-4

where V_s is the air flow rate resulting from buoyancy.

The pressure difference at a given height h above the datum level h_{NPL} is:

$$\Delta p = (\rho_o - \rho_i) g (h - h_{NPL}) = \rho_o g (h_{NPL} - h) \left(\frac{T_o - T_i}{T_i} \right)$$

Equation 6-5

where ρ_o is the air density outside the building (kg/m^3), ρ_i is the air density inside the building (kg/m^3), T_o and T_i are outdoor and indoor air temperature, and g is the acceleration of gravity (m/s^2).

The CIBSE simplified method (CIBSE Application Manual AM!0: 1997, pp. 53) can be used here for air flow rate:

$$V_s = C_d A \sqrt{2\Delta P / \rho} = C_d A \left[\frac{2}{\rho_{in}} \rho_o g (h_{NPL} - h) \left(\frac{T_o - T_i}{T_i} \right) \right]^{1/2}$$

Equation 6-6

The pressure loss along the flow path also limits the use of natural ventilation, especially in deep-plan multistory buildings. In this case, more detailed modeling such as network models taking into account pressure loss along each flow path is needed. Stack ventilation that often works with atria, staircases, shafts or light wells, can be a good solution for deep-plan multistory buildings. For example, the Lanchester Library, UK (Case 2-1), is a 4-story building with the floor plan of 164 feet × 164 feet (50m× 50m). "Each quadrant of the library foot print is punctured by a light well that admits fresh air and daylight into the building."[29] Air is exhausted through a central light well and stacks at the perimeter.

6.3.1.5. Feasibility assessment of night ventilation with thermal mass (Module 2-1-D)

For those hours when the ventilative cooling is inadequate, the feasibility of night ventilation with thermal mass coupling should be assessed. Inputs for minimum daily temperature and mean daily range can be used to estimate the cooling effects when ventilating with night air [56]. The decision process for night ventilation is shown in Figure 6.9.

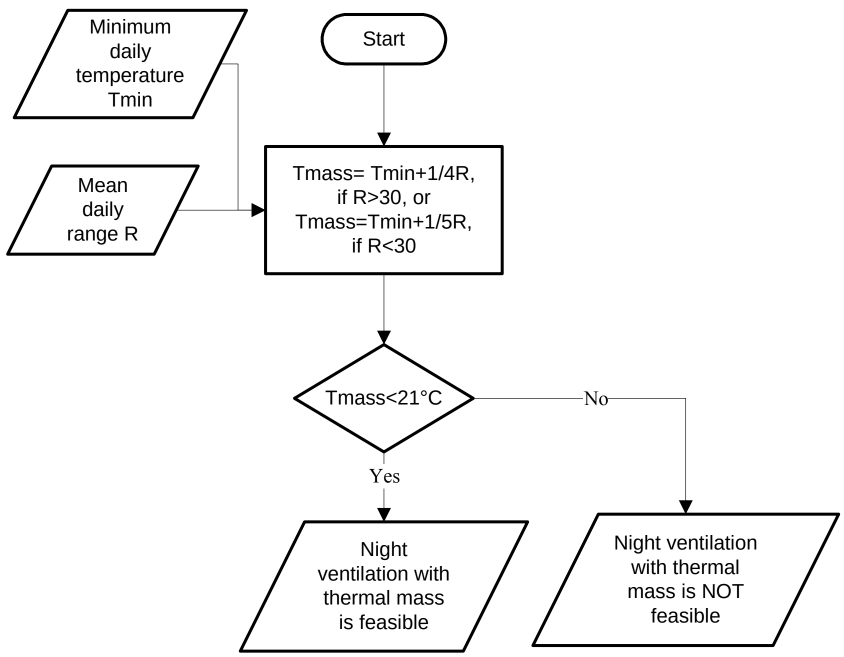


Figure 6.9 The flow chart for feasibility assessment of night ventilation with thermal mass (Module 2-1-D)

The application of night-cooling for different months and climate zones are shown in Table 6.2 [57]. The climate zones are shown in Figure 6.10.

Table 6.2 The application of night-cooling for different months and climate zones in the U.S.

Zone	External loaded Buildings												Internal Loaded Buildings											
	Month												Month											
	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
1	Unnecessary	Unnecessary	Unnecessary	Unnecessary	Unnecessary	Unnecessary			Unnecessary	Unnecessary	Unnecessary	Unnecessary												
2	Unnecessary	Unnecessary	Unnecessary	Unnecessary	Unnecessary				Unnecessary	Unnecessary	Unnecessary	Unnecessary												
3	Unnecessary	Unnecessary	Unnecessary	Unnecessary	Unnecessary					Unnecessary	Unnecessary	Unnecessary												
4	Unnecessary	Unnecessary	Unnecessary	Unnecessary	Unnecessary		Too hot	Too hot		Unnecessary	Unnecessary	Unnecessary							Too hot	Too hot				
5	Unnecessary	Unnecessary	Unnecessary	Unnecessary						Unnecessary	Unnecessary	Unnecessary												
6	Unnecessary	Unnecessary	Unnecessary	Unnecessary			Too hot			Unnecessary	Unnecessary	Unnecessary							Too hot					
7	Unnecessary	Unnecessary	Unnecessary				Too hot	Too hot		Unnecessary	Unnecessary	Unnecessary							Too hot	Too hot				
8	Unnecessary	Unnecessary	Unnecessary	Unnecessary		Too hot	Too hot	Too hot		Unnecessary	Unnecessary	Unnecessary						Too hot	Too hot	Too hot				
9	Unnecessary	Unnecessary	Unnecessary	Unnecessary		Too hot	Too hot	Too hot			Unnecessary	Unnecessary						Too hot	Too hot	Too hot				
10	Unnecessary	Unnecessary	Unnecessary			Too hot	Too hot	Too hot	Too hot		Unnecessary	Unnecessary						Too hot	Too hot	Too hot	Too hot			
11																								
12	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot	Too hot

Notes:

Too hot for NVM   NVM is possible   Cooling unnecessary

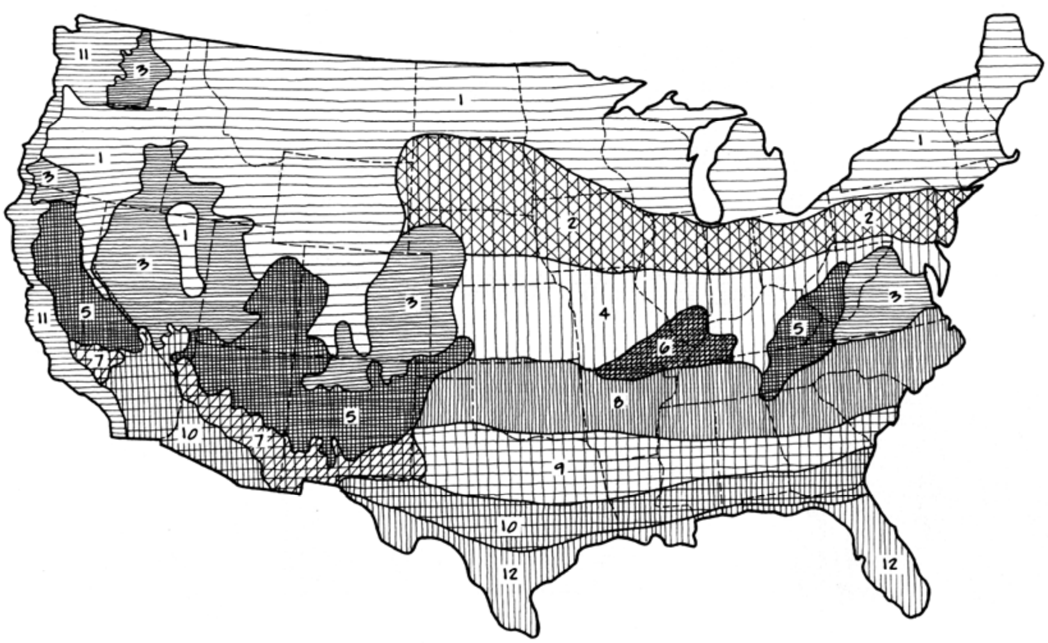


Figure 6.10 Climate zones to assess the potential for night-cooled mass [57]

If night ventilation with thermal mass is feasible, the size of the thermal mass can be determined with design suggestions in Module 5-5.

Other passive strategies can be combined with natural ventilation to extend the cooling ability.

- Natural ventilation with earth-to-air heat exchangers

Earth-to-air heat exchangers can be considered for peak cooling. To cool the incoming ventilating air, ambient air is drawn through buried pipes. The fluctuation of ambient temperature is dampened effectively; the air temperature might be within 4°F of earth temperature [56]. This approach has be shown to have good peak performance in summer. For example, the measured maximum outlet air temperatures in the "SD Worx" building in Belgium, never exceed 22 °C using this approach (Figure 6.11). However, the seasonal cooling capability of this strategy is much lower than natural night cooled thermal mass. Breesch et al simulated and compared the performance of an earth-to-air heat exchanger, night-ventilation with mass and their combination in the "SD Worx" building. The result shows that the earth-to-air system alone cannot provide effective seasonal cooling [58] . It is more suited to buildings which tend to overheat in summer. The combination of earth-to-air exchanger with night cooled mass shows an improved cooling capability than night cooled mass only for larger cooling load.

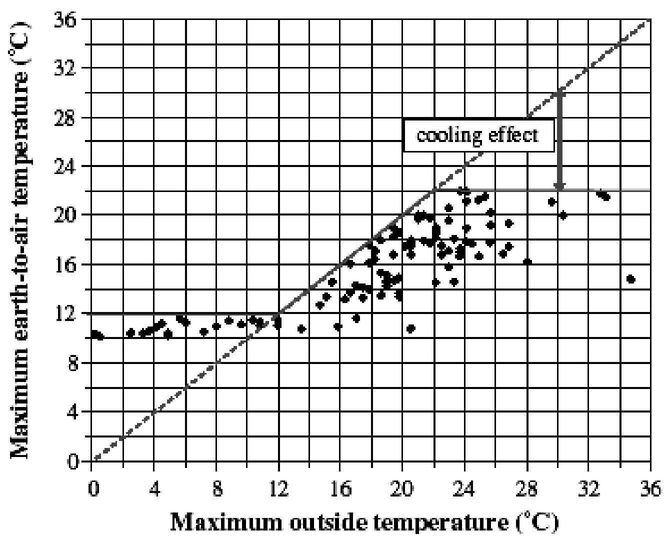


Figure 6.11 The cooling effect of Natural ventilation with earth-to-air heat exchangers [58]

The performance of an earth-to-air heat exchanger depends on the air flow rate, convective heat transfer between the pipe and air, depth of the pipe, dimension of the pipe, soil temperature and soil properties. To apply the system, threshold values for ground temperature should be at least 5-6°C lower than the air temperature [8].

In general, as a rule-of thumb, longer tunnels are recommended; at least 33 feet (10 meter) is suggested by Santamouris and Asimakopolous. They also recommended 2 inch (5cm) thick sand surround the pipe for better thermal conductivity. Kumar et al. find that if the diameter is over a critical value, airflow rate increased, the outlet temperature thus increased, which significantly affected the cooling potential of earth-air-tunnel. In addition, the earth-to-air heat exchanger system might have IAQ problems caused by condensation.

The overall process of Module 2-1 is shown is Figure 6.12.

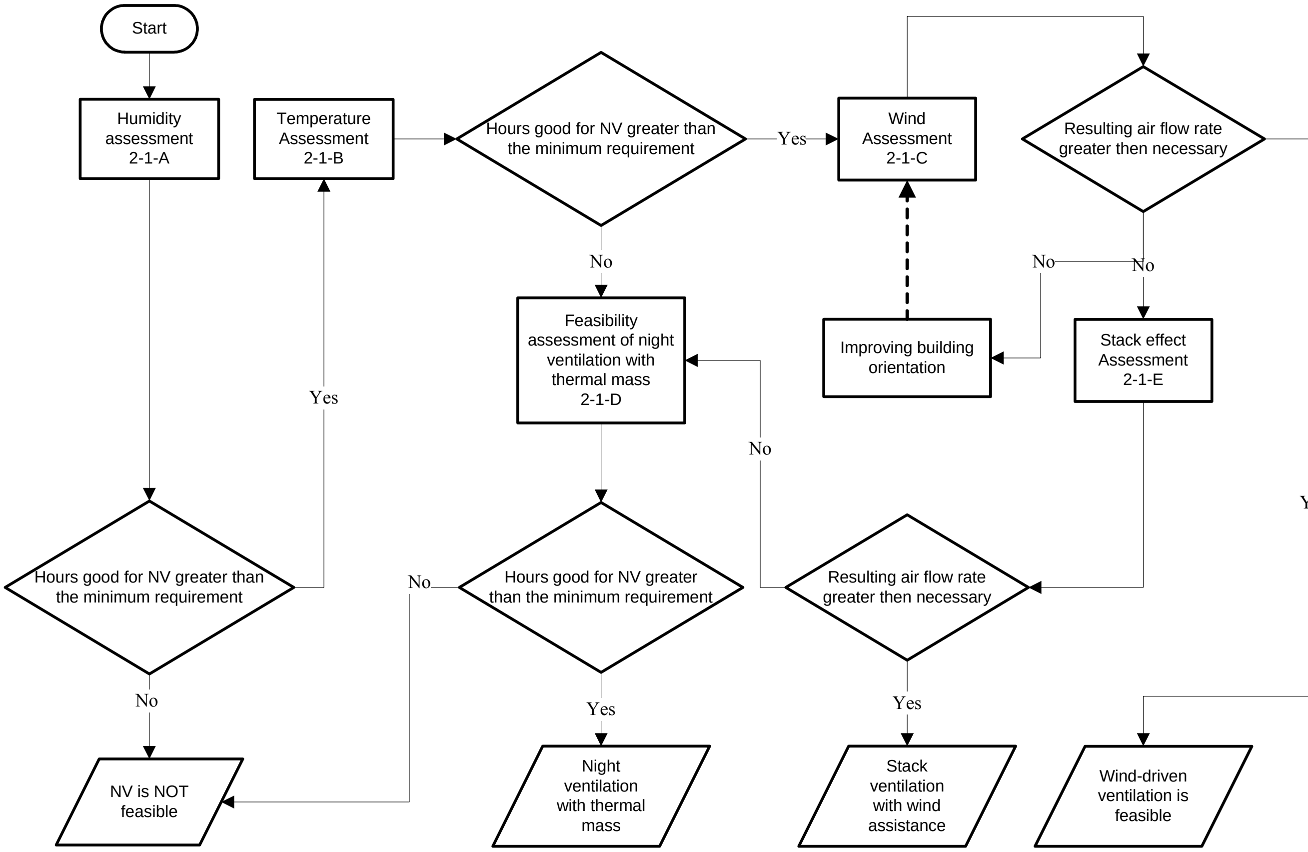


Figure 6.12 Flow chart of outdoor temperature, humidity and wind assessment (Module 2-1)

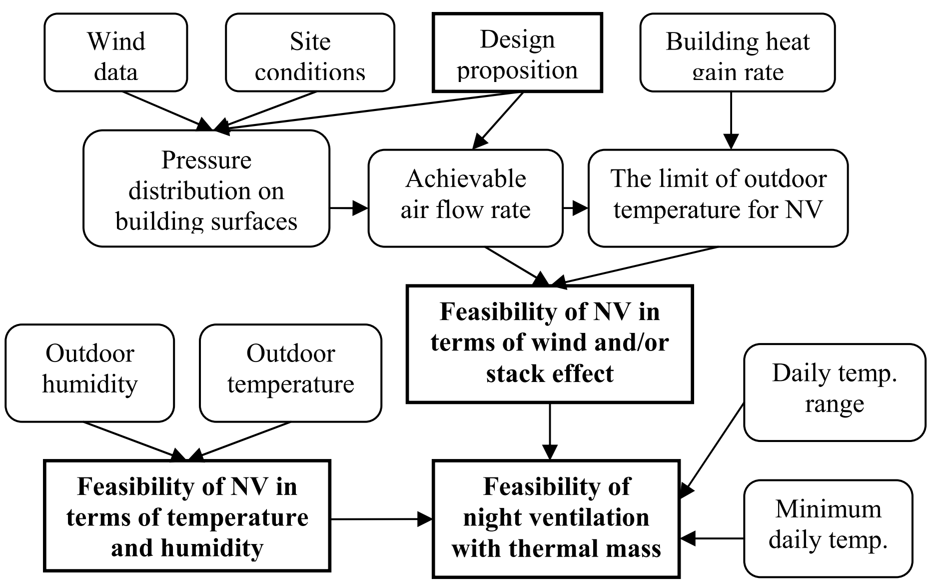


Figure 6.13 Influence diagram of outdoor temperature, humidity and wind assessment

6.3.2. Module 2-2: Noise Assessment

In the noise assessment module, there are algorithms estimating the interior noise intensity levels with input of the outdoor noise intensity level and the proposed envelope characteristics and ventilation openings. The module proceeds with the following sub-modules:

Module 2-2-A: Estimate the total transmission loss of a composite barrier;

Module 2-2-B: Calculate the noise reduction at the receiving room;

Module 2-2-C: With the required indoor NC levels, estimate the required sound reduction and compare with the calculated noise reduction in Module 2-2-B.

Ideally, noise intensity for different octave bands at the building site should be known to determine the acceptable STC rating.

If the exterior wall is composed of more than one component, the effective transmission coefficient τ_{AV} is an average of the area weighted sum of each component's Transmission Loss. If the partition has n separate elements, then the average transmission coefficient is given by [59]:

$$\tau_{AV} = \frac{\sum_{i=1}^{n} \tau_i s_i}{S}$$

Equation 6-7

S = the total area of the partition, m^2

τ_i = transmission coefficients of the elements of the partition, and

S_i = area of the elements of the partition, m^2

The average Transmission Loss (TL), or Sound Reduction Index (SRI) is [56]:

$$R_{AV} = -10 \log \tau_{av} (dB) .$$

Equation 6-8

In a simpler condition, the composite exterior wall includes a ventilation opening whose $\tau = 1$, the transmission loss of the whole element is:

$$R_{AV} = R - 10 \log\left[1 + f(10^{0.1R} - 1)\right]$$

Equation 6-9

R= the Sound Reduction Index of the wall without the opening,

f = the proportion of the open area to the total area.

The noise reduction in the receiving room should also take into account the absorption by the surfaces in the receiving room. Noise Reduction due to internal absorption (NR) is calculated as [56]:

$$NR = R_{AV} - 10 \log(S / \Sigma A) ,$$

Equation 6-10

where S = the area of common surface of barrier (m^2),
ΣA = total absorption of receiving room, sabins, (m^2).

Average absorption coefficient $$\overline{\alpha} = \frac{\sum_{i=1}^{n} S_i \alpha_i}{S} = \frac{\Sigma A}{S}.$$

Equation 6-11

Table 6.3 The classification of the receiving room in terms of surface absorption

$\overline{\alpha}$	<0.05	0.1	0.15	0.2-0.3	0.4	>0.5
	Very live	Live space	Medium live	average	Medium dead	Dead space

The following rules of thumb can be used:

a. For a live receiving room, NR = TL-1db

b. For a medium receiving room, NR= TL+4db

c. For a dead receiving room, NR= TL+7db

An alternative rule-of-thumb can be used to calculate the effect of absorption of the receiving room. A_2/S is substituted for ΣA/S, where A_2 is the area of common wall between the receiving room with the source room. Absorption of the receiving room is assumed average. The noise reduction is listed in the flowing table. For live rooms lower two points; for a dead room raise two points.

Table 6.4 Rule-of-thumb of the noise reduction related to the value of A_2/S

A_2/S	1	2	3	4	5	6	7	8	9	10
Noise Reduction	-2	0	2	3	4	5	6	7	7.5	8

If the estimated noise reduction is not acceptable, the following design suggestions may help reduce the indoor noise level. However, some design strategies may impact the airflow rate.

- *Locate the apertures away from direct noise paths*
- *Screen with external barriers*

Attenuation provided by a screen or barrier can be calculated using techniques found in standard texts (Appendix B).

Barriers are most effective when the difference between the shortest path over the barrier and the direct "line of sight" between source and receiver is at its greatest. Barriers are more effective at attenuating high frequency sounds than low frequency sounds of longer wavelength that will tend to diffract over the barrier more efficiently.

Ghiaus, et al predict the noise reduction at the building surface by balconies in urban street canyon with simulation [41]. The simulation suggests that the noise reduction due to balconies is about 2 dB lower in buildings rising to 3–4 dB near the top of the canyon.

- *Double envelope (double-skin façade)*

Sound transmission may be reduced through the use of a double envelope. There are four types of double-skin facades: box-windows, corridor facades, shaft-box facades which consist of a system of box windows and vertical shaft that extend over a number of stories to create a stack effect (Figure 6.14), and multi-story facades. Generally, the box windows can provide the highest air flow rate but the lowest sound insulation among the four types of double skin façade. The sound insulation of typical ventilated double windows is 15-20 dB [60]. Shaft-box facades and corridor facades provide better sound insulation and medium air flow rate, while multi-story facades can be used when outdoor noise is very high. Similar to the condition when a multi-story stack is used, according to a study by Gratia et al.[61], caution should be taken for the possible reversing of the flow. Corridor or multi-story double-skin facades may transmit noise from adjacent rooms. For workplaces, a properly designed double-envelope can permit window ventilation up to a relevant external noise level of about 75 dBA [62].

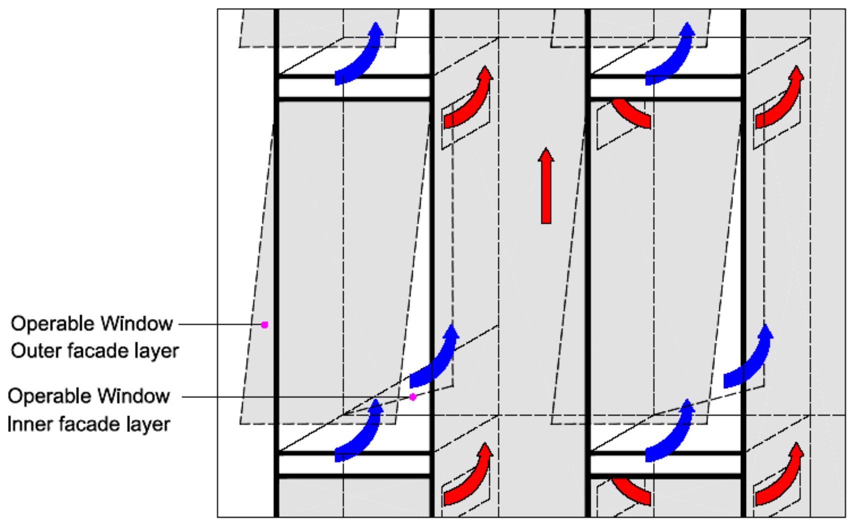


Figure 6.14 A shaft-box façade [62]

A test method proposed by Oesterle et al. estimates the sound insulation of a double envelope with both layers partially opened [62] (Appendix B). The use of absorbing materials in the intermediate space may be effective to dampen transmitted noise.

- *Automatic control of inlets and intermittent ventilation*

Intermittent ventilation is ventilating the room for a certain period by opening the windows or ventilation inlets and then closing them again when the space becomes too cool or when the noise from outside is too loud. For a temporal noise, such as aircraft, windows can be closed when the rise in noise level is sensed. The use of automatic control of inlets can also combine control for thermal and IAQ. With the minimum required ventilation with external air per hour per person known, by calculating the air flow volume of the window, it is possible to define the necessary ventilation period per hour.

- *Acoustic louvers at the inlet and outlet opening*

Acoustic louvers provide attenuation by screening the direct sound path using angled blades. The indirect reflected path is attenuated using absorptive material on the underside of the blades. The

SRI of the louver is limited at low frequencies, but is effective at higher frequencies. The typical the value of sound reduction index of an acoustic louver is shown in Table 6.5.

The limited performance of louvers is noted at De Montfort University, where complaints are caused by traffic noise that transmits to the lecture theatres through the large areas of double louvers (or 'ridge ventilators'). The obstruction to airflow is caused by the closed area ratio of the louver, the redirection of the air path and the resistance of the blade surfaces. Series or double louvers can provide greater attenuation but with a penalty of further restrictions to airflow.

Table 6.5 Typical the value of sound reduction index of an acoustic louver (Developed based on the figure in [59])

Frequency (Hz)	63	125	250	500	1000	2000	4000	8000
Sound reduction index (dB)	6	8	10	13	16.5	17.5	14	12

- *Sound absorbent materials within a shaft or plenum*

Sound absorbent materials such as porous linings can absorb noise efficiently especially for middle and high frequencies. Panel resonators can absorb low frequency noise. If shafts or ducts are used in natural ventilated buildings, bends can attenuate sound well at mid to high frequency by reflecting sound back to the source and absorbing sound when lined. However, bends will further increase the airflow resistance; therefore the use of bends should be as few as possible.

The calculation of sound transmission loss in the duct system can be found in text, such as Wood Practical Guide to Noise Control, by Ian Sharland (1972).

- *Active noise control with ducted systems*

Active noise control can attenuate low frequency noise in ducts or shafts.

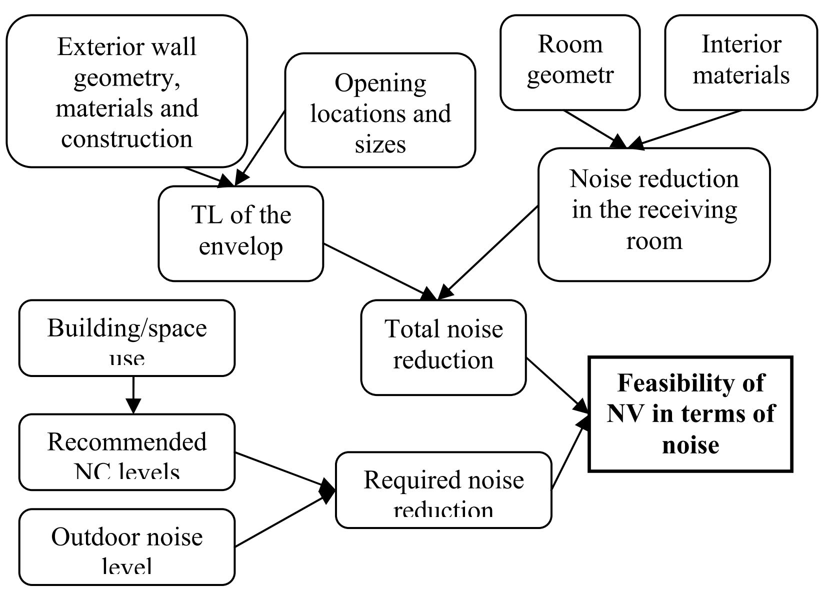


Figure 6.15 Influence diagram of noise assessment

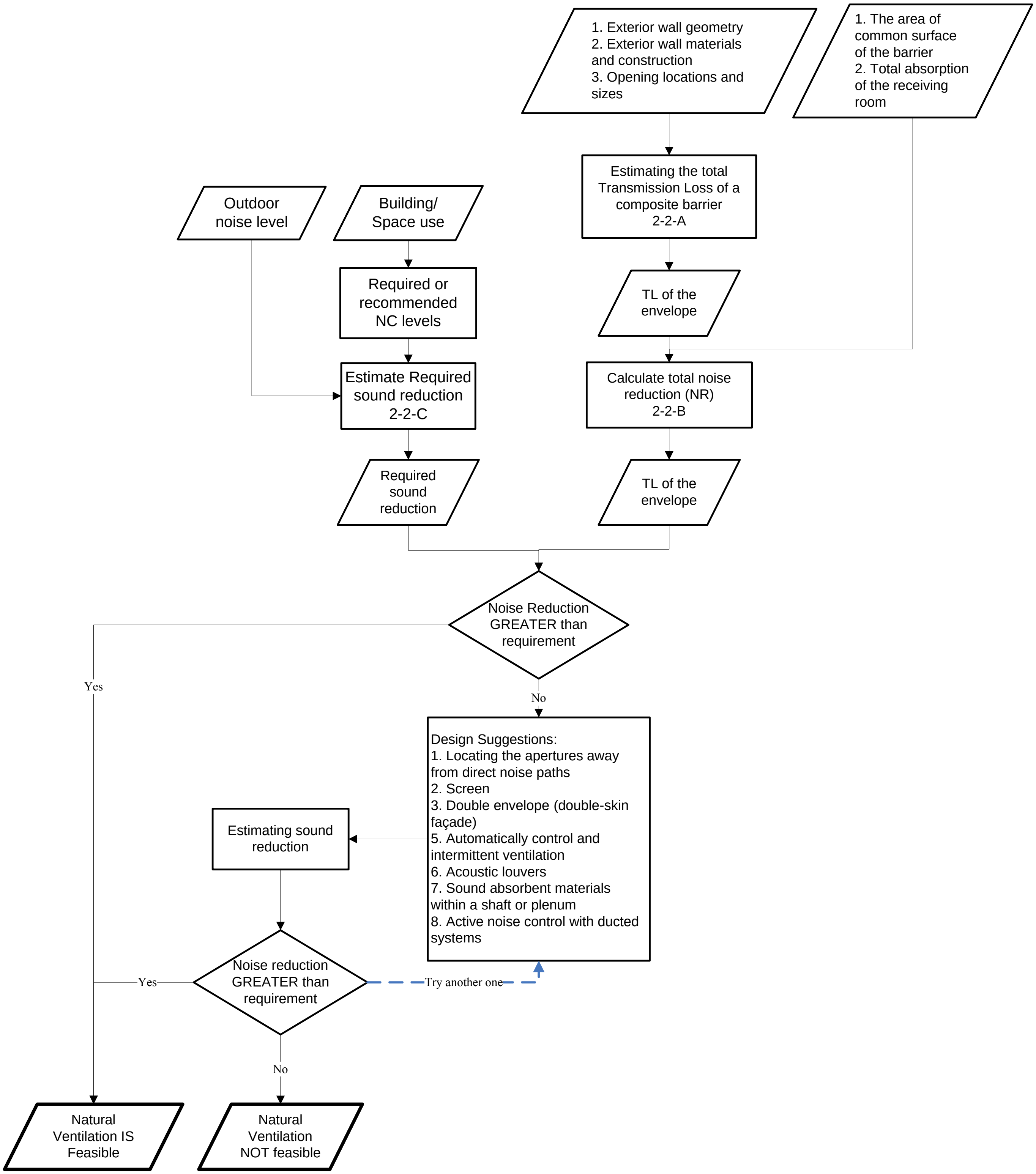


Figure 6.16 Flow chart for noise assessment (Module 2-2)

6.3.3. Module 2-3: Pollution Assessment

6.3.3.1. Outdoor pollution assessment (2-3-A)

Pollution also may restrict the application of natural ventilation. Table 4.1 of ASHRAE Standard 62-2004 can be used to assess if the outdoor air can be used for natural ventilation. The regional outdoor air quality compliance status for the United States as found in the Air Quality System (AQS) Database [57] from the U.S. EPA website is useful for determining the ambient air quality. Local pollutant sources and their location relative to the building and prevailing winds should be assessed on-site. The results of local outdoor air quality investigations are compared with Table 4.1 from this source.

6.3.3.2. Indoor pollution assessment (2-3-B)

Building spaces typically have indoor pollutant sources and consequently potentially high indoor pollutant concentrations. For natural ventilation this has at least three potential consequences. First and easiest to address would be to not include these spaces in the natural ventilation solution and provide only mechanical ventilation. However, this would seem to defeat the intention of natural ventilation. The premise here is, if natural ventilation is properly designed, the adequate flow rates can be achieved for relatively clean or polluted spaces. Second, if applied, the natural ventilation solution must provide both adequate flow volume and ventilation effectiveness to dilute and remove the pollutant. Third, the air flow path must be considered to prevent cross-contamination. For this, compartmentalization and zoning may be an effective strategy. The regulations and guidelines on concentrations of indoor pollutants can be found in Table B-1 and B-2, ASHRAE Standard 62-2004.

For the decision-support framework estimation of IAQ is made by estimating the indoor air flow rate. By estimating the wind and/or buoyancy driven pressures in the building the role of air movement in the occupied zones can be estimated. These flow rates can be compared with recommended minimum flow rates from ASHRAE Standard 62 to determine whether the natural ventilation strategy can satisfy the standard requirements. The overall process is shown in Figure 6.17.

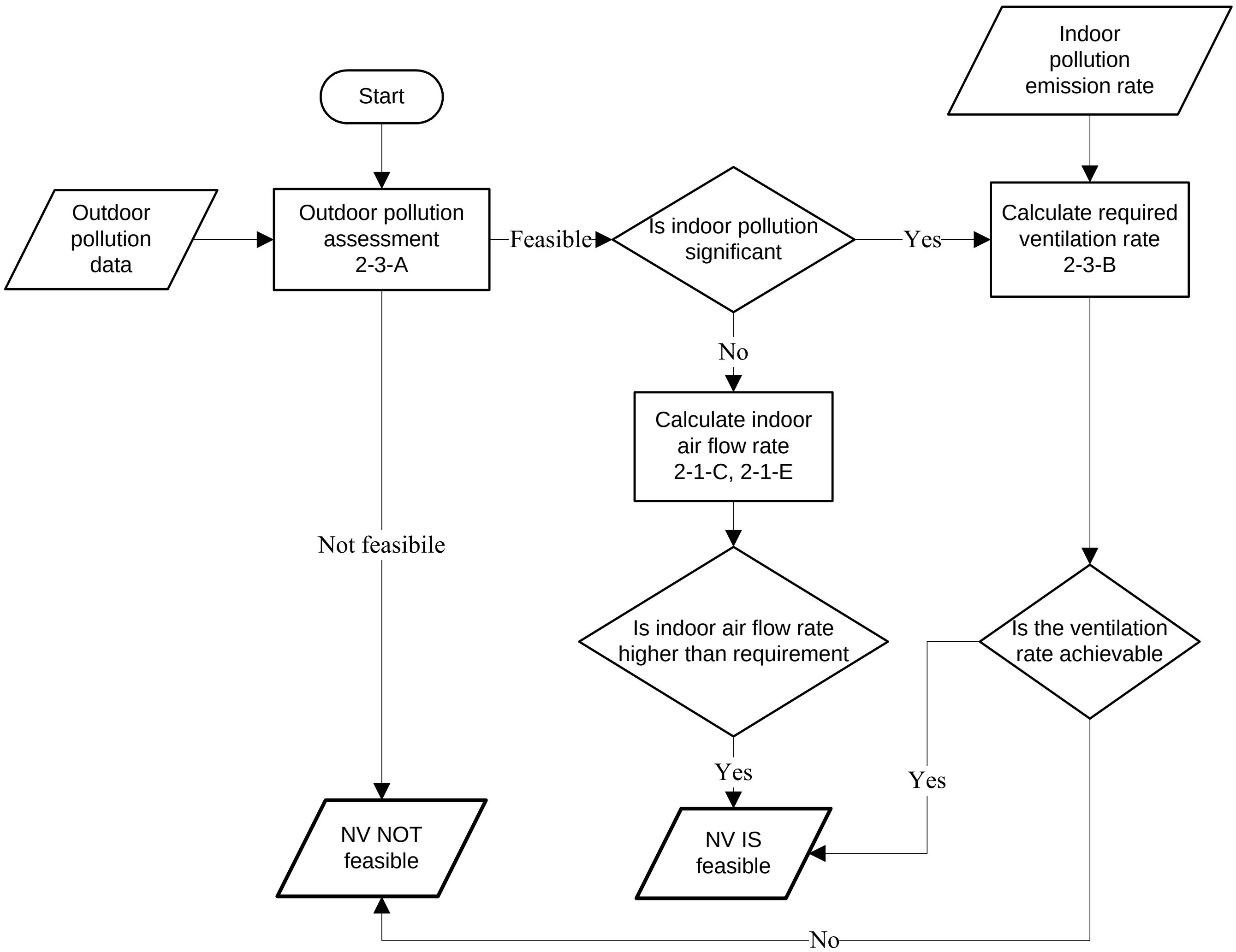


Figure 6.17 Flow chart for pollution assessment (Module 2-3)

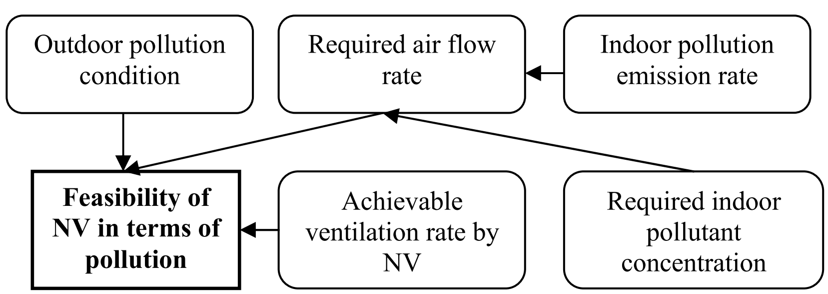


Figure 6.18 Influence diagram of pollution assessment

6.4 CONCLUSION

The chapter provides an introduction to a feasibility assessment framework for natural ventilation in non-residential buildings. The feasibility of natural ventilation is evaluated in terms of climate and site conditions for temperature, humidity, wind, noise and pollution. Design suggestions for the conditions when natural ventilation is not appropriate are given.

Through the feasibility assessment, possible NV approaches may be limited to even one or two certain approaches with certain building design options. The preliminary design proposition (inputs) may be adapted for feasibility if necessary.

In the next step, constraints will be applied to the results of feasibility assessment module, which may further adjust the possible NV approaches and bring more details to the design proposition.

CHAPTER 7 CONSTRAINTS

7.1 INTRODUCTION

All of the possible natural ventilation approaches and system designs are assessed by applying constraints functions to each of the alternatives. As introduced in chapter 2, they are among the critical issues that limit the design of natural ventilation but not as "hard" as those determining the feasibility. The scope of the constraints in the framework is introduced as follows.

(1) Building codes, standards, and regulations that influence and potentially limit the design of natural ventilation systems include the codes for fire safety, standard requirements for indoor air quality, and some regulations for building security.

(2) Designer and client's goals and preferences on natural ventilation options

(3) Zoning requirements

(4) Vector prevention

7.2 BUILDING CODES, STANDARDS AND REGULATIONS

The codes, standards and regulations used in this framework are those currently used in the US.

7.2.1 Model Building Codes

BOCA (Building Officials and Code Administrators International) building codes are widely adopted in the northeastern and mid-eastern regions of the United States. Other building codes often used are the Uniform Building Code (UBC) by International Conference of Building Officials (ICBO) and the Southern Standard Building Code by Southern Building Code Congress International, Inc. (SBCCI).

7.2.2 Standards

Standards published by the following institutes are used extensively: ANSI (American National Standards Institute), ASHRAE (The American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.), ASTM (American Society for Testing and Materials), NFPA (National Fire Protection Association) (the healthcare facilities and life safety code by NFPA with AIA involvement) and UL (Underwriters laboratories, Inc.) In this framework, some requirements in ANSI/ASHRAE Standard 62 for indoor air quality are used as constraints.

7.2.3 US Regulations

Some federal regulations may be involved in the framework. These regulations may be only applicable to some types of buildings, for example, the Vulnerability Assessment of Federal Buildings (1995) by the Department of Justice for federal buildings and the DOD Minimum Anti-Terrorism Standards for Buildings, Unified Facilities Criteria (UFC) 4-010-0 that "apply to all Department of Defense (DOD) Components, to all DOD inhabited buildings, to billeting, and to all DOD expeditionary and temporary structures" [63].

7.2.4 Local Building Codes and Regulations

Local building codes, zoning requirements and other regulations may be added as constraints to the framework by users if necessary.

The overall flow chart for Constraints is shown in Figure 7.1.

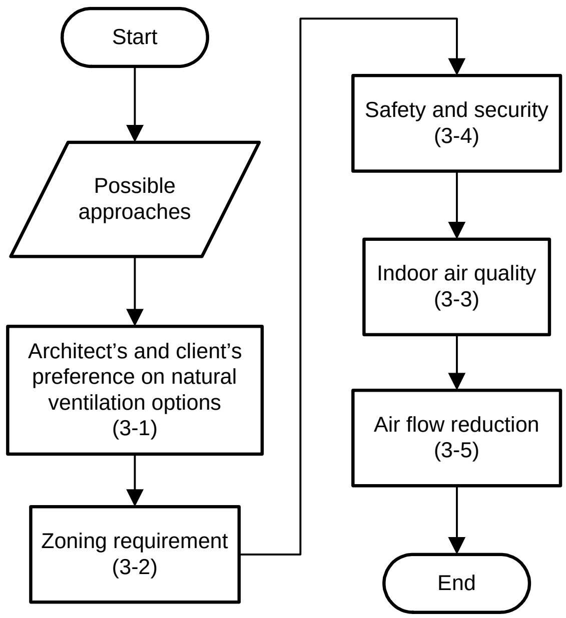


Figure 7.1 The overall flow chart for Constraints

7.3 MODULE 3-1: ARCHITECT'S AND CLIENT'S PREFERENCE ON NATURAL VENTILATION OPTIONS

The architect's and the client's preferences regarding the level of expression of natural ventilation systems and their preferences for natural ventilation options determine the choice of natural ventilation elements to be integrated.

7.4 MODULE 3-2: ZONING REQUIREMENT

The zoning requirements that potentially influence the design of naturally ventilated buildings include:

- Setbacks
- Lot coverage
- Height restrictions
- Building area
- Development densities

For example, the development density may influence local wind direction and velocity; the height restrictions may limit the use of ventilation stacks.

Additionally, size and proxemic relationships among functional zones may potentially limit the implementation of natural ventilation by regulating the geometry of the building. For example, the need to place large zones adjacent to each other may increase the overall depth of the building plan, making it difficult to develop a ventilation flow path.

7.5 MODULE 3-3: INDOOR AIR QUALITY

As presented in Section 5.1, the use of natural ventilation systems is permitted by ASHRAE Standard 62-2004, in lieu of or in conjunction with mechanical ventilation. However, the requirements on location, the size of openings, and control and accessibility in Section 5.1.1 and 5.1.2 are inflexible or inappropriate for natural ventilation system design in most non-residential buildings. For example, if natural ventilation is selected as the method, the spaces should be permanently open. The standard allows that these requirements need not be met when an engineered natural ventilation system is approved by the authority having jurisdiction. Therefore, in most cases, an "engineered" system design is necessary.

Except for the requirements for outdoor air quality, indoor air pollutants and minimum ventilation rate that are incorporated in the feasibility assessment, the following requirements and design suggestions by ASHRAE Standard 62 can also be constraints for the design of natural ventilation systems in terms of IAQ.

7.5.1 Module 3-3-1: Opening location (required by ASHRAE Standard 62)

Outdoor air intakes, including doors and windows that are required as part of a natural ventilation system, should be located such that the shortest distance from the intake to any specific potential outdoor contaminant source is equal to or greater than the separation distance listed in Table 5-1, ASHRAE Standard 62.1-2004, which is reproduced in Table 7.1.

Table 7.1 Minimum separation distance from air intakes to potential outdoor contaminant sources, including exhaust air/vent outlets (recommended by ASHRAE standard 62)

Object	Minimum Distance, ft (m)
Significantly contaminated exhaust (Note 1)	15 (5)
Noxious or dangerous exhaust (Notes 2 and 3)	30 (10)
Vents, chimneys, and flues from combustion appliances and equipment (Note 4)	15 (5)
Garage entry, automobile loading area, or drive-in queue (Note 5)	15 (5)
Truck loading area or dock, bus parking/idling area (Note 5)	25 (7.5)
Driveway, street, or parking place (Note 5)	5 (1.5)
Thoroughfare with high traffic volume	25 (7.5)
Roof, landscaped grade, or other surface directly below intake (Notes 6 and 7)	1 (0.30)
Garbage storage/pick-up area, dumpsters	15 (5)
Cooling tower intake or basin	15 (5)
Cooling tower exhaust	25 (7.5)

Note 1: Significantly contaminated exhaust is exhaust air with significant contaminant concentration, significant sensory-irritation intensity, or offensive odor.

Note 2: Laboratory fume hood exhaust air outlets shall be in compliance with NFPA 45-19913and ANSI/AIHA Z9.5-1992.4

Note 3: Noxious or dangerous exhaust is exhaust air with highly objectionable fumes or gases and/or exhaust air with potentially dangerous particles, bioaerosols, or gases at concentrations high enough to be considered harmful. Information on separation criteria for industrial environments can be found in the ACGIH Industrial Ventilation Manual5and in the *ASHRAE Handbook—HVAC Applications*. 6

Note 4: Shorter separation distances are permitted when determined in accordance with (a) Chapter 7 of ANSI Z223.1/NFPA 54-20027for fuel gas burning appliances and equipment; (b) Chapter 6 of NFPA 31-20018for oil burning appliances and equipment, or (c) Chapter 7 of NFPA 211-20039for other combustion appliances and equipment.

Note 5: Distance measured to closest place that vehicle exhaust is likely to be located.

Note 6: No minimum separation distance applies to surfaces that are sloped more than 45 degrees from horizontal or that are less than 1 in. (3 cm) wide.

Note 7: Where snow accumulation is expected, distance listed shall be increased by the expected average snow depth.

7.5.2 Module 3-3-2: Separation of exhaust outlets and outdoor air intakes (suggested by ASHRAE Standard 62)

Exhaust outlets and outdoor air intakes or other openings should be separated. The separation distance (L) should be determined using either of the following approaches:

(a) Use the values of L in Table 7.2.

Table 7.2: Minimum separation distance (Source: Appendix F, ASHRAE Standard 62.1-2004)

Significant Contaminant or Odor Intensity	Noxious or Dangerous Particles
15ft (5m)	30ft (10m)

(b) Alternatively, L may be calculated using Equation 1 or 2 as shown below.

$$L = 0.09\sqrt{Q}(\sqrt{DF} - U/400) \text{ ft},$$

Equation 7-1

$$\text{or } L = 0.04\sqrt{Q}(\sqrt{DF} - U/2) \text{ m},$$

Equation 7-2

where

Q = exhaust air volume, cfm (L/s). For gravity vents, such as plumbing vents, use an exhaust rate of 150 cfm (75 L/s). For flue vents from fuel-burning appliances, assume a value of 250 cfm per million Btu/h (0.43 L/s per KW) of combustion input (or obtain actual rates from the combustion appliance manufacturer.

DF = dilution factor, which is the ratio of outside air to entrained exhaust air in the outside air intake. The minimum dilution factor shall be determined as a function of exhaust air class, as shown in Table 7.3.

U = exhaust air discharge velocity, fpm (m/s).

Table 7.3 Minimum dilution factors (Source: Appendix F, ASHRAE Standard 62.1-2004)

Exhaust Air Class	Dilution Factor, *DF*
Significant contaminant or odor intensity	15
Noxious or dangerous particles	50*
*Does not apply to fume hood exhaust.	

For exhaust air composed of more than one class of air, the dilution factor will be determined by averaging the dilution factors by the volume fraction of each class:

$$DF = \frac{\Sigma DF_i Q_i}{\Sigma Q_i}$$

Equation 7-3

7.5.3 Module 3-3-3: Air classification and transferring (required by ASHRAE Standard 62)

The requirement by ASHAE Standard 62 limits the air circulation from a space of lower air class to those of higher classes, thus it influences the design of zones and the flow path of a natural ventilation scheme. The space air classification by ASHRAE Standard 62 is listed in Table 7.4.

Table 7.4 Air class of space types (developed from Table 5-2, ASHRAE Standard 62-2004)

Space use	Air Class
Office space, Reception areas, lobbies, Computer (not printing), Photo studios, Shipping/receiving, Transportation waiting, Auditorium seating area, Places of religious workshop, Courtrooms, Legislative chambers, Libraries, Museums, Galleries, Mall common areas, Supermarket, Sports arena (play area), Spectator areas, Disco/dance floors, Bowling alley (seating), Gambling casinos, Game arcades, Stages, studios, Coffee stations, Break rooms, Equipment rooms, Electrical/telephone closets, Elevator machine rooms	1
Bank vaults/safe deposit, Pharmacy (prep. area), Warehouses, Sales (except as above), Barber shop, Beauty and nail salons, Pet shops (animal areas), Coin-operated laundries, Gym, stadium (play area), Swimming (pool & deck), Health club/aerobics room, Health club/weight rooms, Kitchenettes, Private toilet/bath, Employee locker rooms, Laundry rooms, central, University/college laboratories	2
Refrigerating machinery rooms, Soiled laundry storage, Janitors closet, trash room, General chemical/biological laboratories, Daycare sickroom, Commercial kitchen hoods other than grease	3
Storage rooms, chemical, Paint spray booths, Diazo printing equipment discharge, Commercial kitchen grease hoods, Laboratory hoods	4

Air transfer requirements by ASHRAE Standard 62 are summarized as follows:

- Class 1 can be transferred to any other space
- Class 2 air may be transferred to other Class 2 or Class 3 spaces of similar use and with the same or similar pollutant sources. Class 2 air may be transferred to other Class 4 spaces. Class 2 air cannot be transferred to Class 1 spaces
- Class 3 air may not be transferred to any other space
- Class 4 air may not be transferred to any other space and cannot be re-circulated to the origin space

7.5.4 Natural ventilation in health care facilities (Module 3-3-4)

As stated by the 2006 Guidelines for Design and Construction of Health Care facilities by American Institute of Architects, for most health care facilities, although natural ventilation for non-sensitive areas and patient rooms (via operable windows) shall be permitted (when weather and outside air quality permit), mechanical ventilation shall be considered for all rooms and areas in these facilities.[64] That applies for facilities including general hospitals, small inpatient primary care hospitals, rehabilitation facilities, outpatient facilities, nursing facilities, etc.

The exceptions are found in psychiatric hospitals and small (neighborhood) outpatient facilities, that “all occupied areas shall be ventilated by natural or mechanical means” is suggested.

For those areas that natural ventilation is allowed, to reduce airborne transmission of infections, the following design strategies are necessary:

- Small groupings, physical separation, and visibility in public waiting areas;
- Airborne infection isolation, under negative pressure with respect to adjacent spaces;
- All air should be exhausted directly outdoor, with no recirculation to other areas of the hospital;

Exhaust discharge vents must be located away from fresh air intakes.

The flow chart for Module 3-3 is shown in Figure 7.2.

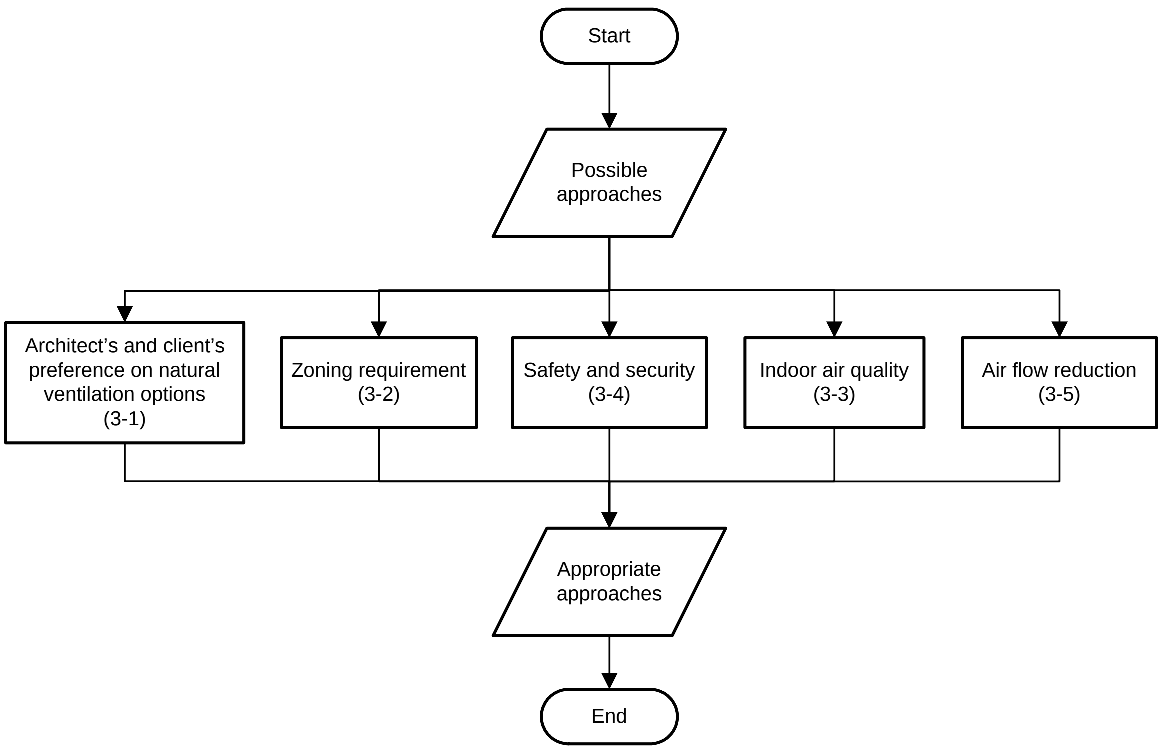


Figure 7.2 Flow chart for the constraint of IAQ

7.6 MODULE 3-4: SAFETY AND SECURITY

7.6.1 Fire prevention (Module 3-4-1)

The risk that fire may spread along a natural ventilation path is a concern that may limit the application of natural ventilation. This concern is usually mentioned as a barrier to applying natural or hybrid ventilation in related literature [14, 16, 65, 66], but detailed information and examples are absent. Since the naturally and hybrid ventilated non-residential buildings in the US are few, less information about how the fire code is met is available. European practices can serve as a good reference, although the codes used are different. However, fire codes may not be a major barrier to the implementation of natural ventilation.

Generally, fire codes regulate the design of a natural ventilation system with several aspects:

First, fire codes establish requirements regarding the design of openings in the exterior walls and the interior partitions, including the size, location, materials, and controls, etc. For example, BOCA National Building Code requires that "the aggregate width of all openings at any floor level shall not exceed 25 percent of the length of the wall," [67] unless buildings at both side are equipped with an automatic sprinkle system.

Second, fire codes set requirements for the materials and methods of construction of building components.

Third, fire codes may determine the need for special compartmentalization. Fire area is "the aggregate floor area enclosed and bounded by fire walls, exterior walls or fire separation assemblies of a building."[67] The ventilation openings penetrating the compartment of the fire area, such as fire doors, fire windows, shutters, or dampers, can be automatic-closing, which will enable the opening to be protected during a fire condition. Automatic-closing doors are permitted as long as this opening will not pose a threat to the occupants' safety [67]. The basic requirement for closing devices and specific requirements for automatic-closing and self-closing devices are given in NFPA 80. Openings in shafts shall also be protected. Strategies such as fire-warning systems and smoke alarm systems can detect a fire and signal the occupants, while openings can be automatically or manually controlled to close, or open for smoke ventilation. In some cases, fire-suppression systems may be necessary.

The requirement of the compartment area can impose some limitations and complexity on the natural ventilation scheme, resulting in a less open plan and less freedom in the design of air flow, even if automatic windows, doors and dampers are used. The extensive use of compartment walls, fire doors, windows, and dampers is a major source of cost of a fire protection approach. For example, Approach A of the design of Lanchester Library shown in Table 7.5, is an approach compliant with the requirements of compartmentalization. The total costs of the compartment walls, fire doors, dampers, and automatic controls are about £400 (about $765). The area limitation can be extended if a sprinkle system is used, while it also increases the cost of the building.

Finally, fire codes require smoke prevention, fire-extinguishing and evacuation that can influence the design of a natural ventilation system. A concern proposed by Short et. al [26] is that the incorporation of a mechanical ventilation scheme for smoke extraction in a naturally ventilated building may add to capital costs so that natural ventilation becomes less attractive (Table 7.5, Approach B). Thus, a natural smoke ventilation scheme is desired - it is efficient to use a natural ventilation system in the building to vent smoke and heat from a fire. Natural smoke ventilation schemes exploit greater buoyancy-driven flows generated by a growing fire and higher flow rates resulting from higher temperatures. The Lanchester Library (UK, case 2-1) and the School of Slavonic and East European Studies (UCL, UK, case 2-2) projects demonstrate that "naturally ventilated schemes for urban, multi-storey, institutional buildings potentially can clear smoke more than adequately and achieve at least the level of safety provided by code-compliant schemes" [26].

Table 7.5 Lanchester Library: approximate additional cost of the various alternatives and combinations to meet the prescriptive requirements of the 1997 codes and regulations [26]

	Item	Subtotal	Overall total
Approach A providing for:			
Fire-rated 'quadrant' compartment wall at each level, inclusive of fire-rated doors, fire dampers, seals around penetrating services and related structural supports		£300 000	
Sixty-minute fire-rating of all five number four-storey lightwells, (insulation and integrity	5@ £80 000	£400 000	
Fire-rated ventilation dampers and automatic controls		£100 000	
			£800 000
Approach B providing for:			
Full sprinkler system to all doors		£250 000	
Full mechanical smoke ventilation system (not including builders work)		£200 000	
Stand-by power		£100 000	
Three additional plant rooms@1400/m2 reducing the net usable floor area, apportioned as below	@£1400/m2		
Standby generator,140 m2	£196 000		
Smoke extract,100 m2	£140 000		
Sprinkler pumps, 40 m2	£40 000		
Subtotal		£376 000	
Total			**£926 000**

Natural smoke ventilation systems must be robust to wind effects. The extract terminations must be resistant to positive wind pressures, which could induce a reversal of flow. However, negative wind pressures formed by proper design can aid smoke removal. For example, wind towers are used for smoke ventilation in the Bluewater shopping Mall (Kent, UK, Case 5-1).

7.6.1.1 Design for fire safety and smoke control in atria

Atria can offer considerable benefits to naturally ventilated buildings. However, smoke and flames can spread into them and affect other areas, thus a smoke control system is required in atria. Because both day-to-day environmental and smoke ventilation are essentially similar, both taking advantage of the buoyancy effect, environmental and fire safety strategies can be combined effectively in atria.

Smoke control strategies and natural environmental ventilation do not conflict in atrium design. BRE, Colt international Ltd., and Ove. Arup & Partners propose smoke control options that are appropriate to different atrium circumstances and usages based on the British Standard Code of practice. Active devices are often used for all these smoke control strategies to make the natural environmental system compatible. [68]

Smoke exhaust ventilation from the atrium uses the buoyancy of the smoky fire gases to form a buoyant layer safely above people's heads, or at some other specified height. This requires detailed design: the designer calculates the exhaust capacity or ventilator areas, the inlet area for replacement air, as well as other parameters needed to keep the smoke layer above the design height.

When atrium façade materials cannot survive high gas temperatures, temperature control ventilation from the atrium can be appropriate. It often allows a trade-off between different costs. "This is a variation of smoke exhaust ventilation where the designer specifies the temperature of the smoke layer gases instead of the vertical position of the smoke layer base."[68]

When the atrium is an open atrium, separate smoke exhaust ventilation from each story prevents smoke from entering the atrium by utilizing automatic drop curtains around the atrium space at each story. Additionally, each story has its own smoke exhaust ventilation system.

Atrium depressurization prevents smoke from leaking from the atrium into adjacent rooms, which uses the same natural ventilation approach to keep the leakage paths across the atrium façade under suction.

Hybrid smoke control is the combination of smoke exhaust ventilation, temperature control ventilation and atrium depressurization. A problem of hybrid smoke control is that the predicted forces to open an escape door from the atrium can be too large.

7.6.1.1.1 Design criteria and tools

In the US, BOCA National building Code Section 922 provides the design criteria and requirements for passive or active smoke control systems. Several formula are used to determine if a smoke interface will remain above a prescribed level for 20 minutes by calculating the approximate height of a smoke layer produced from the design fire. For example, the following formula estimates the height of the interface at 20 minutes for regular spaces:

$$z = 0.67H - 0.28H \ln \frac{tQ^{1/3}H^{1/3}}{A}$$

Equation 7-4

Where z = height from floor to the smoke interface, ft;

t = time for interface to descend to z, t=1200s;

H = height of the space required to be provided with smoke control; floor to flat ceiling, ft;

Q = steady state heat release rate, Btu;

A = horizontal cross-sectional area of the above ceiling space being filled (square ft); maximum A shall be used is $A=14H^2$;

If $z<z_{cr}$, mechanical ventilation is required, otherwise natural smoke ventilation can be used.

Z_{cr} is the critical smoke layer (BOCA National Building Code 922.0)

A passive system is allowed if the smoke interface is higher than the critical smoke layer (Zcr) for 1200 seconds (20 minutes); otherwise, a mechanical system is required, i.e. the smoke layer interface has been determined below the critical level of smoke layer (Zcr). The formula is based on empirical data. It is noticed that no special sizes and locations of openings are utilized in this formula.

The code allows "alternative systems" which achieve the same level of smoke control. They must maintain the level of the smoke layer interface above Zcr for 20 minutes by preventing migration of the smoke from the fire area to other areas of the building Therefore, to apply natural smoke ventilation, an engineered design may be needed to prove the system's ability to meet the two criteria.

BRE, Colt international Ltd., and Ove. Arup & Partners proposed a simplified design tool and a easy-to-use computer model "which allows the user to calculate both the natural environmental and fire ventilation openings required for any specified building." [68]. With this tool, the neutral pressure plane is set higher than the highest occupied story. The conditions for the fire case are identical to the environmental case (i.e. the same neutral plane level, same geometry), except for an elevated temperature in the atrium and an adjusted air flow rate on the lowest story to allow for an extra open escape door, as necessary. The required parameters include: building geometry, required air change rate for fire and environmental cases, temperature for fire and environmental cases, height of natural plane level, outside temperature, wind speed, and pressure coefficients at openings.

There are two options for the roof vent. One is designing the extra opening for the detection of a fire; the other is making the roof vent larger including the extra opening area, which would increase the ventilation rate in normal conditions.

Similarly, UBC Section 1716 (b) requires that "the design of the smoke control system must cause smoke to be pulled to the exhaust openings at the top of the atrium, and provide a continuous supply of fresh air at the bottom of the atrium. Because the smoke is likely to be moisture laden owing to the activation of the sprinkler system, a minimum exhaust capacity of 40,000 cfm is required, regardless of atrium size, unless demonstrated tests prove the function-ability of a smaller system." An enclosure separation is required between the atrium and the remainder of the building. A one-hour fire-resistive separation is required with door openings equipped with 20-minute smoke and draft control assemblies which close automatically via smoke detector signal.

7.6.1.2 Fire Protection for Double-Skin Facades

Similar to atria, double-skin facades that are often used in naturally and hybrid ventilated buildings also potentially spread smoke and fire. A safety assessment of double-skin facades in the case of fire by Wolfram Klingsch [62] is referenced by many German authorities. Klingsch states that attention should be paid to three aspects, and gives the fire protection measures accordingly.

First, Klingsch notes that it is difficult for people behind the double-envelope to break the glass. The double-envelope makes the fire department's access from the outside more difficult. It may be difficult to localize the fire space from outside when there is no deconstruction of the outer skin. Thus, automatic early fire-warning systems in the rooms and the façade intermediate space may be needed.

Additionally, the smoke through the inner façade into the intermediate space may accumulate and spread if the inlets and exhaust openings of the outer façade are not adequate. Thus, smoke alarm systems and mechanical fans may be needed.

Finally, because the risk of fire spread exists where hot gases and flames escape through the inner façade into the intermediate space, automatic fire-fighting systems in the rooms and/or the façade intermediate space may be needed, such as a sprinkler system. "Where there is a sprinkler system in rooms, the problem of fire protection will be reduced basically to the extraction of smoke from the façade intermediate space." [62]

Risk factors are given based on the types of double-skin façade, the height of the building and the building use (Table 7.6).The description of the types of double-skin facades are given in Section 6.3.2. Other building-authority requirements have to be taken into account. Fire protection measures are given in Table 7.7.

Fire codes usually require vertical separation of openings. For example, BOCA National Building Code requires that "openings in exterior walls in adjacent stories shall be separated vertically to protect against fire spread on the exterior of the buildings where the openings are within 5 feet (1524mm) of each other horizontally and the opening in the lower story is not a protected opening in accordance with Section 706.0. Such openings shall be separated vertically at least 3 feet (914mm) …"[67] unless the building is equal to or less than 3 stories, or is equipped with an automatic sprinkler system. Attention should be paid to the distance between inlets and outlets of the double envelope at adjacent levels.

Table 7.6 Risk factors of double-skin facades, height of building and building uses [62]

Parameters		Description		Risk
Type of double-skin facades	A1	Individual room type with peripheral horizontal and vertical divisions	Individual air supply and exhaust openings (box-type window)	Low
	A2	Shaft type	Connected to joint ventilation shaft (shaft-box façade, Figure 6.14)	Low
	B	Story type, in which several rooms are linked, with horizontal divisions story for story (corridor type)		Medium
	C	Multi-story type. In which different rooms and user areas are linked horizontally and vertically		High
Height of building	I	Low-rise buildings		Low
	II	Medium-rise buildings		Medium
	III	High-rise buildings		High
Building use	a	Office use and the like		Low
	b	Housing uses		Medium
	c	Special use such as assembly, hotels, schools, hospitals, etc.		High

Table 7.7 Fire protection measures [62]

Height of building	Form of façade construction	a	b	c
I ($\leq$7 m)	A1, A2	1	1	1
	B	1	2	2
	C	2	2+4	2+4
II (7m~22m)	A1	1	1	1
	A2	1	2	2+4
	B	2	3	3
	C	3+4	3+4	3+4
III (>22m)	A1	3	3	3
	A2	3+4	3+4	3+4
	B	3+5	3+5	3+5
	C	3+4+5	3+4+5	3+4+5

Note:

Measure 1 requires no additional measures. Measure 2 requires an automatic early fire-warning system with ventilated façade intermediate space. An automatic early fire-warning system in rooms is used in Measure 3.

Additional measures for activating ventilation in the façade intermediate space is needed in Measure 4. Measure 5 requires sprinkler installation in rooms.

The decision process of applying the constraint of fire safety is illustrated with a flow chart that is shown in Figure 7.3. Although special design procedures and suggestions are given for fire protection in Atria and double-skin facades, referring to the basic fire requirements are still needed.

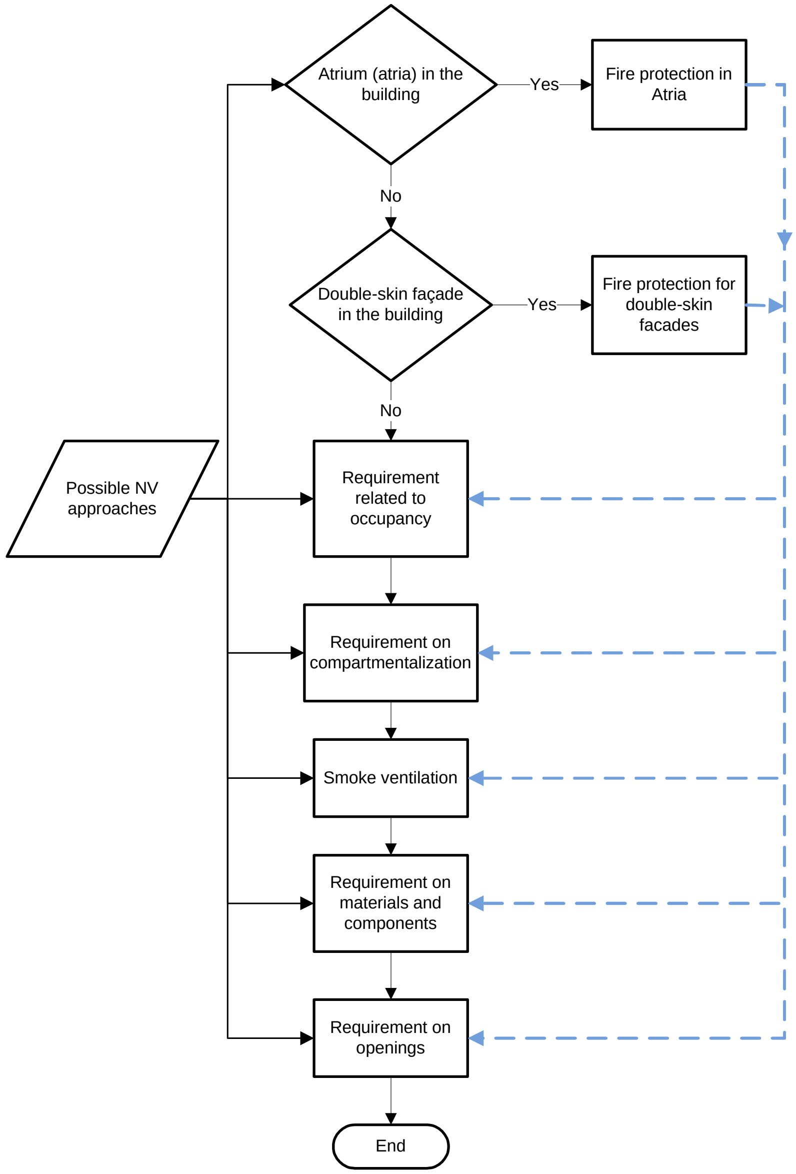


Figure 7.3 Flow Chart for the constraint of fire safety (Module 3-4-1)

7.6.2 **Occupant safety and health** (Module 3-4-2)

7.6.2.1 Opening size and location

Opening size and location should prevent injury by restricting the distance to the operable window and the height of openings above the grade, and by proportioning the length and width of openings such that a person or child cannot pass through, etc.

7.6.3 **Security** (Module 3-4-3)

7.6.3.1 Risk and acceptable vulnerability assessment (Module 3-4-3-1)

Building security design starts at the conceptual phase of the project. The levels of protection depend on the building type, acceptable levels of risk, and decisions made based on recommendations from a project-specific threat assessment, vulnerability assessment, and risk analysis [69]. For example, the Vulnerability Assessment of Federal Buildings(1995), by the US Department of Justice, defines 5 security levels (from minimum to maximum) for federal buildings [69], based on the numbers of employees, building area, public access and sensitive uses such as law-enforcement and intelligence agencies. ASHRAE provides a general risk management guide for health, safety, and environmental security under extraordinary incidents for buildings [70]. Risk should be assessed first with constraints to determine the acceptable vulnerability and corresponding strategies. For this framework, similarly, the security strategies related to ventilation depend on the results of the risk and vulnerability assessment.

7.6.3.2 Design for security strategies related to ventilation

Security related to the design of ventilation systems generally includes two aspects.

First is preventing unauthorized intrusion, which is applicable to most buildings. Ventilation opening design for preventing intrusion includes using bottom hung windows, smaller vents with grilles to minimize the opportunity for intrusion, locating the intakes away from publicly accessible areas, using intrusion detection systems such as video, CCTV, alarms, motion, and acoustic detection devices, and access control systems. All of these decisions are based on the determined levels of protection resulting from risk and vulnerability assessment. For example, in courthouse design, “as a rule, operable windows should be prohibited in all public areas. If courtroom and chambers are located on the ground level, provide blast-resistant or bullet-resistant glazing”[70].

Another aspect is protection from external and internal release of chemical, biological and radioactive (CBR) agents or blast. For the potential of blasts or contaminant release events, fresh air intakes are better located on a higher portion or the roof of the facility, inaccessible to unauthorized people and secured by access-control equipment or devices. In design standards for security of federal agencies, for example, the Department of Defense’s Minimum Anti-Terrorism Standards for Buildings, Unified Facilities Criteria (UFC) (2003) requires that “all air intakes be located at least 10 feet (3 meters) above the ground” for all new inhabited buildings covered by the document [63]; GSA’s Facility Standards for the Public Building Services requires that in buildings of more than four stories, intakes be located on the fourth floor or higher; in buildings of three stories or less, intakes must be located on the roof or as high as practical. Locating intakes high on a wall is preferred over a roof location [71].

For buildings with outside air intakes that are below grade or at ground level, use physical security measures, such as fencing around the intakes, surveillance cameras and motion detectors, explosive/chemical/biological/ materials detection devices, or alarms.

These precautions minimize the opportunity for the direct insertion of an agent into the building through the outdoor air intakes, provide some protection against a ground level release, and minimize the contamination of indoor air from ground applied fertilizers or pesticides, traffic, and similar sources during normal building operation. [70]

Pressurization is a useful strategy where certain zones are positively pressurized relative to adjacent zones, or to outdoor air, even during winds, to minimize air infiltration and building contamination from the external release of agents.

In buildings with a high level of security concern, isolation of high-threat areas is necessary. Isolate spaces with a higher potential for an internal release, such as a mailroom, lobby, or loading dock. Locate the delivery and receiving areas, mailrooms, and similar spaces "remotely and separately from the primary facilities." If this is not applicable, a separate ventilation zone should serve that area, and dedicated exhaust systems should be provided to maintain negative pressure relative to the rest of the building [72].

Fixed and forced-entry-resistant window designs can prevent a container with CBR agents from being thrown through a window. The UFC requires that HVAC systems should be shut down to limit the dispersion of an internal release of CBR agents, and filtration systems are needed to remove CBR agents and enable pressurization of the building with clean air.

If pressurization, isolating big-threat areas and protection from external and internal release of CBR are necessary according to risk and vulnerability assessment, a hybrid ventilation system is appropriate, because isolation zones are required and air filtration and pressurization are needed in emergency. Integrated Building Automation and Control Systems (BAS) are important for buildings with higher level requirements of safety and security. BAS integrates and automates traditionally stand-alone building automation and control systems such as ventilation, fire, lighting, and security into one comprehensive system. This enables electronic monitoring and control of these systems from a single, centralized optimized building operation.

The decision process of applying the constraint of security is illustrated with flow chart that is shown in Figure 7.4.

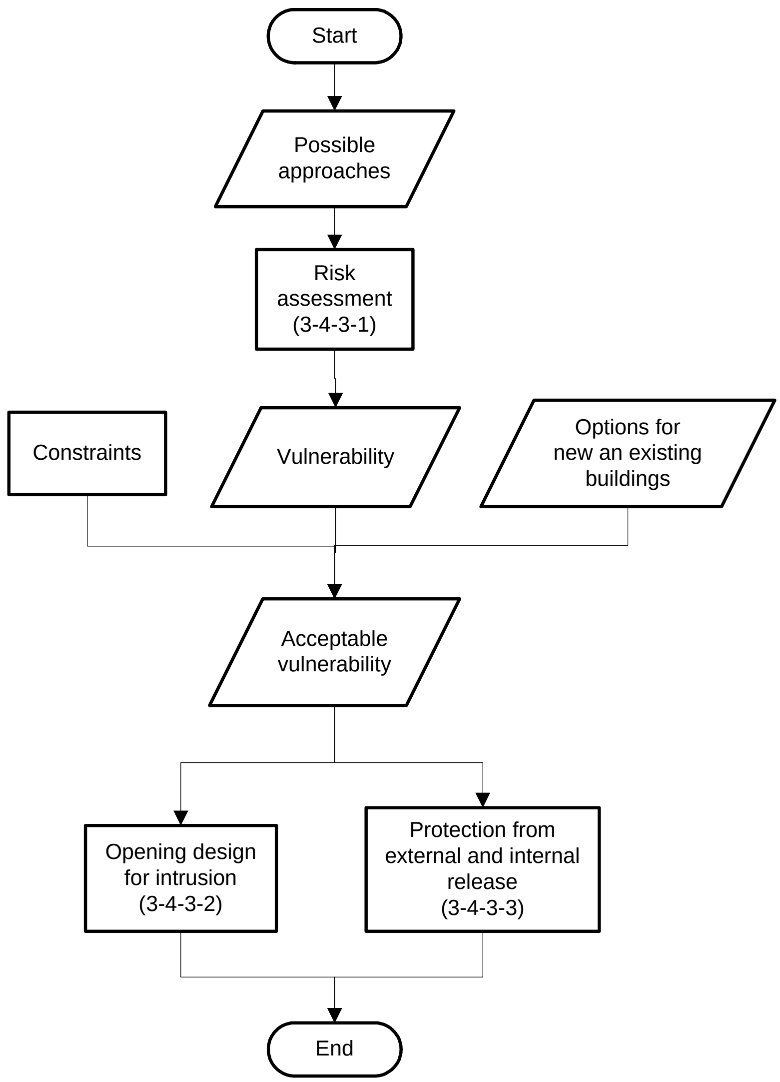


Figure 7.4 Flow chart for the constraint of security (Module 3-4-3)

7.7 MODULE 3-5: AIR FLOW REDUCTION

Air flow reduction is caused by pressure loss. Pressure loss considered in this framework includes the following aspects: loss at large openings (discharge coefficients), loss in ducts and shafts, loss at other components, and air leakage. However, the pressure loss at some building components is difficult to estimate.

7.7.1 Pressure loss at large openings (discharge coefficient)

The discharge coefficient for a window opening cannot be regarded as a constant. It depends on the opening area, window type, temperature difference, wind pressure, wind direction, etc.[73] The discharge coefficient accounts for both contraction and friction loss: i.e. Cd=$\varphi\varepsilon$, where φ is the velocity coefficient and ε is the contraction coefficient.

For large openings, the discharge coefficient is around 0.6. Experiments performed in a real building to determine flow coefficients by Flourentzou et al. [74] confirm the values found in the literature. The velocity coefficients $\varphi = 0.7 \pm 0.1$ and contraction coefficients $\varepsilon = 0.85 \pm 0.1$ found in the experiments agree with the generally accepted value of the discharge coefficient $C_d = \varphi\varepsilon = 0.6 \pm 0.1$.

Favarolo and Manz [75] investigated single-sided ventilation through a large rectangular opening with CFD simulation and experiments. They found that side-wall thickness and the aspect ratio of the opening can affect C_d. C_d decreases as side-wall thickness increases and as the aspect ratio of the opening decreases. Favarolo and Manz found that the vertical position of the opening is the most important parameter. The value of C_d increases as the opening moves toward the top of the wall (Figure 7.6). That may be caused by decreased pressure difference.

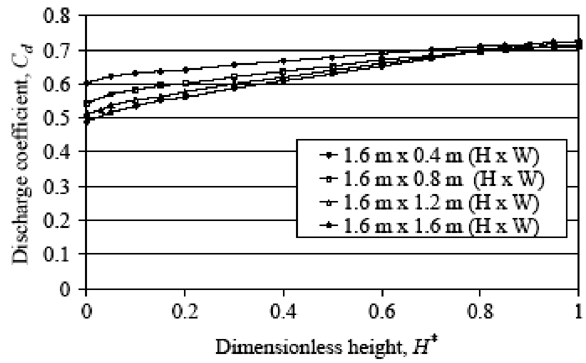


Figure 7.5 Impact of dimensionless height on discharge coefficient (opening height = constant) [75]

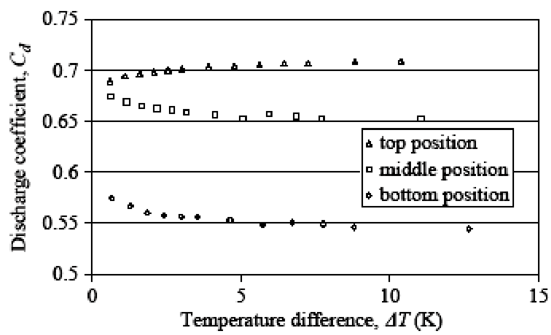


Figure 7.6 Impact of temperature difference and the position on discharge coefficient [75]

Heiselberg, et al. found that the values of C_d of smaller openings are larger (Figure 7.7)

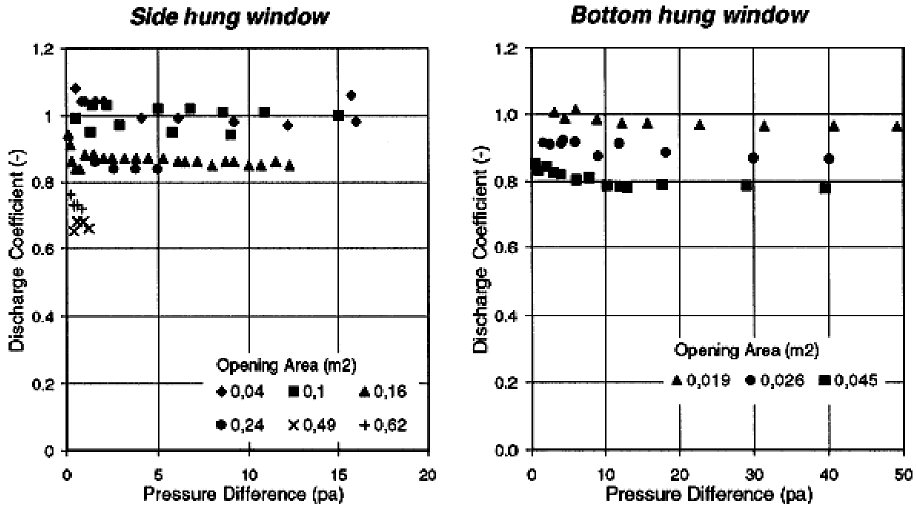


Figure 7.7 Discharge coefficient, Cd, for side and bottom hung windows as a function of pressure difference for different opening areas (The value over 1 may be caused by inaccurate measurement of opening area) [73]

Heiselberg et al. states that the influence of the buoyancy is expressed by the quantity

$$A_r' = \frac{T_{oc} - T_o}{Q^2} 10^{-3} Ks^2 / m^6$$

Equation 7-5

T_{oc} = air temperature in the occupied zone, K,

T_0 = temperature of inlet air, K

Based on Figure 7.8, Heiselberg et al. states "it can be seen that in a situation with both a temperature and a pressure difference across the opening the discharge coefficient can be described as a function of Ar' and the opening area, and that the value of the discharge coefficient is considerably reduced at large temperature differences. For small opening areas the dependency is not so strong." [73] For bottom hung windows, the discharge coefficient showed a very small dependency on temperature difference.

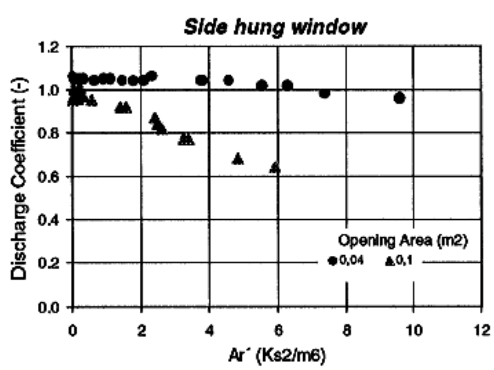


Figure 7.8 Discharge coefficient, Cd, for the side hung window as a function of Ar'[73]

In sum, for large openings, $C_d = 0.6 \pm 0.1$ can be used. Larger values may be used for openings at higher levels, with higher aspect ratios (narrower), and/or with lower potential friction resistance, such as a thin side wall. Lower values may be used for openings at lower levels, especially with larger temperature difference ($\Delta T > 5K$), with low aspect ratios (wide), and/or higher potential friction resistance. For small openings in winter ventilation, the value of C_d in the range of 0.8~1.0 can be used.

7.7.2 Pressure loss at ducts and shafts

Some simple ducts and shafts (few turns and branches) may be used in natural ventilated buildings. The cross-section of the ducts or shafts must be larger than usual to lower pressure loss. The stack effect with shafts is influenced considerably by the friction resistance inside the shaft.

7.7.2.1 Loss in stack turning

The method of Livermore and Woods (2005) [76] can be used to calculate the pressure loss for air that flows into the stack horizontally and then turns vertically upwards. It is assumed $P_D = P_U$, P_U is the pressure just inside the opening of the stack, so $\Delta P = P_D - P_S$. (Figure 7.9)

$$A_s \Delta P = \dot{m} u = \rho A_s u^2 \text{ so } \Delta P = \rho u^2 = \rho \left(\frac{Q}{A_s} \right)^2 .$$

Equation 7-6

Where As is the cross section area of each stack, P_U is the pressure inside the entrance to the stack, P_D is the pressure at the base of control volume, P_S is pressure at the top of the control volume, u is the velocity of the air fluxing up the stack, and $\dot{m}$ is the mass of the air fluxing up the stack.

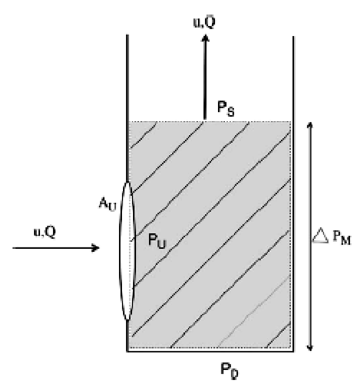


Figure 7.9 Control volume analysis at the base of the stack [76]

7.7.2.2 Frictional loss in stack

Friction loss in a stack can be calculated by the Darcy equation:

$$\Delta P = \frac{fL}{D_h} \frac{\rho u^2}{2}$$

Equation 7-7

f = friction factor

L = duct length, m

D_h = hydraulic diameter

The friction factor depends on whether the flow is laminar or turbulent, which is determined by its Reynolds number.

$$R_e = \frac{D_h u}{v}$$

Equation 7-8

v= kinematic viscosity, m²/s, $v_{air} = 16 \times 10^{-4}$ m²/s

D_h = equivalent hydraulic diameter. For circular ducts, D_h =D; for noncircular ducts, D_h = 4A/P

A = duct area

P = perimeter of cross section of duct

(1) For laminar flow (Re<2,300), the friction factor is a function of the Reynolds number,

$$f = 64/Re$$

Equation 7-9

(2) Turbulent flow with 2,300<Re<10,000, f depends on the Reynolds number and the relative roughness ε / D_h .

f is calculated by Colebrook's equation and can be solved by iterative techniques with equation:

$$\frac{1}{\sqrt{f}} = -2\log\left(\frac{\varepsilon}{3.7D_h} + \frac{2.51}{\text{Re}\sqrt{f}}\right)$$

Equation 7-10

(3) For flow with a high Reynolds number (Re>10,000) and relative roughness ε / D, f is only related to relative roughness.

$$\frac{1}{\sqrt{f}} = 1.14 + 2\log(D_h / \varepsilon)$$

Equation 7-11

ε = material absolute roughness factor, mm. The value of ε can be found in many sources, such as the ASHRAE Handbook, Fundamentals, 2001

7.7.2.3 Duct expansion and contraction

Pressure loss occurs as air flow is suddenly contracted or expanded. The larger the change in area caused by contractions and expansions, the larger the pressure loss. The pressure loss coefficient k of sudden expansion is:

$$k = \left(1 - \frac{A_1}{A_2}\right)^2$$

Equation 7-12

A_1 = area of internal section of the small ducts

A_2 = area of internal section of the large ducts

The pressure loss coefficient k of sudden contraction is:

$$k = 0.5\left(1 - \frac{A_1}{A_2}\right)^2$$

Equation 7-13

7.7.3 Flow resistance of building components

7.7.3.1 Flow resistance of wires and screens

If used at ventilation openings, insect screening may cause significant pressure loss. Sometimes it is not practical to compensate for this loss by increasing the opening areas, thus mechanical assistance may be needed.

Protection against insects is more critical than protection against birds as the geometric obstruction caused by insect screens is considerably greater. "With mesh spacing of 2 mm, and a wire diameter of 0.5mm, the obstructed area amounts to 50%; the effectiveness of ventilation is reduced to about 85% of the initial flow" [62]

Table 7.8 gives the geometric degree of obstruction of wires of different mesh spacing and wire thickness.

Table 7.8 Geometric degree of obstruction[62]

Wire thickness	0.3 mm	0.5mm	1.0 mm
Mesh spacing	Geometric degree of obstruction		
5 mm	12%	19%	36%
8 mm	8%	12%	24%
10 mm	6%	10%	19%
20 mm	3%	5%	10%

Work in this area has been conducted by Givoni, Koenigsberger, and Van Stratten. The screen itself can have a substantial effect on air flow with rough screens leading to reductions in excess of 60 percent. Smooth nylon and synthetic screens result in an average reduction of about 35 percent. Reductions also depend on wind direction, with increases in incidence angle resulting in increasing reductions in air .[39]

Givoni has suggested that flyscreens not be placed at the window itself, but at some distance away from the apertures in the form of screened balconies or porches. This technique does not reduce airflow rates as significantly for either normal or oblique winds. In oblique winds, screening on outlet windows does not reduce airflow rates as severely as it does on inlet windows. This may be because the airflow speed is lower near outlets.

Air is forced to flow through the constricted area at a greater speed in order to achieve the same throughput. The pressure losses increase quadratically as the air speed increases.

$$\Delta P_{Loss} = \varsigma \bullet \frac{\rho v^2}{2}, \text{ pa}$$

Equation 7-14

ς = Pressure loss coefficient

v = wind speed, m/s

ρ = air density, kg/m^3

FLOVENT, a commercial CFD model allows the screen to be modeled with free area ratio, i.e. ζ is correlated to the free area ratio of screens. That can be used to estimate the pressure loss. For example, the pressure loss coefficients for 50%, 60% and 70% free area ratios of screens are listed in Table 7.9.

Table 7.9 The pressure loss coefficient used for 50%, 60% and 70% free area ratio of screens in Flovent [77]

Free area ratio of screens	50%	60%	70%
Loss coefficient	4.0	2.0	0.9

7.7.3.2 Flow resistance of double-skin façades

The flow resistance of double-skin façades is difficult to estimate. CFD may be necessary to study the flow resistance of a double-skin façade.

The air change caused by a double-envelope is much lower than that for a single window ([15], Figure 116, p.102). Through monitoring the performance of double-facades of three buildings, Pasquay (2004) [78] states that the factors influencing the air flow rate of spaces with double-façades are wind speed, wind direction, gap width, opening area, and temperature difference. Greater gap widths and opening areas result in larger air flow rates in spaces; larger opening areas results in less pressure loss ([15], Figure 118, p.102 and [62], Figure 8-11, p.99). For facades separated on each floor, the air change rate in the gap space depends more on wind speed and direction than on the stack effect.

7.7.4 Design suggestions to minimize pressure loss

Several potential sources of pressure loss in naturally ventilated buildings should be avoided.

Partition walls may cause significant pressure drop. A building with an open plan or larger open spaces is better for natural ventilation. Obstructions in the flow route such as furniture, columns, and screens at the inlet and outlet openings add to the resistance.

Direction changes in ventilation routes should also be avoided. Indirect ventilation routes cause extra loss. The number of turns in the ventilation route should be minimized.

The contraction and expansion of air flow as it passes through rooms causes turbulence, and increases flow resistance. Additionally, long ventilation routes result in more loss. Finally, if shafts or ducts are used for natural ventilation, friction loss and dynamic loss need to be considered.

The following strategies can be used to compensate for pressure loss:

- Increase stack temperature difference by a solar chimney. As the air at upper level of the stack above the occupied zone is heated by the sun, the temperature difference increases, so does the pressure difference.
- Decrease the pressure near outlets. Increasing stack height, shaping the building form, and/or applying a wind-chimney with the Venturi effect to the outlet can make the pressure at the outlet lower.
- Increase the pressure near inlets. If wind speed is low due to nearby obstructs, locating wind scoops above the roof can increase the pressure difference.
- Use mechanical assistance.

Because pressure loss calculations are usually considered when estimating air flow rate or sizing the openings, during these process estimation models are often used. The scope of the pressure loss considered in these models is shown in Figure 7.10.

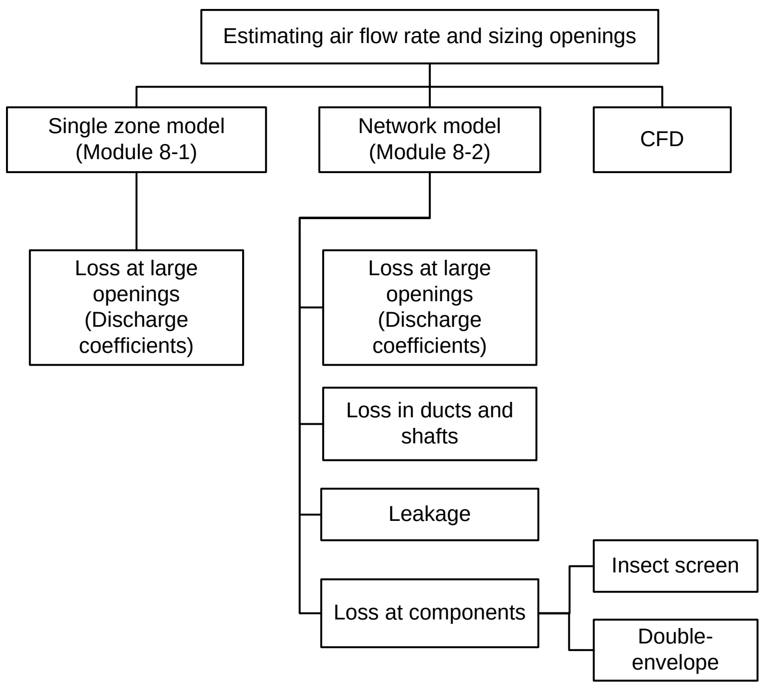


Figure 7.10 The scope of models and pressure loss considered in these models

7.8 CONCLUSION

The constraints and related design suggestions for the decision-support framework are presented in this chapter. These constraints represent various issues that limit the design of natural ventilation systems.

CHAPTER 8 DESIGN SUGGESTIONS

8.1 INTRODUCTION

The ventilation components for natural and hybrid ventilation approaches are summarized in Chapter 2. These are a portion of the design suggestions to which users can refer.

Other major portions of the design suggestions given in this framework are focused on sizing openings and air flow rate estimation. The methods for sizing openings and the methods for estimating air flow rates can be used iteratively in the design process, such as in feasibility assessment and in performance assessment.

Sizing openings and air flow rate estimation can be done at three levels of accuracy. The first level uses a single zone model, and its application is typically limited to very small scale buildings. In most cases, the air flow resistance considered at this level is expressed as discharge coefficients of large openings. At the second level, network models are often used. These models are suitable for early and middle design phases and for larger scale buildings. The costs of using these models are relatively low. The estimation of pressure loss includes determining discharge coefficients for large openings, loss in ducts and shafts, and loss at other components such as insect screens, and air leakage. Computational Fluid Dynamics (CFD) is often used at later stages of design when air distribution in the space, local comfort, local pollutant concentration, the design of ventilation components, and detailed control strategies are required. Although CFD is also good for early phases of design, the cost can be a concern.

Other design suggestions in this chapter include:

- Suggestions for the issues of draft prevention (Module 5-2)
- Control strategies (Module 5-3)
- Sizing thermal mass (Module 5-4)
- Flexibility and adaptability of the deign of natural ventilation systems (Module 5-5)

The design suggestions for the trade-off between critical performance mandates and the feasibility of natural ventilation are given in Chapter 5 and Chapter 6 respectively.

8.2 SIZING OPENINGS AND ESTIMATING THE AIR FLOW RATE (MODULE 5-1)

The scope of the models and the pressure loss issues in these models are illustrated in Figure 7.10.

8.2.1 Single zone model (Module 5-1-1)

8.2.1.1 *Estimate necessary air flow rate (5-1-1-A)*

The necessary air flow rate can be obtained from an estimation of the building cooling load q_i and application of Equation 8-1 to determine the desired air flow rate to remove the heat, or required air flow rate for maintaining acceptable indoor air quality. The larger result will be the necessary air flow rate.

$$q_i = C_p \rho Q (T_{in} - T_{out})\ .$$

Equation 8-1

$$Q = \frac{q_i}{C_p \rho (T_{in} - T_{out})}$$

Equation 8-2

q_i = building cooling load, W/m^2
C_p = specific heat of air, kJ/kgK
ρ = density of air, kg/m^3
Q = necessary air flow rate, m^2/s
T_{in} = indoor air temperature, °C
T_{out} = outdoor air temperature, °C

8.2.1.2 *Sizing openings*

8.2.1.2.1 Sizing openings for single-sided ventilation (Module 5-1-1-B)

If there will be one tall opening in the façade, according to the method provided by the CIBSE [9], the flow rate caused by wind is:

$$Q_w = 0.05 A v$$

Equation 8-3

A = the opening area, m^2
v = the wind speed at the building height, m/s

The stack-driven flow for a single-sided opening is:

$$Q_s = 0.2 A \sqrt{\frac{g h \Delta T}{T_{av}}}$$

Equation 8-4

g = gravity acceleration, m/s^2
h = the height of the opening, m
ΔT = inside-outside temperature difference, K
T_{av} = average of inside-outside temperatures, K

The total flow rate is:

$$Q_T = \sqrt{Q_w^2 + Q_s^2} = Q$$

Equation 8-5

Where Q = necessary air flow rate, m^2/s

Thus, the opening size $A = \frac{Q}{\sqrt{\frac{0.04gh\Delta T}{T_{av}} + 0.025v^2}}$

Equation 8-6

8.2.1.2.2 Sizing openings for wind-driven ventilation (Module 5-1-1-C)

The pressure drop between inlet and outlet openings can be estimated as:

$$\Delta P = \frac{1}{2}\rho v_{ref}^2 (C_{p-in} - C_{p-out})$$

Equation 8-7

v_{ref} = wind velocity at the reference height, m/s
C_{p-in} = pressure coefficient at the inlet opening
C_{p-out} = pressure coefficient at the outlet opening

The flow rate Q_A through the opening of equivalent area A should be equal to the necessary air flow rate:

$$Q_A = C_d A\sqrt{2\Delta P / \rho} = Q$$

Equation 8-8

C_d = discharge coefficient, 0.6 ± 0.1 for large openings

Thus, $\Delta P = \frac{1}{2}\left(\frac{Q}{C_d A}\right)^2 \rho$

Equation 8-9

So, $\frac{1}{2}\rho v_{ref}^2 (C_{p-in} - C_{p-out}) = \frac{1}{2}\left(\frac{Q}{C_d A}\right)^2 \rho$

The equivalent opening area of the zone is:

$$A = \frac{Q}{C_d V}\sqrt{\frac{1}{\Delta C_p}}$$

Equation 8-10

8.2.1.2.3 Sizing openings for stack ventilation (Module 5-1-1-D)

The pressure difference ΔP at a given height h above the datum level is given by:

$$\Delta P = \rho_{in} g(h - h_{NPL})\left(1 - \frac{T_{out}}{T_{in}}\right)$$

Equation 8-11

Applying Equation 8-8,

$$Q_A = C_d A \sqrt{2g(h - h_{NPL})\left(1 - \frac{T_{out}}{T_{in}}\right)} = Q$$

Equation 8-12

This equation is appropriate only for the situations for which there is no internal stratification. If stratification is present, such as in an atrium, the method introduced by the CIBSE can be used:

$$\Delta P = -g\rho_{s\tan} T_{s\tan}\left[h_a\left(\frac{1}{T_{out}} - \frac{1}{T_{ina}}\right) + h_b\left(\frac{1}{T_{out}} - \frac{1}{T_{inb}}\right) + etc.\right]$$

Equation 8-13

Where h_a and h_b are the height of the slice of the stack and $\rho_{s\tan}$ is the density of air at a reference temperature T_{stan}. T_{inn} is the temperature of the "n"th stratified layer.

In all the modules above, the equivalent opening area A related to the area of openings can be calculated by the following equation:

$$\frac{1}{A^2} = \sum_{i=1}^{i=j} \frac{1}{A_i^2}$$

Equation 8-14

Where A_i is the area of the "i"th element in the flow path.

8.2.1.2.4 Sizing openings for combined stack and cross ventilation (Module 5-1-1-D)

The method for sizing openings for combined stack and cross ventilation provided by the CIBSE can be used here. The detailed steps are adapted from pp.56-57, CIBSE Application Manual AM10:1997: Natural Ventilation in Non-Domestic Buildings (1997) and listed in Appendix A.

8.2.2 Multi-zone model (Module 5-1-2)

The multi-zone network model is based on the mass balance of each zone of the building or the pressure balance of each pressure loop and the assumption that the air within each zone is well mixed. The building is treated as a series of interconnected zones (Figure 8.1). Since the mass flow rate $\dot{m} = \rho Q$, in zone i with j flow paths gives:

$$\sum_{m=1}^{j} \rho_i Q_{im} = 0$$

$$Q = k\Delta P^n$$

Q = air flow rate, m^3/s

k = flow coefficient

n = flow exponent, n = 0.6~0.7 for cracks and n = 0.5 for large openings like windows

Or, in each air flow path or loop, by defining the desired air flow rate to each opening, the pressure difference can be expressed in terms of the air flow rate, e.g. for a large opening, $Q = C_d A\sqrt{2\Delta P/\rho}$, so $\Delta P = \frac{\rho Q^2}{2C_d^2 A^2}$, then add all pressure differences in a loop together, and $\Sigma\Delta P = 0$. Continue until all the loops are defined. Finally, the size of each opening can be solved.

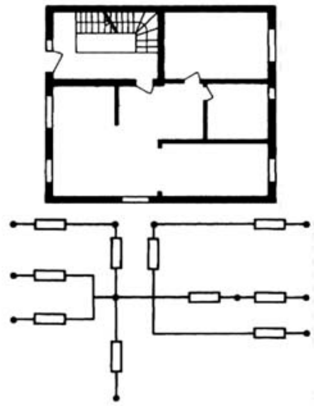


Figure 8.1 Network representation of a multi-zone building [79]

Available computer tools based on the multi-zone model are VENT, COMIS, CONTAM, and LoopDA [80], etc. Figure 8.2 and Figure 8.3 illustrate the flow paths of a building modeled by LoopDA.

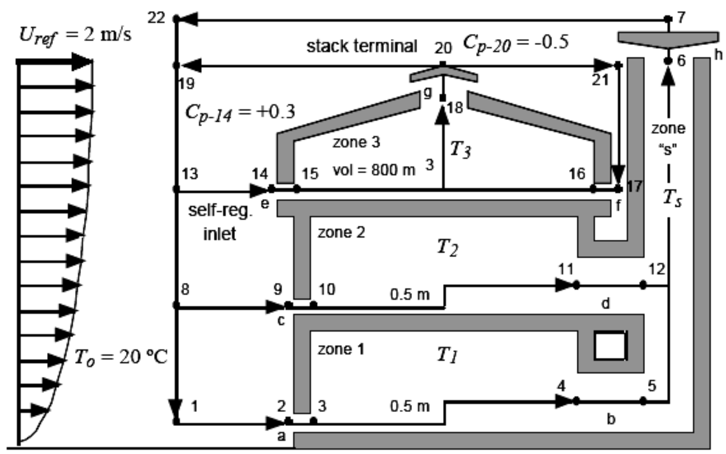


Figure 8.2 Global geometry, topology, and pressure nodes for the ventilation flow loops of a building model based on the Inland Revenue Building, England [80]

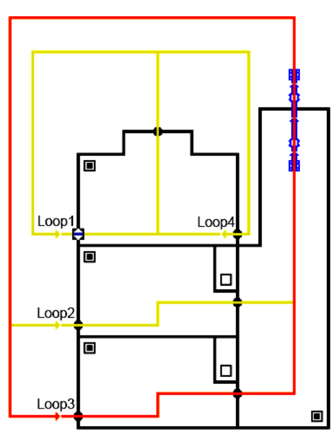


Figure 8.3: Pressure loops of the building in Figure 8.2 [80]

In a calibration study of a multi-zone model CONTAM97R, which compared measured and predicted results, Axley et al. (2002) state that macroscopic multi-zone tools provide "essential spatial and temporal details that can guide system design relating to both whole-building and inter room air distribution and thermal performance." [81]. In certain cases when greater details are required, CFD is used for performance evaluation in individual rooms.

The overall flow chart for sizing openings is shown in Figure 8.4.

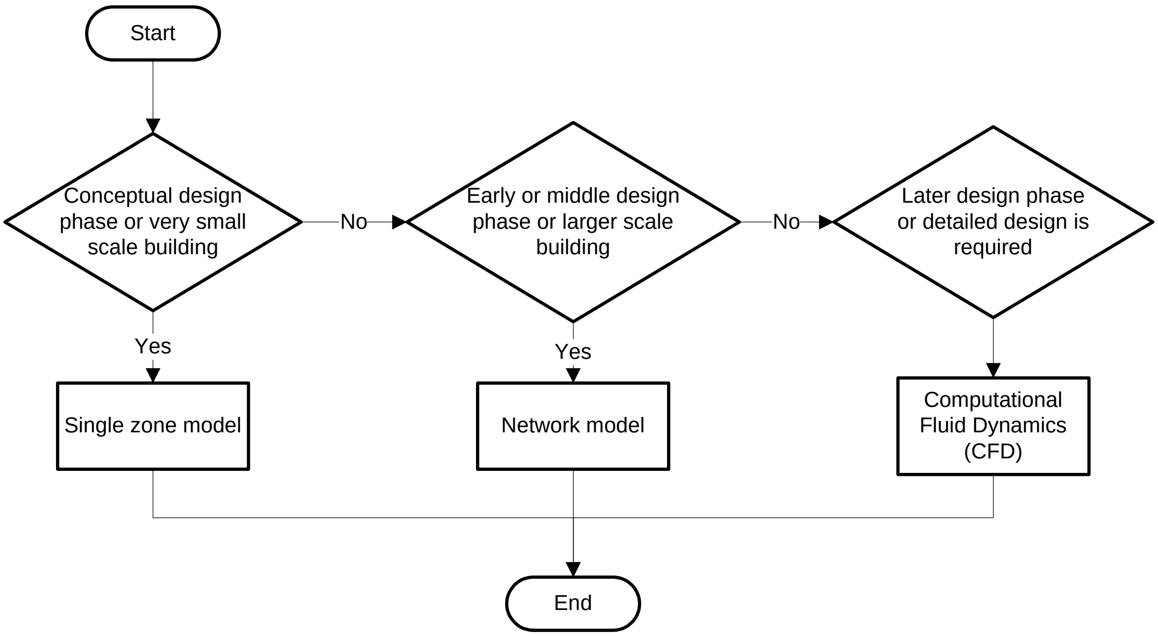


Figure 8.4 Flow chart for sizing openings or estimating air flow rate

8.3 DESIGN SUGGESTIONS FOR DRAFT PREVENTION (Module 5-2)

8.3.1 Draft control in naturally ventilated high-rise buildings

Draft is the unwanted local cooling of the body caused by air movement. Because wind speed increases with the height above the ground, attention to potential drafts should be paid for naturally ventilated high-rise buildings. Even during calm conditions, a lift or buoyancy boundary layer resulting from the temperature difference between the building and outside air may be significant. That is considerably affected by the incident radiation and the solar absorption coefficient of the building envelope. On hot windless summer days, the temperature difference may be significantly greater than 20K. Maximum air velocities in the boundary layer due to buoyancy on the façade are listed in Table 8.1. For a building of 100m height, when $\Delta T > 20K$, the resultant maximum air velocity is higher than 4m/s.

Table 8.1: Maximum air velocity in a boundary layer due to thermal buoyancy on the façade (Developed based on Figure 114 in [15], p. 101)

	Maximum air velocity (m/s)			
Height (m)	ΔT=5K	ΔT=10K	ΔT=20K	ΔT=50K
0	0	0	0	0
50	1.50	2.10	3.00	4.80
100	2.20	3.00	4.40	6.85
150	2.70	3.75	5.35	8.40
200	3.10	4.35	6.10	9.70

The flowing approaches are helpful to prevent drafts for naturally ventilated high-rise buildings. They are also good for buildings in high-wind sites.

First, windward/leeward separation can reduce drafts. The layout can be divided in a way that rooms are clearly oriented to either the windward or the leeward side of the building. The two sides should be separated from each other by self-closing, tightly sealing doors, or, even better, by air locks with two sets of doors. The system has to function for wind from all directions. (Figure 8.5)

Second, a double-skin façade can be used to prevent drafts. A façade with an intermediate buffer space can be used around the entire building. By creating a bypass air stream through the intermediate space, a state of pressure equilibrium that decreases pressure difference can be achieved on the different sides of the building. The types of double-skin facades are limited to corridor façades or multi-story facades. The greater the external pressure difference that has to be reduced, the greater the depth of the façade; intermediate space should be relative to the size of the openings in the external skin.

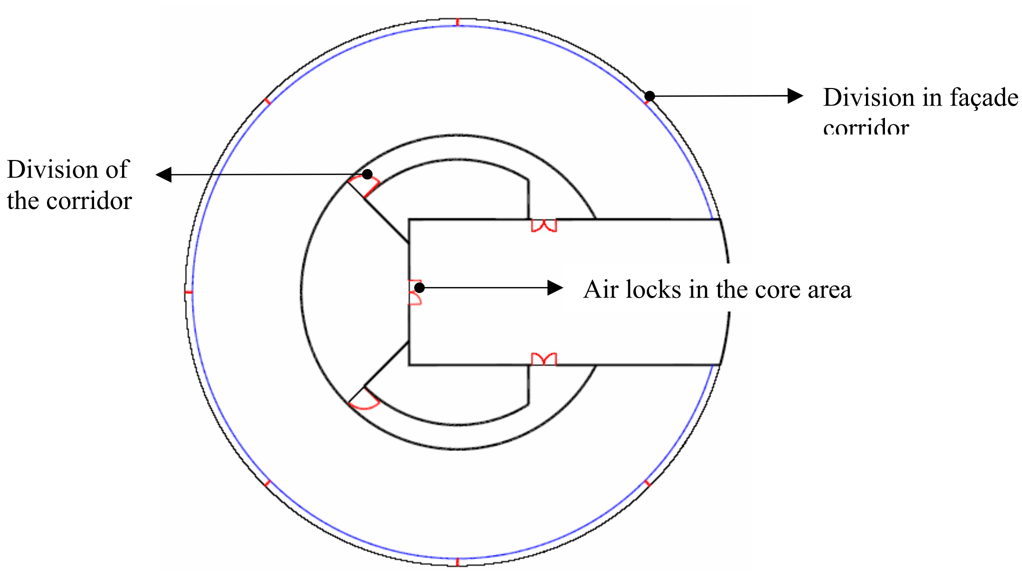


Figure 8.5 Example of measures to achieve a windward/leeward separation by closing off compartments in the layout and in the façade, Business Tower, Muremburg [62]

Finally, self-adjusting openings are good for high wind conditions. Windows should be shut when air speed exceeds 10m/s [15]. Keeping doors closed during average wind velocity (up to 5m/s) will result in low differential pressure and a problem-free environment.

8.3.2 Winter Ventilation

The strategies to prevent drafts in winter ventilation include:

- Temper inlet air with exhaust air by heat recovery
- Preheat inlet air by running across heating coils. If the driving force of natural ventilation is great enough, heating coils with low-pressure drops may be used to pre-treat the outside air before it enters the building [14].
- Trickle ventilation
- Good mixing design occurring before the air reaches people

In a comparison of different window types, Heiselberg et al.[73] found that for single-sided ventilation, the bottom-hung window is the best among most types of windows in winter because the air is supplied outside the occupied zone and can be controlled by changing the opening angle. A side-hung window is not recommended, as the air is supplied directly to the occupied zone and is difficult to control because the amount of air and the velocity levels increase very rapidly with increasing opening angles. For cross or stack ventilation the bottom-hung window is also the best choice in winter, because the air travels the largest distance before it reaches the occupied zone, and the velocity levels, therefore, will be the lowest. For the side-hung window, the problems are even worse compared to the single-sided situation because the pressure difference is increased.

The decision process for draft prevention is illustrated by the flow chart in Figure 8.8.

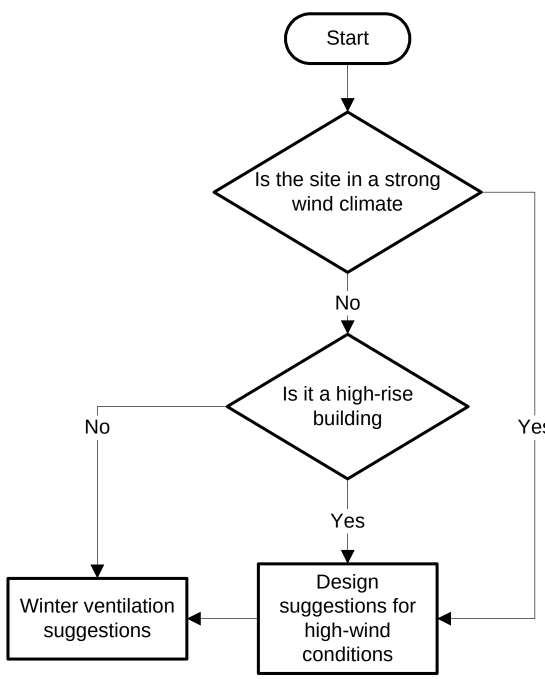


Figure 8.6 Flow chart for draft prevention

8.4 DESIGN SUGGESTIONS FOR CONTROL STRATEGIES (Module 5-3)

The scope of control in a naturally ventilated building often includes control for rain protection, control of air flow rate, control for fire prevention, control for indoor acoustical environment, control for security, and control for solar heat gain. Robust building management systems are needed in naturally or hybrid-type ventilated non-residential buildings.

Rain detectors are often combined with wind speed and direction sensors. Vents are shut when "both factors introduce a risk" [16]. Temperature, humidity, wind speed and direction should be monitored. It is essential to control air flow rate both for cooling and indoor air quality. Air flow rate can be controlled by opening/closing windows, opening/closing louvers or dampers, adjusting opening size, activating fans, or transferring from the natural ventilation mode to a mechanical ventilation mode. Demand control using CO_2 monitoring is suited for buildings with a variable occupancy, such as gymnasiums, auditoriums, and meeting rooms. It is also good for verifying the achievement of higher IAQ requirements in buildings. In order to control for fire propagation, monitoring temperature and smoke, alarming occupants, and controlling openings, automatic-closing fire doors, fire windows and shutters, or activating fire ventilation and/or suppression systems are necessary. Control for the indoor acoustical environment can be achieved by monitoring noise intensity levels and adjusting the exterior and interior openings and ventilation dampers. Openings may be closed intermittently, which is good for buildings in a noisy site and/or spaces with higher acoustic performance requirement. To control solar heat gain, a shading device can be adjusted to limit solar heat gain if adjustable shading devices are used.

8.5 SIZING THERMAL MASS (Module 5-4)

The benefits of natural ventilation can be extended by proper utilization of the thermal mass in the building. For sizing the thermal mass there are rule-of-thumb and simplified spread sheet methods introduced by Stein and Reynolds in *Mechanical and Electrical Equipment for Buildings* (1992) and Brown and Dekay, in *Sun, Wind and Light* (2001). These methods can be adopted into the framework. Detailed descriptions of the decision steps using these methods are listed in Appendix D.

8.6 FLEXIBILITY AND ADAPTABILITY OF THE DESIGN OF NATURAL VENTILATION SYSTEMS (Module 5-5)

The flexibility and adaptability of natural ventilation systems allows the consideration of adding supplementary mechanical cooling after the building has been occupied, which generally includes the following aspects:

- Provide enough ceiling height for installing mechanical system with floor plenum or suspended ceiling;
- Plan for the space and location for mechanical plant;
- Plan for future distribution routes in the design.

CIBSE gives an example of these considerations ([6], Figure 4.1, p. 24). Such design strategies are also called contingency mixed mode approaches.

To evaluate if the flexible design (contingency mixed mode), natural ventilation system only or a hybrid system is suitable to the building, Greden et al. (2006) proposed a simulation model, Natural Ventilation Option Valuator (NVOV) [82], that may be included in the framework. It is similar to an energy simulation tool for feasibility assessment, but the simulation is conducted over a multi-year period with stochastic outdoor temperature variable. One result is the possibility of distribution of the time when the maximum allowable indoor temperature with natural ventilation is exceeded. Several temperature standard deviations and trends are assessed for the sensitivity of the results. Thus, when the results show that a natural ventilation system cannot cool the building for all of the hours, but the immediate need for a hybrid ventilation system is not necessary, users can estimate if future climate continues to be suitable for natural ventilation, and if it is economic to install the mechanical system.

The flow chart in Figure 8.7 illustrates the decision process for flexibility and adaptability.

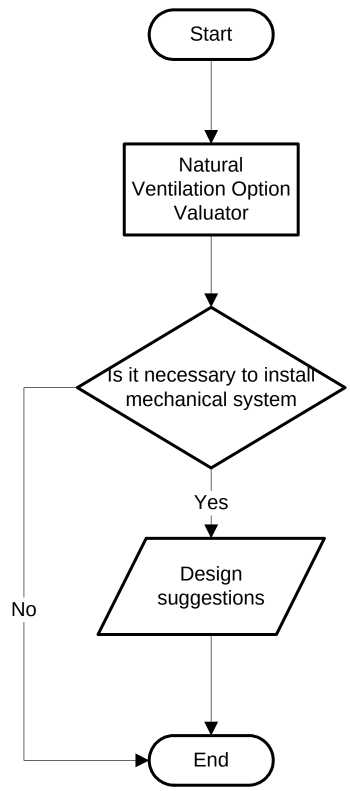


Figure 8.7 Flow chart for flexibility and adaptability

CHAPTER 9 PERFORMANCE ASSESSMENT

The performance assessment has five modules: energy saving assessment, thermal comfort assessment, indoor air quality assessment, acoustical effect assessment, and cost assessment.

9.1 ENERGY SAVING ASSESSMENT (MODULE 4-1)

An important potential benefit of natural ventilation is lower energy consumption. The decision-support framework proposes a simplified assessment approach, which is good for comparative assessment rather than prediction of absolute savings of each alternative.

For the approaches with natural ventilation only, the following procedures are used to assess performance:

1. Calculate the hourly heat gain rate
2. Estimate hourly air flow rate in the space with the design opening sizes (see Module 5-1-1 and Module 5-1-2)
3. Estimate the heat removal rate (Equation 8-1) vs. the rate of heat gain for each hour
4. Sum the estimated number of hours per year when natural ventilation can effectively remove heat from the building
5. Sum the heat removal for all applicable hours
6. Compare the heat removal of alternative ventilation approaches.

For the approaches with hybrid ventilation systems, an energy simulation for the whole system may be needed to determine which approach results in the lowest level of energy consumption.

The assessment procedures are shown in Figure 9.1.

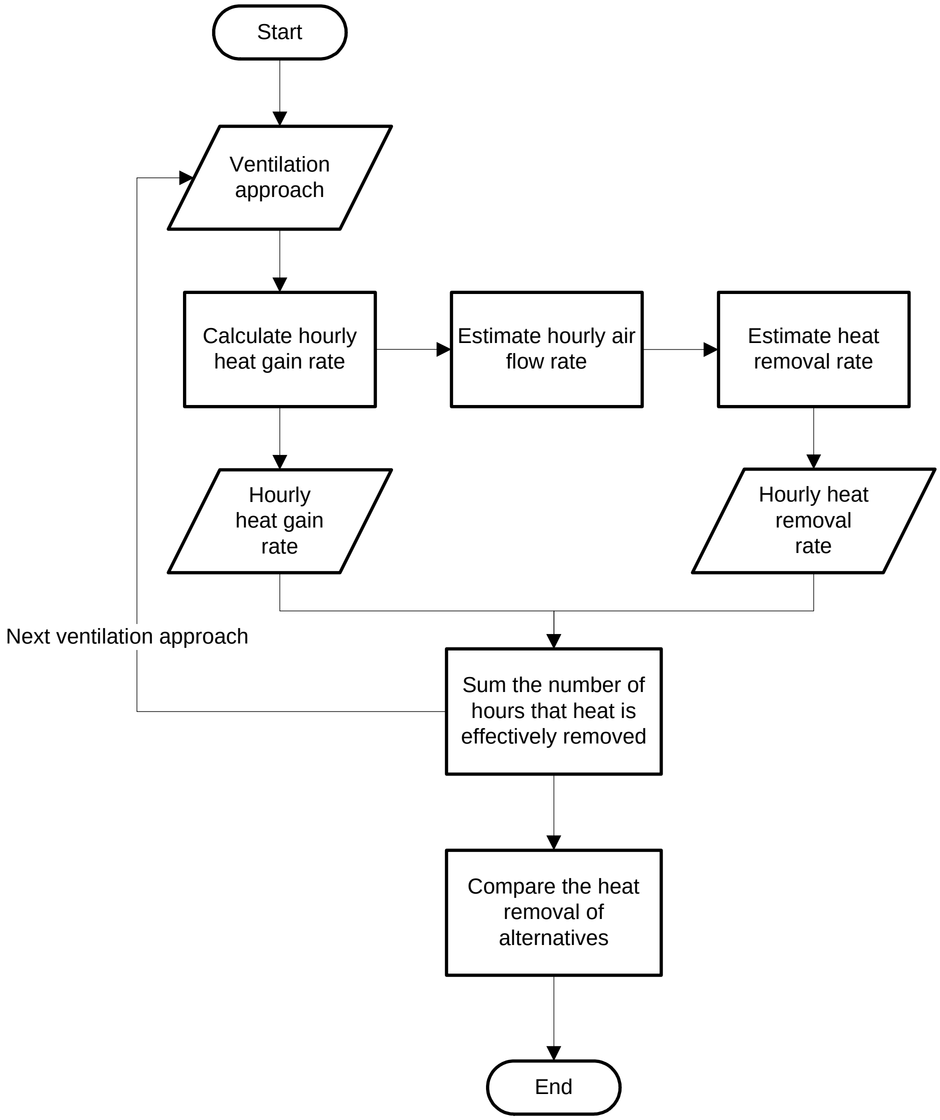


Figure 9.1 Flow chart for energy performance assessment

9.2 THERMAL COMFORT ASSESSMENT (MODULE 4-2)

Performance assessment of thermal comfort is constrained by the conditions specified in ASHRAE Standard 55-2004. The combined effects of temperature, humidity, radiation, and air movement are assessed. The adaptive model [66] is used to assess indoor operative temperatures. As suggested by ASHRAE Standard 55, for "more extreme conditions,"the conditions for drafts and allowable limits for turbulence intensity can be determined according to the requirements on the local discomfort criteria. For comparison of alternative natural ventilation strategies, the constraints can be applied to a proposed assessment procedure that might include the following steps using TMY data and the given inputs:

1. Hourly air flow rate estimation in the building (Module 5-1-1 and Module 5-1-2)
2. Estimate heat removal rate vs. the rate of heat gain for each hour

3. Estimate the temperature rise in the occupied zone. In this step, the linked thermal-air flow models are needed to estimate temperature in the occupied zone, for example, EnergyPlus with COMIS was used in thermal comfort assessment in the design for the New San Francisco Federal Building.
4. Estimate the humidity level. Currently, no simplified methods for estimating the indoor humidity level are available. For the early design phase, in this framework, if the outdoor relative humidity is compliant with the requirements in the feasibility assessment for the indoor humidity level, it is considered acceptable, except for buildings with high internal latent heat gain, such as assembly buildings with high occupant density. In this case, CFD simulations may be needed.
5. Compare the resulting air flow rates, temperatures, and humidity to the constraint functions. This step includes the following assessments:

(1) Temperature assessment (Module 4-2-1)

The adaptive model is used to assess the indoor thermal comfort conditions, which already accounts for people's clothing adaptation and local thermal discomfort effects. No humidity limits and air speed limits are set [83]; 80% acceptability limits are used in the framework. Therefore, the criteria are translated as follows:

- 15.8°C $\leq T_i \leq$ 22.8°C for the mean monthly outdoor air temperature T_o < 5°C
- $T_{i\text{-}upper} = \frac{9}{28}T_o + 20.4$ °C, and $T_{i\text{-}lower} = \frac{9}{28}T_o + 13.4$ for 5°C $\leq T_o \leq$ 33°C
- 23.7°C $\leq T_i \leq$ 31.8°C for T_o > 33°C

Where T_i is the indoor operative temperature, and T_o is the mean monthly outdoor air temperature, $T_{i\text{-}upper}$ is the upper limit of indoor comfort temperature, and $T_{i\text{-}lower}$ is the lower limit of indoor comfort temperature.

(2) Humidity assessment (Module 4-2-2)

Humidity ratios <0.012 at the comfort zone and RH<70% at the extended comfort zone are allowed.

(3) Draft risk assessment (Module 4-2-3)

For greater detailed performance assessment, indoor air speeds are predicted by CFD simulation. The draft risk for certain conditions can be assessed with Module 4-2-3 with local discomfort criteria in Section 5.2.4 of 2004-ASHRAE Standard 55. The predicted percentage of people dissatisfied (PD) due to draft is a function of local air temperature, air speed, and turbulence intensity (Equation 9-1). If PD < 15%, the risk of draft is low.

$$PD = (34 - T_{in})(V - 0.05)^{0.62}(0.37VT_u + 3.14)$$

Equation 9-1

Where PD = the percentage of occupants feeling draft

V= mean air speed, m/s

T_{in} = air temperature, °C

T_u = Turbulence intensity in %, $T_u = 100\frac{V_{sd}}{V}$,

V_{sd} = Standard deviation of the velocity

6. Sum the annual number of hours for each alternative when the constraint functions are satisfied.

The overall flow chart for comfort assessment is shown in Figure 9.2.

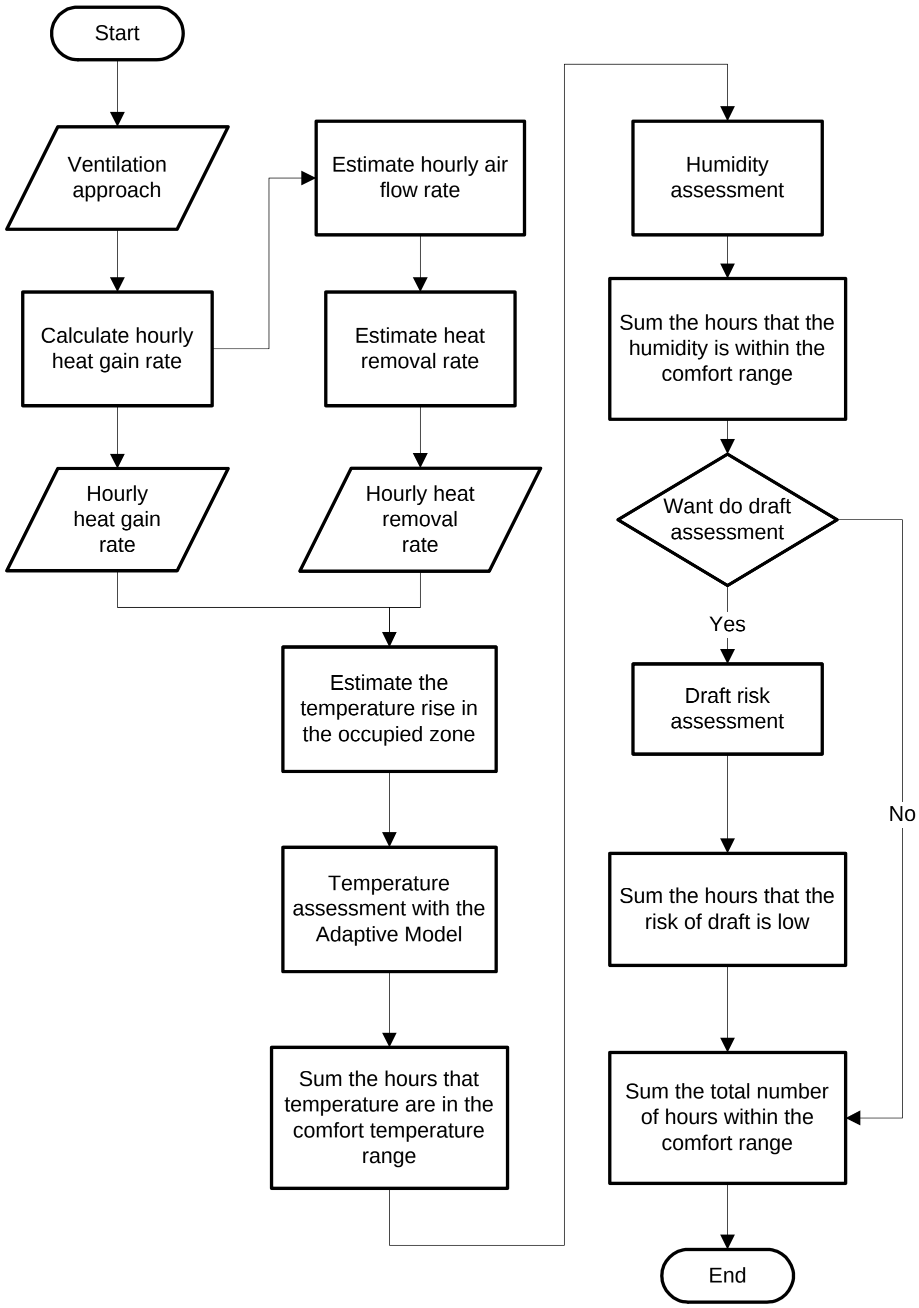


Figure 9.2 Flow chart for comfort assessment

9.3 INDOOR AIR QUALITY ASSESSMENT (MODULE 4-3)

A third performance mandate is indoor air quality. If the proposed building passes the preliminary IAQ feasibility assessment, then the relative performance of the alternative natural ventilation strategies should be evaluated. The IAQ assessment includes evaluation of two performance criteria: ventilation flow rate and ventilation effectiveness from ASHRAE Standard 62. For ventilation flow rate the following steps are proposed:

1. Estimate air flow rate (Module 5-1-1 and Module 5-1-2)
2. Estimate the average air flow rate per unit floor area and volumetric air change per hour, compare to ASHRAE Standard 62 minimum requirements for outdoor airflow.
3. Ventilation effectiveness assessment

Addressing ventilation effectiveness will be concerned with uniformity of distribution and the relative size and location of inlets and outlets. The rules-of-thumb to compare the ventilation effectiveness of each ventilation approach qualitatively can include the following aspects:

(1) No shortcuts in the ventilation flow path;

(2) Flow across the occupied zone;

(3) No undesired direction of flows, such as the backflow from exhausting shafts;

(4) The distribution of inlets and outlets ensuring the uniformity distribution of airflow;

(5) Displacement ventilation is used.

One credit can be given to an approach if one of the criteria above is met. Therefore, a higher total score suggests the approach is achieving better ventilation effectiveness. However, detailed flow distribution and air speeds in the space should be estimated with CFD for a more reliable judgment. Figure 9.3 shows the process of the indoor air quality assessment.

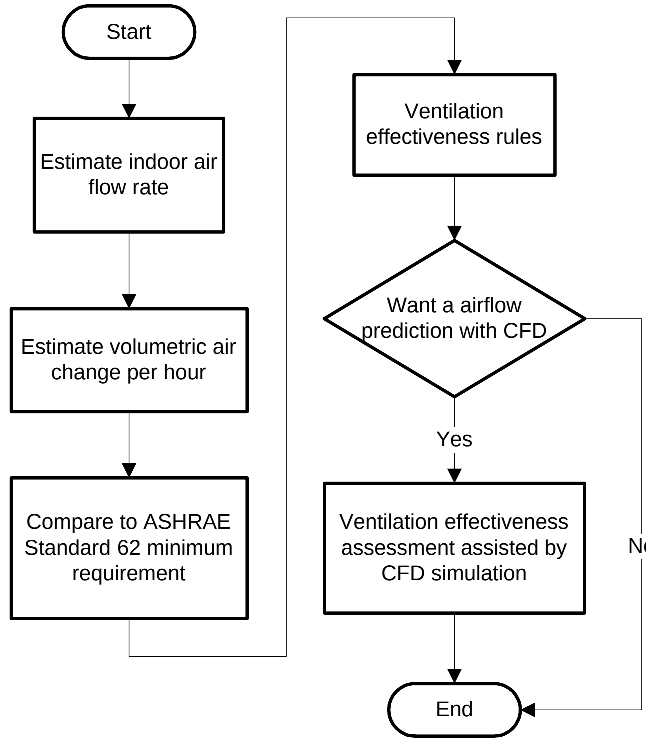


Figure 9.3 Flow chart for IAQ performance assessment

In the airflow rate estimation of Module 4-1, 4-2 and 4-3, using linked thermal and airflow models is highly recommended.

9.4 ACOUSTIC PERFORMANCE ASSESSMENT (MODULE 4-4)

To assess noise levels inside the building, estimated indoor noise intensity levels are compared to published noise criteria ratings for the given building functions. The suggested procedure estimates the attenuation of the ambient noise levels through the envelope openings into the occupied zone. Then, for the worst-case condition (i.e. direct line of sight), the estimated noise levels are compared to the constraint functions. Sounds with information content transmitted from major indoor sources, such as from an adjacent meeting room through ventilation openings, are also assessed for speech privacy.

The assessment procedures are:

1. Estimate the attenuation of ambient noise levels through the envelope openings to the occupied zone (with the worst case condition, see Module 2-2).

2. Estimate the levels of the noise transmitted from major indoor sources through ventilation openings, if the sources exist. The method is the same as the method used in Module 2-2. The noise reduction includes the transmission loss through the partition wall and the absorption characteristics of the receiving room.

3. Calculate the combined noise levels in the receiving room and compare with recommended noise levels that can be easily found in the literature. For example, Table 9.1 lists the recommended noise criteria for steady background noise [56].

Table 9.1 Recommended noise criteria range for steady background noise

Type of Space	NC curve	Approximate dBA
Concert halls, opera houses and recital halls	10-20	20-30
Broadcast and recording studios	15-20	25-30
Large auditoriums, large drama theatres, and houses of worship	20-25	30-35
Broadcast, television, and recording studios	20-25	30-35
Small auditoriums, small theatres, small churches, music rehearsal rooms, large meeting and conference rooms(for good listening), or executive office and conference rooms for 50 people (no amplification)	25-30	35-40
Bedrooms, sleeping quarters, hospitals, residences, apartments, hotels, motels, and so forth(for sleeping, resting, relaxing)	25-35	35-45
Private or separate offices, small conference rooms, classrooms, library, and so forth (for good listening conditions)	30-35	40-45
Living rooms and similar spaces in dwellings	35-45	45-55
Large office, reception areas, retail shop and stores, cafeterias, restaurants, and so forth(for moderately good listening conditions)	35-50	45-60
Lobbies, laboratory work spaces, drafting and engineering rooms, general secretarial areas (for fair listening conditions)	40-45	50-55
Light maintenance shop, office and computer equipment rooms, kitchens and laundries(for moderately fair listening conditions)	45-60	55-70
Shops, garages, power-plant control rooms, and so forth (for just acceptable speech and telephone communication). Levels above PNC-60 are not recommended for any office or communication situation.	-	-

4. Level of disturbance (Module 4-4-2)

If indoor noise sources exist, most likely they are sounds with information content, which can be transmitted through openings from adjoining rooms. The degree of disturbance can be determined by comparing the required background noise of the receiving room and the sound level in the receiving room resulting from the source of speech sound. If the difference from background noise is greater than zero, the disturbance could be annoying. The assessment procedures are illustrated with the flow chart in Figure 9.4.

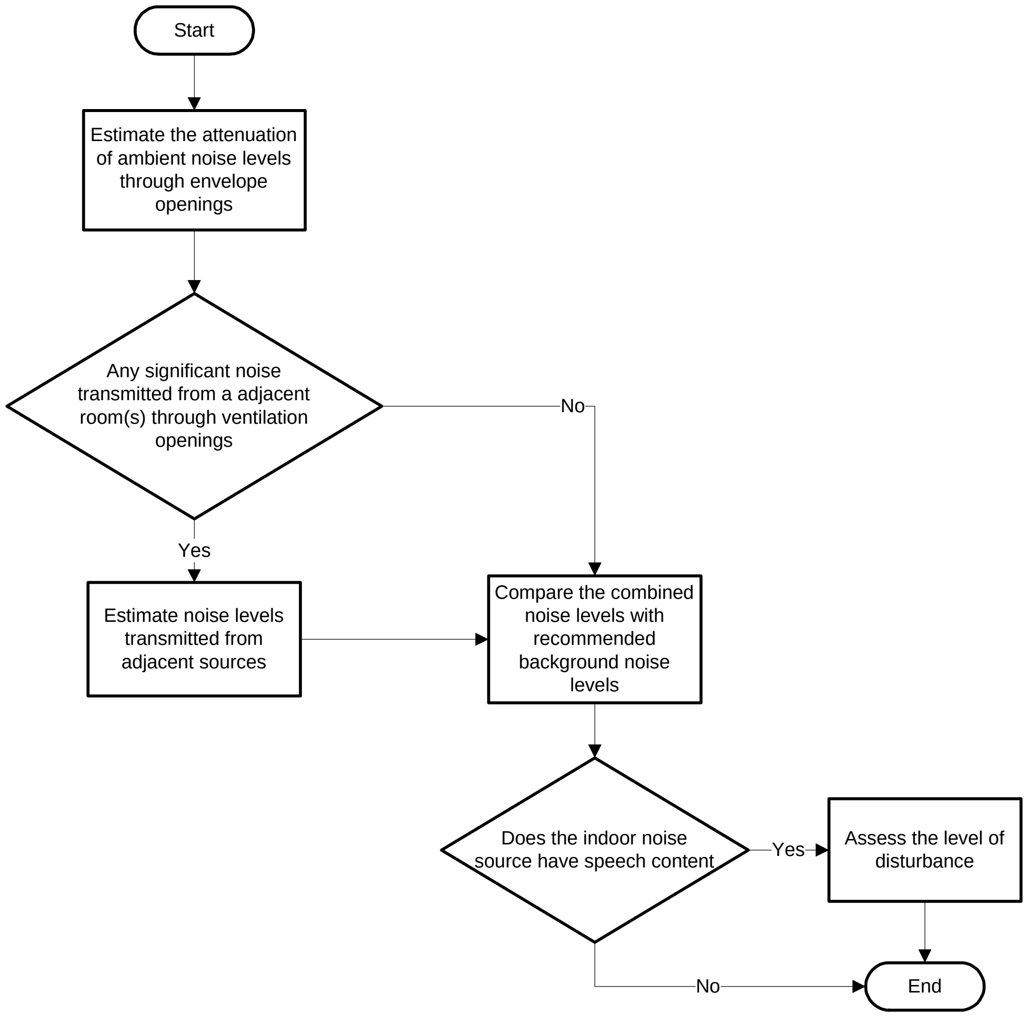


Figure 9.4 Flow chart for acoustic performance assessment

9.5 COST ASSESSMENT (MODULE 4-5)

Ideally, a detailed life cycle cost evaluation of alternative natural ventilation system approaches should be performed. In early design phases, relative comparison of design features and natural ventilation system elements should be assessed. In the framework, because the comparison is only between those natural or hybrid ventilation approaches, the assessment can be simplified based on the method of Ghiaus and Roche [41], in which only the incremental cost and benefits related to these alternatives are considered. The major inputs of cost comparison include:

- Initial costs include the cost of ventilation systems and building elements associated with natural ventilation. Initial costs also include the cost increase associated with building components such as an atrium, if it is not used in all approaches, as well as devices such as monitoring and control system (if any) and mechanical assistance system (if any).

- Operation costs include maintenance costs, energy consumption (such as the energy used for mechanical assistance), and energy savings.
- Replacement costs include the replacement cost of some components with short lifespan. To simplify the method, the replacement cost of components with long life spans may be ignored.
- Determine the discount rate.
- Determine the time period to be investigated.

The cost comparison calculation can be easily done with a spreadsheet. The discounted cost or benefit is calculated for each year by multiplying the total cost or benefit for each year with the discounting factor, $1/(1+I)^n$, where I is the interest rate and n is the year from the start. Then the total discounted cost or return is summed for the total cost or returns for the period investigated. An example is given by Ghiaus and Roche in [41], p. 227-235.

A major hidden cost or benefit is the cost resulting from the impact on worker productivity. Productivity is influenced by thermal comfort, IAQ, and acoustics. However, productivity can be difficult to quantify. The quantitative relationships between productivity and performance mandates are currently not available. The default assessment, therefore, excludes productivity and focuses on the life-cycle cost of the building system itself. When considering the cost of employment, a linear relation of productivity to performance mandates can be assumed for the preliminary assessment. Thus, the cost of total salary adjusted by productivity can be estimated by multiplying a coefficient that is inverse to the standardized value of the sum of the three performance scores. The alternative with the best overall performance will tend to be the one with the higher performance of thermal comfort, indoor air quality, and acoustics, when compared to the results of the default assessment with productivity excluded.

9.6 NORMALIZATION

Before comparisons between alternatives can be made, two additional decision making steps are necessary. These include first obtaining a normalization scale for each performance mandate outcome. For example, estimation of thermal comfort conditions can be scaled from 0 to 1, 0 being total failure to meet a performance mandate and 1 being total compliance. Or, a set of performance outcomes can be normalized as: [84]

$$f(x_j) = \frac{x_j - \min x_j}{\max x_j - \min x_j}.$$

Equation 9-2

Where $\max x_j$ and $\min x_j$ indicate the maximum and minimum value observed for objective x_j among all alternatives. In this normalization method, only comparison between the values of $f(x_j)$ is important to the evaluation.

In addition to the quantifiable performance factors, qualitative assessment data are also presented in this framework. Users may also define or select some intangible criteria of environmental quality to assess the natural ventilation approaches. The scores can also be translated into the scale of value from 0 to 1, worst to best.

Therefore, based on the normalization methods described above, the scores of each alternative for each performance mandate can be obtained in the following way.

For the energy saving assessment, the output is the heat removal of alternative ventilation approaches. For the thermal comfort assessment, the output is the annual number of hours for each alternative when the constraint functions for temperature, humidity, and draft are satisfied. The outputs of these assessments can all be normalized with Equation 9-2; therefore, the result for an alternative i can be defined as $P_{i1} = f(E_i)$ and $P_{i2} = f(T_i)$, where E_i is heat removal of ventilation approach i, and T_i is the annual number of hours when thermal comfort is achieved.

The outputs of IAQ assessment include the total hours that the minimum outdoor airflow rate is achieved and the number of criteria achieved for ventilation effectiveness with an alternative approach. The hours and the number of criteria achieved can be simply normalized separately to obtain the score Q_{1i} and Q_{2i} for alternative i. Then, the average value of each pair of Q_{1i} and Q_{2i} is taken as the final output of the performance score of IAQ for each alternative, i.e. $P_{i3} = (Q_{1i} + Q_{2I})/2$.

In the acoustic performance assessment, the upper limit of the background noise level requirement is defined as N_b. Since the background noise level requirement should be met, if the predicted indoor noise level is higher than N_b, the alternative will fail the assessment and will not be compared with other alternatives in the following steps. Therefore, for alternative i, if $A_{ni} > N_b$, alternative i is invalid; if $A_{ni} \leq N_b$, the normalized performance score for indoor noise level is $A_{1i} = f(N_b - A_{ni})$, where A_{ni} is the predicted indoor noise level of an alternative. The standardized performance score for the level of disturbance is defined as $A_{2i} = f(N_b - A_{si})$, where A_{si} is the speech sound level in the receiving room. If $N_b - A_{si} < 0$, the alternative fails the assessment and will not be compared with other alternatives. The final score is $P_{i4} = (A_{1i} + A_{2i})/2$.

In the cost assessment, the LCC of alternatives C_i will also be normalized with Equation 9-2, i.e. $P_{i5} = f(C_i)$.

9.7 WEIGHTING AND RANKING

Because ranking design approaches needs to examine several performance factors, the multi-purpose optimization method is used to assess the performance of alternative natural ventilation system design approaches by weighting these factors. Therefore, the second step involves weighting the relative importance of each performance mandate. For example, when comparing and selecting between natural ventilation alternatives, if the building is a library, the acoustic performance may have higher relative importance to the other mandates. While these weightings are often applied intuitively, surveys are needed in future study to gather these weightings for various typical uses of buildings from experienced professionals as benchmark and default values of weightings in the framework.

For alternative i (i =1, ...i) and factor j (j = 1, ... j), the performance of alternative i on factor j is defined by P_{ij}. With a set of normalized weightings ω_j ($\sum_{j=1}^{k} \omega_j = 1$), the overall performance score of an alternative i is $P_i = \sum_{1}^{j} \omega_j p_{ij}$ (Table 9.2). Thus, system design approach alternatives can be ranked. The vectors of the performance elements P_{ij} are illustrated with a radar diagram (Figure 9.5).

Table 9.2 Example of weighting approach

	1. Energy Saving	2. Thermal Comfort	3. IAQ	4. Acoustic performance	5. Cost	Total
Weightings (ω_j)	0.3	0.2	0.2	0.1	0.2	1.0
Alternative 1	$P_{11} = 0.7$	$P_{12} = 0.65$	$P_{13} = 0.9$	$P_{14} = 0.5$	$P_{15} = 0.85$	$P_1 = 0.74$
Alternative 2	$P_{21} = 0.6$	$P_{22} = 0.8$	$P_{23} = 0.9$	$P_{24} = 0.75$	$P_{25} = 0.4$	$P_2 =$ 0.675

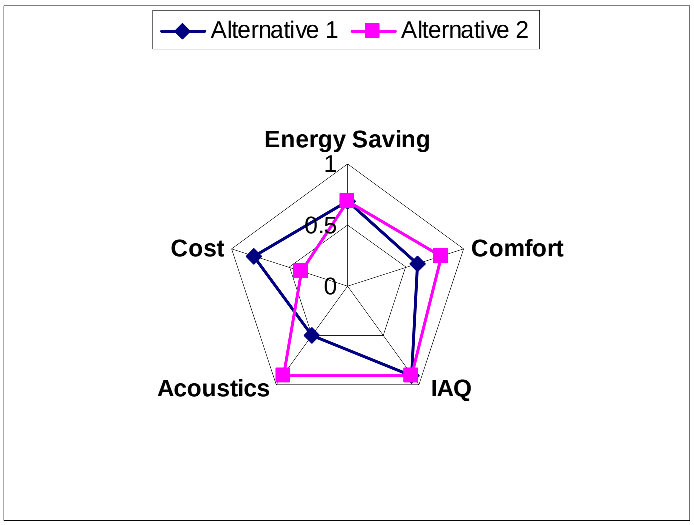


Figure 9.5 The vectors of the performance elements P_{ij}

The overall flow chart for the performance assessment module is shown in Figure 9.6.

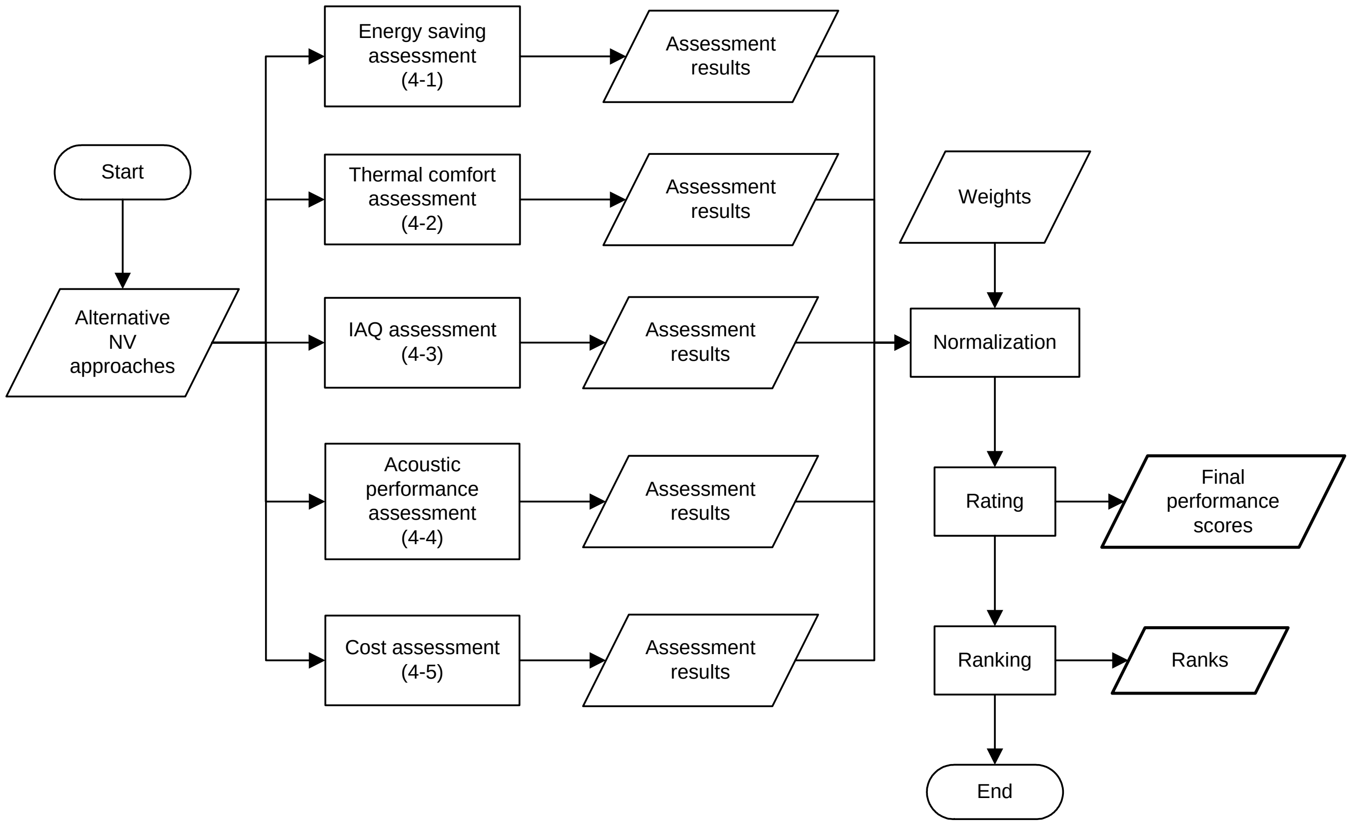


Figure 9.6 Overall flow chart for performance assessment module

9.8 CONCLUSION

The scope and procedures of performance assessments are presented in this chapter. After normalization and assignment of weightings, alternative ventilation approaches can be ranked.

CHAPTER 10 CRITICAL REVIEW AND FEEDBACK

10.1 INTRODUCTIONS

As introduced in Chapter 1, in order to gain critical review and feedback for the framework, comments from experienced professionals and researchers are solicited. The dissertation reviewers (Reviewer I, II and III) include two mechanical engineers with experience designing naturally ventilated buildings, and one researcher whose area of research is thermal performance of buildings and HVAC system selection and design. In addition, the comments from the reviewers (Reviewer IV to VII) of the *ASCE Journal of Architectural Engineering* and the *ASHRAE Journal* for the paper "Decision-support for Natural ventilation Non-residential Buildings" are also included. Before the contents of this paper were included in the dissertation, they had been revised according to the comments from the *ASHRAE Journal* reviewers. In this chapter, the comments from the dissertation reviewers and the *Journal of Architectural Engineering* are cited and summarized. The themes or common issues from the reviewers are summarized first, and then comments on specific reviewer issues are included. Any changes to the framework are included here as well. The detailed reviewer comments are included in the appendix. Those comments and suggestions which could not be incorporated are addressed as future developments or concerns in the final chapter.

10.2 SUMMERY OF THE COMMON ISSUES OF REVIEWERS' COMMENTS, CHANGES AND DISCUSSION

10.2.1 The usefulness of the framework

Generally, the reviewers approve the usefulness of the framework. They state that the framework "is thorough and could prove to be useful for designers" and is "a great attempt to pull together a detailed logic path to evaluate and provide decision criteria for naturally ventilating a building"." Reviewer IV states that "the decision-support tool will be of great value to the profession." As suggested by the reviewer, the timeline for the completion of the tool, the platform it will run on, and expertise needed to use it, are added as requested.

10.2.2 The level of details

Because it is emphasized that the framework is for early design phases, reviewer I cautioned that "it is important to keep in mind the limited available detail in the early stages of a design." Reviewer III stated that the framework is "overly complicated." Detailed inputs should be limited in the framework.

To clarify the presentation of the framework, the following changes have been made: Introducing the modules of environmental input transformation and estimation in Chapter 6 and supplying all the descriptions of the modules in an appendix if necessary.

10.2.3 Validation method

No dissertation reviewer disagreed with the validation method. The reviewers from *ASHRAE Journal* prefer to see the tool or portion of the tool, along with validated results, being presented and discussion of one or two examples of the framework on a project, so that the readers can better understand and follow the framework.

Developing and testing the tool will be a goal for future work. As discussed in Chapter 1, using built examples to validate the framework has its limits.

10.2.4 Critical issues

All the reviewers agreed that the critical issues were captured in the framework. In addition, some reviewers suggested other factors that could be included; they are:

- Humidity/moisture
- Local climate
- Outdoor/ambient air quality

However, the critical issues are captured in terms of the outcome or the performance of the naturally ventilated buildings, or the designer/client's objective intention that has critical influence on the decision-making. For example, although outdoor air quality is directly related to indoor air quality, as a critical issue, indoor air quality is typically what the designer is finally interested in,; therefore, outdoor air quality is not considered as a critical issue other than on its indirect influence on indoor air quality. Similarly, local climate conditions are important inputs. Humidity/moisture issues are critical for the feasibility and performance of natural ventilation, as they directly relate to thermal comfort and indoor air quality, and probably indirectly to energy savings and costs.

Condensation and moisture control problems potentially happen when a building is naturally ventilated. Reviewer II suggested that building envelope issues should be included and discussed. "Negative air pressure inside the building in moist climates may cause secondary building envelope moisture control issues where the building envelope has to be maintained under negative internal air pressure to induce the natural ventilation into the occupied spaces." Air movement accounts for more than 98% of all water vapor movement in building cavities. Therefore, any unintended paths for ventilation need to be well air-sealed. This will be added to the framework in the future as a concern and design suggestion.

The issue of moisture is not directly in the scope of this framework, see Figure 4.2. It may be included in a future study.

10.2.5 The general process of the framework

No reviewers disagree with the major modules including site and climate data adjustment and estimation, feasibility assessment, constraints, performance assessment and ranking, and the general decision procedures of the framework described in Chapter 4. Therefore, it can be concluded that the basic structure and the process of the framework are accepted by the reviewers.

The comments and suggestions about the process of the framework are focused on the detailed procedures of feasibility assessment. The revisions are described in Section 10.2.7.

10.2.6 Microclimate and local conditions

Most reviewers emphasize the importance of on-site measurement of microclimate and local conditions as inputs. In this framework, on-site measurement is suggested prior to climate and environmental input transformation and estimation.

Reviewer V cautioned that if doing on-site measurement, time is a limitation. “It requires years of measurement to cover the seasonal variation for NV utilization. In the design decision-making process, since time is limited, on-site measurement is forced to be done within a limited time period. The feasibility assessment analysis by using limited on-site data might mislead the selection of NV approaches (strategies).” Add the following cautions to using on-site measurements to Section 4.3, after the second sentences of the first paragraph, as suggested.

“If on-site measurements are available, they should cover a long enough time span to represent the actual environmental conditions of the site, as limited on-site data may mislead the assessments.”

If on-site measurement is not feasible, the necessary inputs must be obtained by transforming or adjusting the regional climate data, or be predicted based on available site information. The level of detail of current available methods varies from rules-of-thumb to complicated computer tools. Many of these models or tools need very detailed input and moderate effort to get reliable results. However, as emphasized by Reviewer II, local climate and site conditions are critical to the feasibility of natural ventilation; these models might still be introduced.

It is necessary to mention that both on-site measurements and input estimation and transformation require some time and effort. A concern is that this work may be done in a serious pre-design phase by people other than the designers.

10.2.7 Feasibility assessment

Reviewers’ comments on feasibility assessment focus on the following issues:

(1) Design proposition and design suggestions

The design proposition cannot be excluded from the feasibility assessment of NV because building design interacts with climate and environment conditions in determining the suitability of NV. However, excluding those design factors that do not have essential influences on the feasibility is important to simplify the decision process. In addition, the design suggestions that only have limited effect to correct an unsuitable environment can be taken out. As suggested by Reviewer III: “you only need a limited amount of data to start, and then many other things are just nuances on your basic files,” and “if your basic site-data isn't meeting the required criteria, the feasibility portion of the program should kick you out as being fundamentally unsuitable -- it is only when you are barely borderline that you should look at the tricks of water, vegetation, or sound barriers, but these are insufficiently effective to correct a wrong climate.”

Changing building orientation and adding stack effect as a driving force may be more effective than modifying building geometry. In the feasibility assessment modules, all the buildings are approximated to rectangular, thus orientation is much more important than the shape of the building.

Natural ventilation with earth-to-air heat exchangers and natural ventilation with evaporative cooling can be effective strategies. In this framework, they are suggested when the assessment result is not feasible or near the boundary of feasibility. It has been explained that the seasonal cooling ability of earth-to-air heat exchangers is much lower than natural night cooled thermal mass. Natural ventilation with evaporative cooling is good for dry climates.

(2) Temperature assessment

Although natural ventilation can be a cooling and ventilation system, it is useful to maintain IAQ even in cold seasons. In this framework, the hours the building is estimated to be below the heating balance temperature are not counted.

In the temperature assessment, the building's heat gain is an important factor to determine the feasibility of NV for non-residential buildings. As commented by Reviewer III: "in nonresidential occupancies, the internal heat gains and solar heat gains are often quite high; you cannot just look at outdoor air temperature unadjusted in order to determine whether the natural ventilation is feasible -- an offset of approximately 6°F in temperature to account for, so that inside the space internal heat loads are accounted for." It is clear that internal gains expected in non-residential buildings can extend the ventilative cooling season well into winter months in North America.

Section 6.3.1.1 with the following paragraphs is deleted.

Temperature limits for thermal comfort can be established from ASHRAE Standard 55-2004. However, for natural ventilation recent studies suggest that when occupants are given control of an operable window for ventilation, the boundary of the thermal comfort zone can be extended both to warmer and cooler temperatures. ASHRAE Standard 55-2004 also provides useful tables that indicate the interactions between temperature, air speed, and thermal comfort. Using TMY climate data, hourly values for outdoor air temperature and wind speed can be compared to the limits of the extended comfort zone and the annual number of hours in or near the comfort zone can be determined. The summation of the number of these hours of occurrence can then be compared to a target value to assess feasibility relative to thermal comfort. This is similar to procedures of analysis used in Climate Consultant.

The assessment method proposed by Axley and Emmerich (2001) to determine the suitability of a climate for natural ventilation of commercial buildings [85] can be a method to assess the feasibility of temperature. The method is described as the following:

"The heating balance point temperature $T_{o\text{-}hbp}$ establishes the outdoor air temperature below which heating must be provided to maintain indoor air temperatures at a desired internal heating set point temperature $T_{i\text{-}hsp}$. Hence, when outdoor temperatures exceed $T_{o\text{-}hbp}$, direct ventilative cooling can usefully offset internal heat gains to maintain thermal comfort. At or below $T_{o\text{-}hbp}$, ventilative cooling is no longer useful although ventilation would still be maintained at the minimum level required for air quality control.

The heating balance point temperature, based on a prescribed $T_{i\text{-}hsp}$ set equal to the lowest T_i that is acceptable for thermal comfort, establishes a lower bound of acceptable outdoor temperatures for ventilative cooling. The T_o equal to the highest acceptable temperature for thermal comfort establishes an upper bound above which ventilative cooling will not be useful. Here, this limiting temperature will be assumed to equal the indoor cooling set point temperature $T_{i\text{-}csp}$ above which mechanical cooling would normally be activated to maintain thermal comfort."

When outdoor air temperatures exceed $T_{o\text{-}hbp}$, yet fall below $T_{i\text{-}csp}$, ventilation can directly offset internal gains. Recognized conductive losses during warm periods are typically small relative to internal gains for commercial buildings; the ventilation rate required to offset internal gains while maintaining indoor air temperatures within the comfort zone may be estimated using the steady state model, the ventilation rate:

$$\dot{m} \approx \frac{q_i}{c_p(T_i - T_o)}$$

Equation 10-1

If $T_o < T_{o\text{-}hbp}$, no ventilative cooling will be required. When outdoor air temperatures fall within an increment of ($T_{i\text{-}csp}$-$T_{i\text{-}hsp}$) above $T_{o\text{-}hbp}$, the minimum ventilation rate will suffice:

$$\dot{m} = \dot{m}_{min} \text{ when } T_{o-hbp} \le T_o \le T_{o-hbp} + (T_{i-csp} - T_{i-hsp})$$

Equation 10-2

Above this range, the ventilation rate will have to increase as T_o increases:

$$\dot{m} \approx \frac{q_i}{c_p(T_{i-csp} - T_o)} \text{ when } T_{o-hbp} + (T_{i-csp} - T_{i-hsp}) \le T_o \le T_{i-csp}$$

Equation 10-3

Equations 10-1, 10-2, and 10-3 may be used to determine periods when direct ventilative cooling may be applied and to estimate the ventilation rates needed to maintain thermal comfort during these periods. If $T_o > T_{i\text{-}csp}$ then ventilative cooling is not useful.

(3) Humidity

Reviewer I commented that night ventilation strategy should also consider humidity control. The relative humidity at night may be high and, therefore, hourly limits should be considered when assessing the feasibility of night ventilation with thermal mass.

Reviewer III cautioned "to be careful in saying that higher humidity limits are acceptable." How to set limits for the humidity criteria for natural ventilation is controversial. Givoni's zone for natural ventilation has nearly no humidity limit (Figure 10.1). Emmerich and Axley (2001) followed the ASHRAE comfort zone [85]. CIBSE guidance recommends that the relative humidity should be kept between 40% and 70% [9]. In this framework, the upper humidity limit is set to 70% relative humidity or 0.012, whichever is higher. How this is considered is described in Section 6.3.1.2.

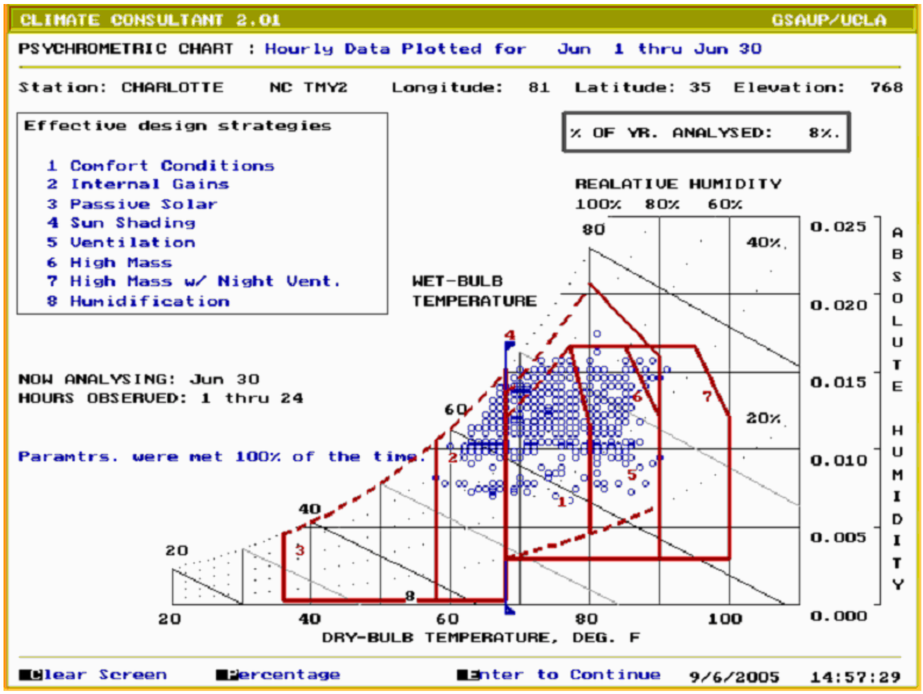


Figure 10.1 Givoni's zones on the phychrometric chart (Generated by Climate Consultant)

(4) Decision criteria and process

Reviewer III suggested the following decision process for the feasibility assessment:

a. Is the temperature/humidity versus indoor and solar heat gain still going to put you into the Brager de Dear range of comfort?

b. If yes, then do you need to do nighttime cooling of thermal mass to pull it off?

c. If yes, then is your air and noise environment conducive to opening windows and having air come in directly from outside?

c. If yes, do the wind regime and wind-shadows around you support the use of wind as a driving force?

d. If yes, then you flip to the design tool because now you have to start placing mass in a wind environment and you have to start placing and sizing windows.

For step a, the adaptive model was not selected for use in the feasibility assessment.

The adaptive model gives a range of comfort temperature occupants adapting to the surrounding environment. The upper limits of indoor temperatures (Ti-upper) of the adaptive model can be described as:

- $T_{i\text{-}upper} \leq 22.8°C$ for the mean monthly outdoor air temperature $T_o < 5°C$
- $T_{i\text{-}upper} = \frac{9}{28} T_o + 20.4$ °C for $5°C \leq T_o \leq 33°C$
- $T_{i\text{-}upper} \leq 31.8°C$ for $T_o > 33°C$

The adaptive model exhibits the relation of indoor comfort operative temperature ranges to the outdoor temperature. The former might be difficult to determine with inadequate design information at the feasibility assessment stage. In addition, some occupancy types and building locations do not allow such adaptation. The adaptive model is used later in the performance assessment module.

To evaluate the sufficiency of wind for natural ventilation, it is difficult to set separate criteria, such as a limit of wind speed of 1m/s, with no regards to the resulting air flow and the building heat gain rate. The sufficiency of wind should be evaluated together with (1) the building orientation, (2) approximate building dimensions (including length, width and height), and (3) the area and location of openings. Users should be able to change these basic parameters of the building if possible when the result is not feasible.

It is also inappropriate to set a single criterion concerning how many annual hours is considered good for natural ventilation for different projects in different conditions. It should be left to the user of the framework as an input.

As a result of these suggestions, the decision process for climate suitability was revised as:

1. Check if the humidity is acceptable for NV; if yes, then use the method above to assess temperature and calculate necessary air flow rates.

2. If the total annual hours when NV is estimated to be appropriate is less than the minimum target level, then determine the feasibility of night ventilation with thermal mass.

3. If the total hours when NV is estimated to be appropriate is greater than the minimum target level in step 1, then check if the wind driving force is enough, see Section 6.3.1.3, Module 2-1-C; the air flow rate Vw through the opening of equivalent area A can be calculated by $V_w = C_D A\sqrt{2\Delta P/\rho}$, where $\Delta P = \frac{1}{2}\rho V_{ref}^2 (C_{p-in} - C_{p-out})$. Then compare Vw with $\dot{m}$. If Vw $< \dot{m}$, the wind driving force is insufficient. The designer can check the orientation of the building to see if the wind pressure can be increased, or check if stack ventilation can be used to increase the pressure driving force, see Section 6.3.1.4, Module 2-1-E.

4. If the total hours when NV is estimated to be appropriate is greater than the user's minimum target level, NV is feasible, otherwise NV is not feasible.

10.2.8 Constraints

Most reviewers agree with the constraints. Constraints allow designers the ability to have flexibility in shaping the building. Constraints may be solved by design. Therefore safety, security, and zoning remain as constraints, contrary to reviewer IV's comments.

For example, the levels of protection for security depend on the building type, acceptable levels of risk, and decisions made based on recommendations from a project-specific threat and vulnerability assessment and risk analysis. If pressurization, isolating big-threat areas, and protection from external and internal release of CBR agents are necessary according to risk and vulnerability assessment, a hybrid ventilation system with integrated building automation and control system (BAS) that enables monitoring and control of traditionally stand-alone building systems is appropriate, because isolation zones are required and air filtration and pressurization are needed in emergencies. Therefore, security issues can limit the application of natural ventilation. For most non-residential buildings such as commercial office buildings, carefully designed openings can overcome the security problem.

Reviewer V suggested adding more constraints, such as:

- Weather is added as a constraint, suggested by Reviewer V: "in addition to variables such as insects, monsoon rain and sand storm can be the significant factors and should be emphasized in the framework. In some climate locations, these factors strongly affect the NV decision-making."
- As also suggested by Reviewer IV, except for insect screens that cause air flow reduction, other ventilation components can also cause significant pressure loss. Therefore constraint "vector prevention" should be changed to "air flow reduction". The whole Section 8.3 (pressure loss) has been moved to this section.

10.2.9 Performance Mandates

Most reviewers agree with the current five performance mandates. Some reviewers suggested adding the following two performance mandates:

- Health and occupant productivity
- Humidity and moisture control

For "Health and occupant productivity," the following discussion is added to Chapter 4:

Occupant health and productivity are other important issues that can be considered as performance mandates since naturally ventilated buildings can potentially achieve better indoor air quality, while window openings also provide daylight and views that improve occupants' health and a biophilia connection to outdoors. However, occupant health and productivity are difficult to estimate and quantify especially in the early design stage. They are comprehensive metrics resulting from various factors including thermal comfort, acoustical environment, IAQ, view, etc. Therefore, to simplify the problem, users may add more such factors that are concerned with occupant health and productivity in the early design stages.

Humidity is considered in the thermal comfort assessment module. Moisture control is not covered in the current framework.

10.3 REVIEWERS' SPECIFIC COMMENTS, SUGGESTED CHANGES AND DISCUSSION

10.3.1 Chapter 1 introduction

Reviewer II suggested that the disadvantages and inappropriate applications of NV should be included in the framework to help designers avoid these problems.

Some negative issues including safety, security, draft, maintenance, etc., are addressed in constraints and design suggestions. The assessment procedures including feasibility assessment, constraints, and performance assessment in the framework could help prevent inappropriate application of NV approaches in the early design stage.

Due to the limitation of the case studies, negative lessons learned from these projects may not be easily obtained. In the literature, "successful" buildings are mostly available with positive comments, but seldom include performance records. Buildings for which NV was less successful often do not find their way into the literature. Although it would have been ideal to visit and interview the designers, owners, and occupants of these less successful buildings to get direct information, this would have been time prohibitive.

The timeline for the completion of the tool, the platform it will run on, and expertise needed to use it, are added as requested by Reviewer IV:

The tool is planned to be completed one year after the framework is completed. It will be developed on a Windows platform with a user-friendly interface and for use in the early design phases.

10.3.2 Chapter 2 Literature Review

Reviewer I comment that "peak summer condition" is too vague as it depends on local climate. Thus, the first sentence of Section 2.2.3.1 was changed to: "When outdoor temperatures are not much lower than the internal temperatures in occupied areas, the stack pressure resulting from indoor and outdoor temperature difference will be minimal."

The first sentence of Section 2.2.3.2 was changed to: "For isolated buildings with no local flow interference, CIBSE application manual AM10 (1997) provides the minimum height of stack above roof level to avoid back draught."

Reviewer II commented that the current non-residential buildings tend to have larger internal heat gains that contribute to "a lot of internal, localized air movement energy" and suggested furniture layouts that should ensure every work station gets code complaint ventilation rates. Although it is a good suggestion, it is beyond the scope of the framework for early design phases in which such detail is not generally covered.

The following reference to McCarthy's statements on wind scoop will be added in Section 2.2.4.1: McCarthy, C. and B.M.C. Engineers, Wind Towers: Detail in Building. 1999: John Wiley & Sons, Ltd.

10.3.3 Chapter 3 Case Studies

As suggested by Reviewer II, the presentation format of case studies is better if uniform. Due to the limitation of resources, some necessary information was not available. It is difficult to keep similar levels of detail for all the cases. However, the presentation of the case studies can be changed to the same format and "information not available" can be noted in the corresponding places.

Reviewer II suggested adding negative air quality issues to Case 1-6, Telus William Farrel Building. The following discussion will be added to that case study:

The available case study information reflects a positive response toward the Telus William Farrel Building. However, the outdoor air quality may be unsuitable, since the building is located on the corner of the two major urban roads with “constant stop and go traffic all day.” To overcome this, the building uses a double-skin façade ventilation system; however, no measures are taken to address the air quality issue. It would have been desirable to monitor the indoor air quality to determine its acceptability. Unfortunatly, no records are available showing such measure was taken.

10.3.4 Chapter 4 Framework Overview

Reviewer I raised the issue concerning whether or not the feasibility assessment should include consideration of local building codes and standards. Local building codes and standards should be applied if they are more stringent than the criteria proposed in the framework. The framework should allow for this.

Based on the comments by Reviewer II, the statement “Natural ventilation strategies may be categorized as wind-driven or buoyancy driven (stack effect) ventilation” was changed to “The basic driving forces of natural ventilation are wind and buoyancy. Natural ventilation in buildings is most often the combination of these two basic effects.”

Constraint “Vector prevention” was changed to “Air Flow Reduction with Insect Screens.” And the following statement was added to the end of the paragraph: “Similarly, to reduce noise transmission and provide sound buffering, building components such as double-envelopes, shafts, plenums, atria, acoustic louvers and acoustical attachment and insulation may induce air flow resistance. The device for shading or glare control can also add flow resistance. CFD may be necessary to study the degree of flow reduction by these components or devices.”

”Weather” was added as another constraint, as was the following statement: “Another issue that potentially constrains the application of natural ventilation is weather, such as monsoon rain in tropical climates and sand storms in hot arid regions”.

10.3.5 Chapter 5 Interaction Between performance Mandates

As suggested by Reviewer I, the negatives of displacement ventilation should be indicated in Section 5.2.2. The following statements were added to the 3rd paragraph in Section 5.2.2, (4) ventilation zone and flow path:

“Recent review on the studies of displacement ventilation found and cautioned that the ventilation effectiveness of displacement ventilation may not be satisfying when contaminants from sources not associated with heat generation. Stable stratification may also not be established due to occupant activity or the distribution of heat sources or sinks” [86].

As pointed out by Reviewer II, the diagrams in Figure 5.2 are inaccurate; separate stratified layers from each person do not happen. Simulation of a theatre provided by Reviewer II shows that “the more densely the occupants seated, the more the buoyant plumes are mixed into large scale air movement patterns.” This was deleted.

Based on the suggestion by Reviewer I, the following statement was revised and a reference added to the carpet example in Section 5.2.6 (4), Interior materials and indoor pollutant:

For example, the US Environmental Protection Agency (EPA) reported the impact of carpet on IAQ. New carpet and products that accompany carpet installation such as adhesives and padding can be a source of volatile organic compounds (VOC) emissions. In addition, carpet can trap particulates and pollutants, such as VOCs, dust mites, and residues of cleaning products. Wet carpet is an ideal breeding ground for another allergen: mold and mildew. Evidence suggests that carpeting may contribute to an increase in respiratory problems; eye, nose, and throat irritation; headaches; skin irritations; and fatigue. [87] However, carpet may improve the acoustic character of a space by minimizing the impact of noise and reducing reverberating sounds and background noise.

In the discussions about interactions between Energy Saving and IAQ in Section 5.2.4, the following statement about intermittent ventilation was added to (2):

Sherman (2004) developed a method for the designer or decision-maker to determine how intermittent ventilation can achieve the same indoor air quality as continuous ventilation.[88]

Sherman found that with intermittent ventilation, when turn over time (the inverse of air change rate) is below a critical value, the efficacy, i.e. ventilation effectiveness, is high and stable and relatively independent of the fraction of time that the space is under-ventilated. Above this value, the efficacy drops and depends strongly on the fraction of time that the space is under-ventilated. In low density spaces, such as offices, typically the critical time is much more than an hour, and therefore there is a great deal more flexibility for the designer.

The results of this study have not been incorporated into current standards such as ASHRAE Standard 62, and, therefore, they will be incorporated into the framework in the future.

According to the comments by Reviewer I, the inaccurate statement “Limited application of natural ventilation leads to increased energy consumption” in Section 5.2.4 (1) was deleted. The following statement was added to the end of the paragraph:

Pure natural ventilation can save cooling and fan energy, but may increase heating load in cold and cool seasons. A study done by simulating the performance of the natural and hybrid ventilation systems in an office building in different locations in the US [89] showed that using only natural ventilation in cold and cool seasons may result in higher heating loads than using a hybrid ventilation system; see the following table.

Table 10.1: Simulated fan and energy consumption summary of a building in four locations in the US [89]

	System	Natural			Hybrid			Mechanical		
		Cool Load	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*	*Cool Load*	*Heat Load*	*Fan Energy*
		kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h	kW•h
San Francisco	February	0	490	0	0	300	240	50	0	1900
	April	**0**	**660**	**0**	**180**		**140**	180	0	1900
	July	0	470	0	220	0	30	1040	0	1900
Los Angeles	February	0	40	0	0	20	20	270	0	1900
	April	0	0	0	160	0	130	670	0	1900
	July	0	0	0	160	0	20	5830	0	1900
Minneapolis	**February**	**0**	**73100**	**0**	**0**	**35860**	**3130**	0	32120	2880
	April	0	10780	0	0	9160	1950	0	3140	1900
	July	0	0	0	4140	0	660	7810	0	1900
Boston	**February**	**0**	**44660**	**0**	**0**	**18480**	**2240**	0	16340	2060
	April	**0**	**10010**	**0**	**0**	**8130**	**1730**	0	3050	1900
	July	0	0	0	3850	0	610	7260	0	1900

Reviewer I suggested indicating a tool for life cycle cost analysis to paragraph two, Section 5.2.10.

To evaluate all of the trade-offs related to the cost of the natural ventilation system, a life cycle cost analysis should be done. A tool which can be used is BEES (Building for Environmental and Economic Sustainability) from NIST. "BEES measures the environmental performance of building products by using the life-cycle assessment approach specified in the ISO 14040 series of standards. All stages in the life of a product are analyzed: raw material acquisition, manufacture, transportation, installation, use, and recycling and waste management."[90]

The following statement was added to the beginning of the second paragraph of the conclusion, as suggested by Reviewer I:

This is a very limited discussion of interactions between performance mandates, which introduces the concepts and issues. It is not comprehensive and thorough. The interaction can be studied quantitatively in the future. For example, sensitivity analysis can be done to explore the influence of the related parameters in each interaction.

10.3.6 Chapter 6 Feasibility Assessment

Add CARB (California Air Resource Board) as a source of air pollution data in Section 6.2.4, website: http://www.arb.ca.gov/aqd/aqdpage.htm

10.3.7 Chapter 7 Constraints

Reviewer I requested an explanation of what the "architect's and client's preference on natural ventilation options" entails and how it effects the decision making process.

This refers to Section 2.2.7 Components of natural ventilation systems. For example, air exhausting elements could be atria, staircases, shafts with wind towers, roof, double-skin facades, etc. Designers may prefer atria to shafts with wind towers based on his/her aesthetical preference. The clients may prefer using staircase or wind towers to maximize the building's occupied area. These preferences can affect the design integration and may affect the performance of the NV system.

10.3.8 Chapter 8 Design Suggestions

The three levels of "accuracy" used in the third paragraph in Section 8.1 was changed to three levels of "detail," as commented by Reviewer I. In the later design phases, although more complex models are used, more detailed inputs are needed, and more detailed answers are given by the model, it cannot be concluded that these models are more accurate.

Reviewer II stated that the spread sheet method for sizing thermal mass is "slightly erroneous." "The example in Table D.1 presents a very simplified thermal mass heat flow and heat transfer model that can lead users astray." Since the errors of algorithms are more tolerable in early design stage, this simplified method may be left there until a better one is available.

10.4 CONCLUSION

The comments from the experienced professionals and researchers are addressed in this chapter. Generally, they agreed with the usefulness of the framework, and they agreed to the appropriateness of the critical issues, major assessment modules, and the general decision process of the framework.

The framework was improved based on the reviewers' comments and suggestions, including reflections on common issues they brought up and the revisions they suggested.

CHAPTER 11 CONCLUSION

11.1 RESEARCH SUMMARY

11.1.1 The contribution of the research

The contribution of this research is the application of a grounded theory methodology to establish a decision-support framework to assist the design of natural ventilation in non-residential buildings. The framework involves holistic issues and concerns that a designer may encounter in the early design phases for designing naturally ventilated non-residential buildings. This framework establishes reasonable and detailed decision procedures and integrates available knowledge, assessment algorithms, and tools. The framework is a first-of-its-kind identification of relevant issues, proposition for assessment procedures, and logical structuring of the issues and precedures.

In addition, the framework is developed into a modular structure, which is flexible and expandable. Future work can be easily added to the framework. The modular structure with working flow illustration makes it easier to develop the framework into a computer-based tool.

11.1.2 The task completed in the research

In order to develop such a framework, the research has completed the following tasks:

- Reviewed the existing literature concerning natural ventilation and current natural and hybrid ventilation approaches. Studied the contemporary application of natural ventilation in categorical non-residential building case studies.. These case studies focused on the issues including site and climate conditions, client's requirements, constraints, natural ventilation strategy, interactions between performance goals, design verification, system performance monitoring results, and lessons learned.
- Identified the critical issues in designing with natural ventilation, establishing the categories of the inputs, assessments, outputs, and general decision procedures of the framework. Presented the assessments modules that include feasibility assessment, constraints and performance assessments, and design suggestions in detail.
- Introduced the concepts and issues of the interactions between the five performance mandates.
- In order to validate the framework, the framework was reviewed by experienced professionals and researchers. Reflection on their comments and suggestions and changes for improving the framework are included.
- Identified possible areas for future research that may improve the framework or may contribute to the knowledge of natural ventilation design in non-residential buildings.

11.1.3 The usefulness of the framework

The purpose of developing the framework was to assist the decision process for designs utilizing natural ventilation in non-residential buildings. Therefore, its usefulness was the primary concern and goal as it was developed. In this study, the framework is critically reviewed and the usefulness is accepted by experienced professionals and researchers.

11.2 DISSCUSSION ON ERROR PROPOGATION

Errors in the framework could come from (1) inaccurate inputs, (2) assessment algorithms and rules-of-thumb, and (3) inappropriate weightings. Because error may exist in each step, as the process goes on, the accumulated effect of errors could be very large and lead to mistakes. It is an important concern in the framework that error propagation could result in wrong decisions. Moreover, it is extremely difficult to predict the error propagation in such a framework designed for the schematic design stage.

Other than from inaccurate inputs and inappropriate weightings, error coming from the assessment algorithms and rules-of-thumbs may not lead to wrong decisions eventually, because the primary goal of the framework is to select better alternatives. For such purpose, absolute accuracy of real values is not a major concern in the early design phases. More attention is paid to the relative performance scores of design approaches. Right selection is much more important. It is assumed that the outputs of the assessment algorithms will be underestimated or overestimated for all the candidate alternatives. This one direction shift implies that the order of suggested solutions can be maintained. When several algorithms are involved in sequence, if each of them holds the order, the final results of selections can also be acceptable.

The threshold of feasibility assessment and constraints are also critical in the framework. Most criteria for feasibility and constraints coming from building regulations and codes are assumed to be correct. However, when these criteria are applied to the results from the assessment algorithms used in each module, although these methods can hold the order of solutions, their shift effect may result in wrong decisions.

11.2.1 Sensitive test

In the future development of the framework, more attention could be paid to the variables with greater impact on the results than those of lesser impact because stronger influences potentially lead to larger error. Thus, in the future development of the framework, as all the algorithms are identified, those more sensitive variables will be identified. The accuracy of these data should be improved if practically feasible. The limitation of this method is that it can only reduce the propagation of error caused by inputs based on the current algorithms.

11.3 DISSCUSION ON FUTURE RESEARCH

This research is the first step towards the development of a complete computer based decision-support program for the design of natural ventilation in non-residential buildings. The study proposed a systematic approach with an adaptable and hierarchical modular structure. This allows the framework to easily integrate future work.

The possible areas identified for future development are summarized as the following:

First, due to the limitation of the case studies in this research, lessons learned and the performance records of these buildings are scarcely found. Less successful buildings are typically not written about. Although it is ideal to visit and interview the designers, owners, and occupants of these buildings to get direct information, due to time and travel constraints it was not possible. The lessons learned from thorough study of these cases may add to the practical value of the framework. This could be an area of future work for which there are other issues to explore, for example, how the trade-offs during the early design phase are manifest in the actual building performance.

Second, the issues of the interactions between the critical performance mandates are introduced but not studied comprehensively in this research. In the future, the interactions can be studied quantitatively. For example, sensitivity analysis can be done to explore the degree of influence of the parameters on the performance mandates in each interaction. The results of thorough study on interactions may also provide good design guides for balancing the performance goals and for system integration.

Third, in this framework, there are areas of decisions for which no models are currently available. For instance, if measuring on-site data is not feasible, the necessary inputs have to be obtained by transforming or adjusting the regional data, or be predicted based on available site information. Some of these areas are still waiting for new models to be filled in, such as evaporative cooling by nearby bodies of water, transpirative cooling by vegetation, or warming of the air due to the heat island effect. In some situations, no simplified methods or rules-of-thumb are available. This may lead to the direct inclusion of complicated tools in some of the decision procedures. For example, CFD may be necessary for studying the air flow reduction of building components, such as a double envelope. However, CFD is typically not appropriate for early design stages. Future studies could focus on the building components related to natural ventilation, so that the research results can be used directly into the framework as simplified methods or rules-of-thumb. For the double envelope, possible areas of research can be to investigate air flow reduction, sound attenuation and propagation, security and safety, and cost.

Similarly, since application of the framework is intended for the early design stages, the details of the inputs should be limited in the framework, which can be a problem as some currently available models are complicated. There is a need to improve the framework by simplifying these models or adapt them to rules-of-thumb if possible.

Fourth, detailed development on the sub-modules of constraints for building codes and regulations, fire safety, and security issues are needed in the next step. For example, in the module concerning fire prevention (3-4-1), because of the inadequacy of available information, the decisions related to the design of a natural ventilation system regulated by fire codes were only generally discussed in several aspects, and details could only focus on fire prevention in atria and for double-envelope designs. Further developments should include discussion on the details and how to respond in design to these interacted aspects.

Fifth, further research is also needed in the following areas, which have been discussed in Chapter 10: (1) the criteria of humidity limits should be established for the feasibility module, (2) moisture control guidelines should be developed, and (3) improve the rules-of-thumb or simplified methods for sizing thermal mass.

Sixth, as detailed validation of the decision-support framework, three to four recently designed projects could be used to process through the framework. The output from the framework would be compared with the as-built case as evidence of the usefulness of the framework. The scales and types of these cases should be varied.

Finally, the framework has the potential to be developed into a computer-based tool. It is planned to be a plug-in module in AutoCAD or similar program, so that the users can work with a user-friendly graphic interface. This is the ultimate objective for this work.

APPENDIX A REVIEWERS' COMMENTS AND SUGGESTIONS

REVIEWER I: Researcher, Anonymous

General Comments:

I've attached my detailed comments to this email. There are many comments, but most are just intended to provoke thought on your part. Overall, the proposed framework is thorough and could prove to be useful for designers. The key is the supporting details for each step of the process. It is important to keep in mind the limited available detail in the early stages of a design. The tools must fit that stage of a project.

Specific Comments:

Chapter 2

2.1.1.1 There should be reference for this material. Is it based on simulation or measurement or something else?

2.1.1 Other empirical tools are available.

2.2.1 Can single-sided not occur due to wind fluctuation?

2.2.2 Should give references to others that cover these strategies in more detail, (like "Axley JW. 2001. Application of Natural Ventilation for U.S. Commercial Buildings – Climate Suitability, Design Strategies & Methods, Modeling Studies. GCR-01-820. National Institute of Standards and Technology" and others).

2.2.3.1 "Peak summer condition" is too vague as it depends on local climate. Give some example with numbers to back the claims of wind relative to buoyancy.

2.2.3.2 Where does this come from? Provide reference or simulation or experimental detail.

2.3 Some statements are too general. For example: "In a rainy environment, since the building is operated under negative pressure, moisture will more easily infiltrate into the building and cause problems." In fact, moisture will not necessarily cause problems in all NV buildings, but the possibility must be considered in the design.

Chapter 3

Useful summary with references for further information.

Chapter 4

Critical issues are captured well.

4.3 Some resources are available on outdoor air quality such as EPA data or CARB data in California.

4.4.1 Should Feasibility assessment include consideration of local building codes and standards?

4.4.1 No discussion on level of detail of assessment (maybe later) – this is PRE-design.

4.4.2.2 Humidity/moisture control should probably be a separate performance mandate.

Chapter 5

5.1 Again, it seems humidity/moisture is a complicated critical issue and deserves a separate treatment.

Table 5.1 Will interior openings impact both thermal comfort and acoustic performance?

Similarly, cannot equipment and lighting affect both also?

5.3.2 Though you must be brief, you should also be balanced. For example, displacement ventilation has potential benefits but brings risks also (lower effectiveness for contaminants not associated with heat source). See review by Emmerich.

Other studies have suggested that occupant perception of IAQ improves with NV regardless of thermal comfort issues (see Axley review).

Occupant control should be a parameter in the tables as NV can be done either with or without it and may yield different results.

5.3.3 You may wish to review Emmerich and Crum report also.

5.3.4 Please provide reference or evidence for this “limited application of natural ventilation leads to increased energy consumption.”

I don’t understand why part of Chapter 5 presents quantitative analysis but other parts only minimal qualitative discussion which may be oversimplification.

5.3.6 Again, statements like the one on carpet MUST be backed up with references and consider a balanced viewpoint to be credible.

5.3.7 Recent analysis by Sherman provides a basis for evaluating intermittent relative to continuous ventilation. While it is important to consider current requirements of Standards like 62, future changes could be suggested.

5.3.7-5.3.10 All cost discussion should refer to a life cycle cost method such as the BEES tool from NIST.

5.4 Conclusion should state that this is a very limited discussion of interactions and performance that introduces the concepts and issues but is not comprehensive.

Chapter 6

Table 6.1 requires more explanation.

6.2.4 EPA, CARB and others also have outdoor air pollution data.

6.3.1.1 Axley also proposes and demonstrates a pre-design Climate Suitability analysis procedure that could be used to assess feasibility.

6.3.1.2 I don’t see how this helps use to assess feasibility.

6.3.1.3 & 6.3.1.4 LoopDA tool from NIST could also be used for pre-design analysis of stack and wind ventilation potential.

6.3.1.5 Night ventilation strategy should also consider humidity. Check out reference 62 & 63 and compare to Axley method.

6.3.2 I cannot critically review this material, but please be sure the methods discussed are appropriate for a pre-design assessment (i.e., very little design detail available).

6.3.3.2 LoopDA is one tool that could be used at this stage.

6.4 This section should emphasize that feasibility is done pre-design and thus methods/tools must require very minimal design detail.

Chapter 7

7.2 Some discussion on current code requirements beyond Standard 62 would be helpful.

7.3 Please explain what these preferences might entail and how they affect the decisions.

Specifics such as in 7.4 are needed in 7.2 and 7.3

7.6 Lots of good detail here – unfortunately I cannot evaluate it. Hopefully you have a reviewer with expertise in fire safety & smoke control.

7.5.4 This should be more specific as different design criteria apply to different types of spaces in healthcare buildings. For details see the 2006 AIA Guidelines for Design and Construction of Health Care Facilities. I suggest including a few criteria and then the reference.

7.7.4 Good information but it would be nice if the user knows the order of magnitude of these various effects so they can make choices.

Chapter 8

8.1 Paragraph 3: I prefer to say three levels of "detail" instead of accuracy. Any of those methods could be more or less accurate depending on input data, assumptions, etc. Also, the differences are in what question the model can answer and not just "accuracy."

Equation 8-3&8-4: Provide a very brief summary of basis for equations.

8.2.2 I feel it's important to note that, while COMIS and CONTAM are set up to solve multi-zone airflow for a defined network, LoopDA is specifically intended to assist in the design process. Also, these tools can be used to solve the single-zone case discussed in the previous section.

8.3 Much of draft reduction requires consideration of strategies that will increase pressure losses. Perhaps some discussion or analysis of trade-offs is needed.

8.4 Nothing on control strategy.

Chapter 9

Steps 9.1 and 9.3 can all be (and must all be) done with a coupled thermal/airflow/IAQ building model. It would be very helpful to users to discuss this and list some of the many tools available.

Appendix B

1-3-A & B need some detail.

1-3 Are these methods simple enough for feasibility assessment?

1-4 An introduction is needed to set the stage.

1-4 As above, are these methods expected to be used for feasibility?

Appendix C

2-2 Same question on appropriateness of use for feasibility assessment.

REVIEWER II: Mechanical engineer, anonymous

General comments:

How would the decision framework and weighting react to “opinionated” inputs? For example, people with pollen allergies would rate/weight indoor air quality/outdoor air quality very low relative to others who aren’t allergic?

All in all a great attempt to pull together a detailed logic path to evaluate and provide decision criteria for naturally ventilating a building.

Specific Comments:

Chapter 1

1.1 Problem Statement: It would be useful to mention here that in addition to the benefits there are other disadvantages and inappropriate applications for natural ventilation, and that is what this decision framework should hope to help designers with. I find that natural ventilation has almost become a “belief system” where it becomes a primary goal in spite of a number of issues that would logically prevent/preclude the use of natural ventilation in many applications. For this to be a balanced framework, it should be a goal here that all positives and negatives are part of the logic tree that the framework is built around.

Building envelope issues regardless of natural ventilation potential must be included and discussed – negative air pressure inside the building in moist climates needs to be included in the discussion. I find that many architects, as progressive as they think they are, become surprised when I tell them that parts of a building have to be under negative internal air pressure to get outdoor air inside in climates where it is rainy/wet or hot humid. This may cause secondary building envelope moisture control issues where the building envelope has to be maintained under negative internal air pressure to induce the natural ventilation into the occupied spaces. There may be many climate zones where the moisture and vapor barrier integrity outweigh the potential benefits from natural ventilation.

Step 1, Identifying critical issues: must have local climate characteristics and assessment of the local potential for natural ventilation. Is the building in an urban/country/suburban environment? Is the location appropriate? Then how much of the building ventilation and cooling loads can be served by natural ventilation? This section must have a General local macro and micro climate assessment.

Chapter 2

2.2.3, Buoyancy Driven Ventilation: More emphasis should be placed on this with more information added. The internal heat sources in buildings these days (computers, equipment, people) are very high, and contribute a lot of internal, localized air movement energy. Internal furniture layouts are also part of this critical path for internal buoyancy driven and natural ventilation from the perimeter (or internal atria) to insure that every workstation gets code complaint ventilation rates.

2.3 Must add “microclimate at building location”to performance mandates.

Chapter 3

General - The reporting and results format was different from one to the next – it would be helpful to make the case study presentation all with similar formats of design intent vs. actual results so readers can get good learning "sound-bites" from each one.

Case Study 1-6, Telus William Farrell Building: I would caution the use of this example since it is an attempt to use natural ventilation via the double skin façade in an urban location that is subject to a large degree of traffic fumes and outdoor air pollution. In spite of the many positive case study materials that mention this building, the reality is that the double skin ventilation system has been very problematical to the occupants and the outdoor air quality. Again, this is anecdotal information since the building is only a few blocks away from my office here, and one of the other engineers in the Office has Telus as a primary client and I get the stories second-hand. It would be useful to mention that the building location is right on the corner of two major urban roads which receive constant stop and go traffic all day.

Chapter 4

4.2 Critical issues: Outdoor/ambient air quality must also be a critical issue.

4.3.(4) Should add a summary of what the ASHRAE requirements are here in this section for ease of use.

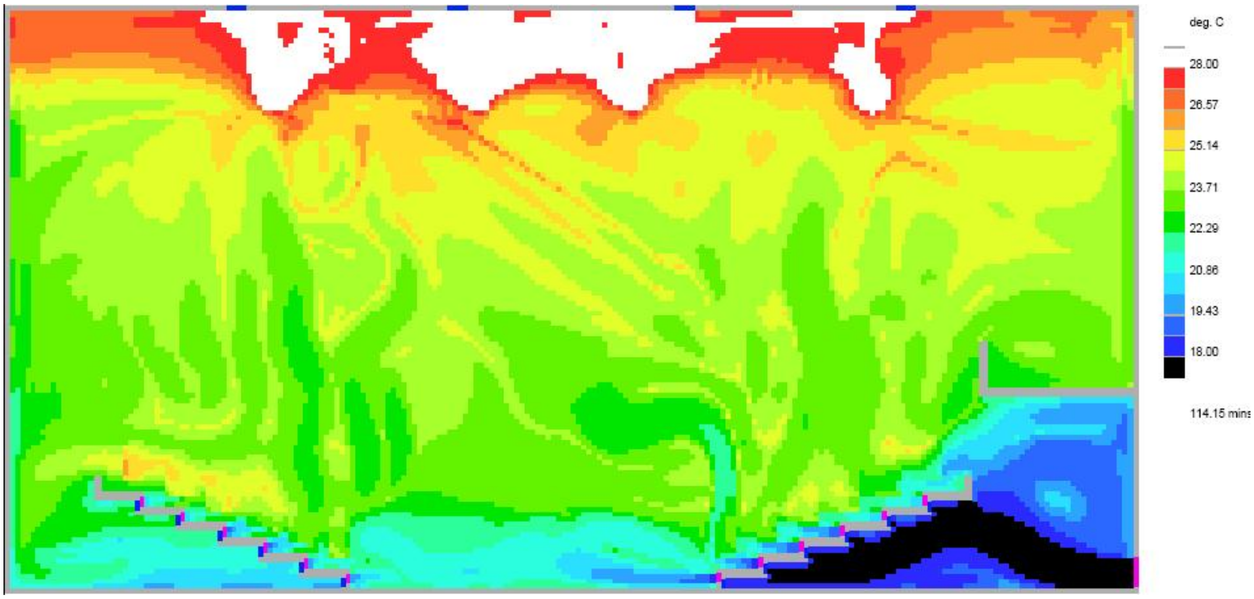
4.4.2 For the statement "natural ventilation strategies may be categorized as wind-driven or buoyancy driven (stack effect) ventilation," I think that these rigid categories are a road block and in nearly all cases natural ventilation is a combination of these two major effects. It's not an "either/or" decision, but an "and" set of categories.

Figure 4.1 This should be simplified and put into the Introduction – so the intent of the framework is shown; then in the conclusions section at the end of Chapter 11 show the whole framework logic path in greater detail – basically take figures 4.1 and 4.2 and enhance with logic path descriptors.

Chapter 5

5.3.2 (4) Sentence starting "In the design…." – I suggest stronger wording – CFD MUST be used to provide a reasonable estimate/prediction of airflow patterns…."

The DV Diagram in Figure 5.2 is inaccurate. There shouldn't be separate little stratified layers from each person. That just does not happen. See screen capture of a recent project we were modeling here:



This model shows a 35 foot high space with tiered seating at the bottom right hand side for a "theatre in the round" application with displacement ventilation air delivered at floor level, with exhaust air off the ceiling level of the room. You can see that the more densely packed the hot little humans are, the more the buoyant plumes are mixed into large scale air movement patterns.

Chapter 6

Introduction to Chap. 6 – shouldn't this or similar statement be made at initial introduction as a statement of the problem?

6.2.4 Should add a bit more summary of outdoor air issues for impact brought by insects, dust, and pollen on housekeeping and maintenance costs, such as the Liu Center and CK Choi buildings at UBC. These two naturally ventilated buildings are located in what some would consider "ideal" outdoor locations – surrounded by green space and limited vehicular zones, yet housekeeping and the effect on natural ventilation is a real housekeeping problem such as clogged trickle vents, hard to clean, localized seasonal effects, cottonwood and flower fluff, pollen, yellow pollen dust, and insects.

Web links:

http://www.gvrd.bc.ca/sustainability/casestudies/ckchoi.htm

www.tud.ttu.ee/material/piirimae/ecodesign/Case%20studies%20VIII/Case%20study%20building.pdf

www.greenbuildingsbc.com/new_buildings/case_studies/Lui_Centre.pdf

Note that the case studies on these two buildings are very light on the negatives about the building operations, but since I do work out at UBC all the time, I am familiar with the day-to-day Facilities Dept. comments, and my own first-hand site reviews while I've attended meetings and workshops in those two buildings.

Appendix D

Table D.1 - The mass cooling example is slightly erroneous since using air to cool the mass only affects the mass surface to depth 'X' – one needs FEA/CFD modeling to show actual mass heat transfer and surface temperatures over time – Example: If only the first inch of mass is pre-cooled, then it doesn't take very long for that surface temp to get back to T_{room} depending on indoor heat sources (radiation + convection) – this example in the Table presents a very simplified thermal mass heat flow and heat transfer model that can lead users astray – the time/temperature/depth of concrete heat transfer issue rule of thumb is: ± 2 hours per inch for temperature modulation/change.

REVIEWER III: Mechanical engineer, anounymous

Comments:

I spent most of my time reviewing the feasibility assessment portions as they are the new research and intellectual methodology that seemed unique to the project. I do believe that the literature review and clear evidence of research collection is impressive, but I find the actual decision-making framework simultaneously overly complicated and insufficiently supported in the following ways.

The decision making framework itself is lacking in identifying what criteria should be met in order to designate a condition as "feasible" or not. In order to have a framework which is useful within the industry, these types of rules of thumb which are independent of the derivatory case studies would be necessary. For instance, the following particular questions arise:

6.2.1 For wind at the building site , I believe that CFD is insufficient to model open boundary condition problems such as exterior wind regimes. I think that wind tunnels are a necessity if one is considering wind-driven ventilation mechanisms. That said, in the question of feasibility, you need only an algorithm that says "no you can't do natural ventilation'." You do not need an algorithm that shows that natural ventilation will work -- you should use the wind tunnel testing for that.

6.2.2 Temperature and Humidity - You are suggesting that ambient temperature should be reviewed prior to recommending natural ventilation and say that there are limitations on the ability to adjust for local elements. The more fundamental question is this -- what range of temperatures/humidity and what percentage of time across those ranges is actually suitable for considering natural ventilation? I didn't see any guidance in that regard, but that is the most fundamental question, as its answer makes all else moot. Again, all you need is an algorithm that says "no you can't do natural ventilation."

6.2.3 Noise Intensity levels - Noise is particularly localized and I would suggest that the on-site measurement method is the best method.

6.3.1.1 In nonresidential occupancies, the internal heat gains and solar heat gains are often quite high; you cannot just look at outdoor air temperature unadjusted in order to determine whether the natural ventilation is feasible -- an offset in temperature to account for the approximately 6 deg F that you will get inside the space from internal heat loads must be calculated in. Also, you should look at the adaptive comfort model from Brager and de Dear, as these will allow the upper limit to slide upwards with regards to the expected comfort temperature in naturally ventilated offices.

6.3.1.2 Humidity limits - I think that we have to be careful in saying that higher humidity limits are acceptable -- in most tropical climates, you must create "wind-on-skin" and people have to have dressed for inducing airflow across large portions of skin on their bodies in order to allow natural ventilation to be beneficial. This is related to the actual cooling mechanism of sweat evaporation -- when high humidity exists, the air's ability to absorb static moisture off of the skin is severely limited, and this is a prime area in which heat exhaustion can begin to occur. ASHRAE fundamentals have graphs in this regard.

6.3.1.3. Again, in this area, it is quite difficult to tell what the purpose of the section is, as you are essentially placing design calculations into the feasibility section. I also don't understand why all of the text regarding temperature/humidity isn't clustered together to have the complete discussion, then wind, etc, instead of things being spread out as is currently organized.

6.3.1.5 Feasibility of night ventilation with thermal mass - The map is quite interesting; what were the criteria used to generate it? Again, a rule of thumb like "if x% of time at night, the temperature is below Y, then it is likely that NVM is possible."

I think that my main comment is that the organization is spreading out all of the relevant information into too many places to be useful to the professional. Theoretically, this would all be embedded in a computer program and thus transparent to the user eventually, but the way the dissertation is laid out is very confusing. Fundamentally, you want two tools which may be interlinked:

A feasibility tool

a. Is the temperature/humidity versus indoor + solar heat gain still going to put you into the Brager de Dear range of comfort?

b. If yes, then do you need to do nighttime cooling of thermal mass to pull it off?

c. If yes, then is your air and noise environment conducive to opening windows and having air come in directly from outside?

c. If yes, do the wind regime and wind-shadows around you support the use of wind as a driving force?

d. If yes, then you flip to the design tool because now you have to start placing mass in a wind environment and you have to start placing and sizing windows.

So you only need a limited amount of data to start, and then many other things are just nuances on your basic files. Water-cooled air or vegetation is a nuance on your climate file. Vegetation is a nuance on your pressure coefficient or wind speed files. Sound barriers are just a theoretical adjustment to the environmental noise climate. If your basic site-data isn't meeting the required criteria, the feasibility portion of the program should kick you out as being fundamentally unsuitable -- it is only when you are barely borderline that you should look at the tricks of water, vegetation, or sound barriers, but these are insufficiently effective to correct a wrong climate.

It is only within the context of design (i.e. decisions regarding building shape) that the calculations that you are proposing are actually useful. All the other rules that are imposed on the designer with regards to setback etc, don't actually have anything to do with the natural ventilation, but are design parameters associated with the architect's ability to have flexibility in shaping the building. Within those externally imposed constraints, basically, you are only looking for two natural ventilation mechanisms: stack-driven or wind driven. The neutral plane/ driving force mechanisms are sufficiently different that you know for a non-residential building that you will need at least 3 floors to drive a stack large enough to be worthwhile without any wind energy. Then once you have three floors open to each other, you are an Atrium in America and thus now you have fire issues and other controllability issues, since one person's actions have repercussions on others.

But assuming you can find a mass/opening configuration that can ensure airflow through the building for all wind directions and speeds, now you have a situation where natural ventilation is feasible -- this is where simple zonal dynamic heat balance coupled with mass flow software makes sense. Then you build the model with your heat gain assumptions (acknowledging the very complex interaction of sun with building skin) and see if it actually works.

Hopefully, these comments are useful.

Reviewer VI (Anonymous), the American Society of Civil Engineers (ASCE), Journal of Architectural Engineering

Comments:

This Decision Support Tool will be of great value to the profession, and the construct will be of significant interest to the journal readership. I have a few suggestions for revisions, would argue that the first bullet is critical, but would accept the manuscript as written if the authors disagree with the other suggestions.

- State clearly the timeline for the completion of the tool, the platform it will run on, and the level of expertise that will be needed to use it. I assume it will be used in the early design stages.
- Outdoor Temperature

Recognize that operable windows are effective as a cooling system as well as a ventilation system, offsetting cooling loads that exist when outside temperatures are "too cool for comfort" and allowing for night ventilation in climates with large diurnal swings to offset the next day's loads. This means the calculations must extend through the cool and cold seasons - indeed natural ventilation was the typical ventilation and cooling system in use prior to air conditioning (beyond Givoni's relevant phychrometric zones of l, 2, 5 and 7, to include 3, 4, even 8).

- Constraint Functions

Eliminate the prescriptive recommendations for sizing openings for safety, since restricted window apertures compromise natural ventilation and bottom hung windows raise concerns about rain penetration. Leave the challenge to provide for views, ventilation, daylight, access to outdoor spaces, and safety to the designers. Indeed, I would eliminate the safety and security criteria since it can be solved with good design, as can zoning requirements, without restricting natural ventilation design. I do not consider these restraint functions. Retitle 4) Vector Prevention as Airflow Reduction with insect screens/glare control devices.

- Performance Mandates

Add Health and Occupant Performance to list. These are significant factors in prioritization, since operable windows have the potential to provide higher air flow rates at low energy costs and quick thermal comfort control, as well as views and daylight that impact human health and performance.

- Cost

Consider the cost of operability not the cost of apertures that are typically added for daylight and views. Skylights are also for daylight not ventilation, so operability is the cost. Atria are often added for reasons other than natural or stack ventilation. True natural ventilation aperture costs would include vent areas, chimneys, transoms, and of course screens, louvers, and controls as itemized thereafter.

- Weighting

I have trouble considering a weighting for indoor acoustics as higher as or lower than comfort or IAQ; these must all be met at the highest level achievable and both natural and mechanical ventilation have pros and cons. The real question is whether outdoor noise, pollution, or climate conditions make it infeasible to allow natural ventilation without very careful facade engineering, not whether indoor noise reduction is compromised by natural ventilation-this requires good design to solve, as does HVAC noise. If the range of 4 outdoor conditions are suitable, the biggest negatives against natural ventilation are: cost, maintenance, concerns about rain penetration, security, HVAC system balancing, possible energy waste. The biggest positives for natural ventilation are: increased outside air rates without energy costs, immediate thermal control and the value of control in user satisfaction and comfort, natural and nighttime cooling potential with energy savings, contact with the outside for biophilic gain and possibly educational gain, and possibly the reduction of HVAC noise and pollution. The radar diagram should, at a minimum, include health and performance (7 sides?), but will require a lot of user assumptions to fill out the natural ventilation, mixed mode, and sealed mechanical conditioning trade-offs (better IAQ with which system? Better acoustics with which system?). I would leave the performance mandates as required goals, introduce them as feasibility factors only if they are heightened by building type (eg. Need for complete IAQ control in hospitals, noise control in theatres) and use the external feasibility factors for ranking systems in the early design stages.

Reviewer V (Anonymous), the American Society of Civil Engineers (ASCE), Journal of Architectural Engineering

Comments:

The low-cost (natural) ventilation for various types of buildings is being explored by many researchers. Given this current energy situation, this issue becomes very important. In this paper, the authors have provided a framework for decision making –in order to apply natural ventilation (NV) in non-residential building. Four major steps including feasibility assessment, constraints, performance mandates, and approach comparison and ranking are suggested. Based on this format, researchers, engineers, and architects can systematically consider the potential of NV in their projects. However, it should be motioned that in non-residential space the environmental factors (environment mandates) are critical. Thus, the use of NV in these building types is yet fully promoted. For example, the turbulence now of NV sometimes fluctuate the temperature and velocity within the space beyond the acceptable range. On the contrary, the mechanical ventilation on including full air conditioning and hybrid ventilation can be easier controlled. The hybrid ventilation provides the choice between full air and NV depending on climate condition [1]. Since this strategy can be operated in sealed environment, factors such as noise from outdoor can be less of a concern. Based on the authors' framework, if the noise analysis failed, then natural ventilation is not feasible. Nevertheless, mechanical NV might be still applicable. As a result, the framework should represent the different concerns between mechanical NV and passive NV.

In order to improve the practicality of this framework, the authors should be concerned with issues such as microclimate factors, additional variables, experimental matrix, and ranking method.

Due to microclimate factors, the data obtained on-site can be different from the recorded data (TMY). Differing from a mechanically ventilation building, microclimate factors created by site and climate issues [2] heavily impact NV buildings. The location of a body of water (lake) provides additional cooling effect for the nearby site [3]. To avoid this consequence, the necessity of on-site measurement is also emphasized by the authors. However, the limitation of on-site measurement is time. It requires years of measurement to cover the seasonal variation for NV utilization. In the design decision making process, since time is mostly limited, on-site measurement is forced to be done within a limited time period. The feasibility assessment analysis using limited on-site data might mislead the selection of NV approaches (strategies).

The additional variables such as insects, monsoon rain, and sand storms can be significant factors and should be emphasized in this framework. In some climate locations these factors strongly affect the NV decision making. In tropical climates, the monsoon rain might limit the use of NV. In the desert, sand can be a major obstacle of NV for non-residential construction.

After selecting NV approaches, five performance criteria (mandates) including thermal comfort, IAQ, acoustic performances, energy saving, and cost need to be tested. In mechanical ventilation, a small set of parametric simulation is required. In the HVAC study, sometimes only two cases, including summer and winter, was tested. [4] Conversely, due to fluctuation of outdoor conditions, a large set of parametric simulations is required if NV is applied. Wind can comes from 360-degrees with a variety of speed, turbulence intensity, temperature, humidity, etc. As a result, each NV simulation might be both time and resources consuming. This might lead to impartiality in real design activity.

In the ranking method, the authors rank the energy saving score by number of hours when NV effectively removes heat gain. It should be cautioned that if thermal mass and moisture absorption effects are not included in the algorithm, the energy consumption in NV space can be worse. For example, if the natural ventilation is used in 2-3 pm, the higher air enthalpy (than conditioning enthalpy) might be utilized. Although under this condition the thermal comfort is achieved and energy saving is credited, the heat and moisture might sink into the construction material. This leads to higher energy consumption at 4 pm, when HVAC is re-operated. The effect of moisture and heat sink in HVAC spaces can be found in [5].

All in all, the systematic approach of NV decision making is challenging. The complex climatic condition in various site locations makes the research in NV continuous. Some non-residential spaces such as offices, which require precise thermal comfort, increase the limitation of NV applications. The suggestions under this review demonstrate some issues that this framework might face in real design activity.

References

1. Bourgeois. D., A. Potvin, and F. Haghighat. Hybrid Ventilation of Canadian Non-Domestic Buildings: A Procedure for Assessing IAQ. Comfort and Energy Conservation, in ROOMVENT2000.2000. Oxford: Elsevier.

2. Stern, B., J. Reynolds, and W. J. McGuinness, Mechanical and electrical equipment for buildings. 1992, New York :J. Wiley & Sons.

3. Olgyay, V. and A. Olgyay, Design with climate: bioclimatic approach to architectural regionalism. Some chapters based on cooperative research with Aladar Olgyay. 1963, Princeton, N.J.: Princeton University Press.

4. Karimipanah, T., M. Sandberg, and H.B. Awbi. A comparative study of different air distribution systems in a classroom. In ROOMVENT2000. 2000. Oxford: Elsevier.

5. Kunzel, H.M., et al., Simulation of indoor temperature and humidity conditions including hydrothermal interactions with the building envelope. Solar Energy, 2005.78(4): p. 554-561.

Reviewer VI (Anonymous), ASHRAE Journal

It is still unclear how this framework is used. It is written on a very general level, but the problems probably are in the details. One or two examples of the framework on a project must be included, so the reader can better understand and follow the framework. How was fig. 2 established?

Critical issues and inputs

- "TMY data should be adjusted for local effects…." Provide explanation and/or citation how this can be done.

Assessment 1: Feasibility

- Outdoor temp & humidity. Not everyone is familiar with the zones on the Building Bioclimatic Chart, the author might need to explain (briefly), and then give references. It is not clear how the building's balance point temperature is used. Is this a cooling balance point temperature? You refer to "established minimum number of hours" – who establishes this? How is this established? (Note – this is an example of what occurs in many places, where the actual method of analysis is left unclear.)
- Wind. Simplified methods for predicting pressure distributions are perhaps one of the weakest links in this method and deserve more discussion. Please be more explicit about the scope of applicability and limitations of the methods used in the references. Also, you say "For buildings with irregular shapes, adjustments must be made," but you don't say anything about how.
- Noise. You refer 3 times to algorithms, but don't tell us what they are, or give citations for further information. Here, as in many places, such a vague reference leaves the paper feeling thin and superficial. It sounds like the authors have done a lot of work in this area, so better explanations and citations will give them more well-deserved credit for the work that they've done.
- Pollution. You don't need to introduce a new hierarchy of subheadings with "Indoor air pollution." Having separate paragraphs dealing with outdoors and indoors will suffice.

Suggest removing the heading and then modifying the first sentence that follows to say "….spaces may have indoor pollutant sources …."

Assessment 2: Comparison

- Energy Savings. Method unclear. Pressure distribution would change every hour – is that what is being done? Also, heat removal rate will require an assumption about ΔT, and both Tin and Tout will vary every hour. Last bullet – unclear what is meant by "adjust by an estimated overall mechanical HVAC system efficiency" – how is that relevant for naturally ventilated buildings?
- Thermal Comfort. When referring to the adaptive model, use a better reference with authors of the model de Dear & Brager. The Olesen & Brager paper is a broad overview of changes to Std. 55 and is not the right reference, since Olesen wasn't the author of the adaptive model. Try using: Brager, G.S., and de Dear, R.J., "A Standard for Natural Ventilation," ASHRAE Journal, October 2000.
- What method is being proposed for estimating the humidity level? As with other places, either explain or give citation.
- IAQ. Again, as with other places, either explain or give citations for methods used. Otherwise too vague and thin.
- Cost. How are operation and other hidden costs best assessed?
- Productivity is important to include or is that independent on the type of ventilation? "For example, the benefit of productivity gains that may dominate other savings by natural ventilation approaches may be ignored"- I do not see how this may be ignored; both Thermal Comfort and IAQ will be influenced by the type and rate of ventilation, so why should productivity not be influenced.

Ranking

- It would help if these two examples is explained in detail to illustrate the use of this concept

Reviewer VII (Anonymous), ASHRAE Journal

Comments:

The paper proposes a procedure for assessing the potential viability and expected performance of natural ventilation (NV) when designing a commercial building. In places, the paper reads as if it is describing an actual computer-based design tool, and the paper would be of much more interest if this were the case. At the end of the paper, the authors indicate that they are floating a proposal for a specification of a tool and are seeking feedback. It would be much better if this were made clear at the beginning.

Only a limited amount of feedback can be obtained via the Letters page. An e-mail list server would support the on-going issues and level of detail needed to advance this project.

The paper lists, and briefly discusses, the main issues relating to NV and the criteria for its viability in a particular project. Unfortunately, no actual publication is cited for a number of the assessment procedures (see below).

Critical issues and inputs

- "Design proposition" – what is this? Is it the "design proposal"? Since the proposed tool is to be used in the early stages of design, isn't the idea to influence the design and pre-empt a design process that ignores NV, rather than respond to a design proposal that ignores NV?
- Replace "mandate" by objective.
- "Adjust TMY … for local effects …" How? Give references. If none, indicate that there is a research agenda linked to this proposal.
- "GIS tool integrated with a noise model" see last comment.
- Explain how the results of the local outdoor air quality investigation would be incorporated.

Assessment

Feasibility

- In the adaptive model, the thermal comfort zone is variable, being related to the previous month's average temperature so can't be overlaid on a chart showing weather data for a whole year – it has to be done by month. Note that the adaptive model only applies to occupants who have control over an operable window, so two procedures are needed – one for those with control and one for those without. Those without control can still have an extended comfort zone if enhanced air motion can be provided (for example).
- Explain balance point temperature and how it is used to estimate NV feasibility. What ventilation/infiltration rate is used to calculate it (zero?)? Discuss how night vent is handled – are daily lines rather than hourly points needed to indicate diurnal range? Does the balance point humidity need to be defined and identified as well?
- URL for AQS?
- References for British Standard IAQ method and network models. Would the network models be integrated into the decision framework/tool? If not, what guidance/requirements would be provided regarding their use?

Constraints

- "Person or child" - "adult or child"? Which/when? Are there regulations?
- What are "rough" and "smooth" screens?

Conclusion and summery

- "The framework will be adapted to a computer-based tool based on the modular design." In principle, it can easily be adapted. In practice, it would involve a substantial amount of work, both for coding and for testing.

APPENDIX B INPUT TRANSFORMATION AND SITE ANALYSIS

Module 1-1: Wind at the building location

1-1-A Terrain and height corrections at the building location

Wind velocity from meteorological stations available in typical meteorological year archival files can be transformed with the terrain and height corrections at the building location, by the correction to the hourly wind speed U_{met} from nearby meteorological station:

$$U_H = U_{met} \left(\frac{\delta_{met}}{H_{met}} \right)^{\alpha_{met}} \left(\frac{H}{\delta} \right)^{\alpha}$$

Equation B-1

δ, H, α are wind boundary thickness, height and exponent α for the local terrain

δ_{met}, H_{met}, α_{met} are wind boundary thickness and height and exponent α of the meteorological station

Table B.1 The exponent for different terrain categories
Note: Detailed description of the terrain category can be found in Table 1, ASHRAE Handbook, Fundamentals, 2001, 16.3. The wind speed U is the wind speed at height H above the average height of local obstacles.

Terrain Category	Description	Exponent	Layer Thickness
1	Metropolitan sites	0.33	460
2	Urban and suburban areas	0.22	370
3	Open terrain with scattered obstructions	0.14	270
4	Flat, unobstructed areas	0.10	210

1-1-B Winds in the urban street canyons

The dimensions of a street canyon are expressed by its ”aspect ratio”, i.e., the ratio of the height of the building (H) to width of the street (W). A shallow canyon has an aspect ratio below 0.5; and a deep canyon has an aspect ratio over 2. The length of canyon (L) expresses the road distance between two major intersections subdividing the street canyon into short (L/H=3), medium (L/H= 5) and long (L/H =7). Ahmad et al. (2005) summarized the flow fields in street canyons through literature review (Table B.2) [91].

Table B.2 Summary of flow fields in street canyon

Canyon characteristics	Flow fields		
	Perpendicular flow	Flow along the canyon	Oblique flow
Aspect ratio >0.05	Flow fields do not interact, resulting in the disruption of wakes. This type of flow regime is known as '**isolated roughness flow regime**' (Figure B.1).	There is no predominant wind direction inside the canyon. At higher wind speeds, the flow is almost parallel to the axis of the canyon.	Similar to the perpendicular flow.
Aspect ratio <0.65	The bolster and cavity eddies are disturbed and the flow regime changes and is known as '**wake interference flow**' (Figure B.2).		
Aspect ratio>0.65 and <2, L/W >20	The bulk of the flow does not enter inside the street canyon and forms a single vortex within the canyon. This type of flow regime is known as '**skimming flow regime'**. (Figure B.2)	Mean wind along the canyon axis with possible uplift along the canyon walls.	A spiral vortex is induced along the length of the canyon with a cork screw-type of action.
Aspect ratio ≥ 2 and L/W <20	Described the formation of **two vortices** in deep canyons. Ambient wind flow drives the upper vortex while the circulation of upper vortex drives the lower one. The direction of the lower vortex flow is opposite to that of the upper one. (Figure B.3)	Intermittent vortices are shed on the building corners. These vortices are responsible for the mechanism of advection from the building corners to mid block creating a convergence zone in the mid block region of the canyon.	Similar to the parallel flow.
Higher aspect ratios	A third weak vortex might also be formed.		

"The average vertical displacement of vortex for a symmetric street canyon is equal to the canyon width. In the step up canyon, the vortex is smaller and the mean vertical displacement is equal to 0.61 of the canyon width."[91]

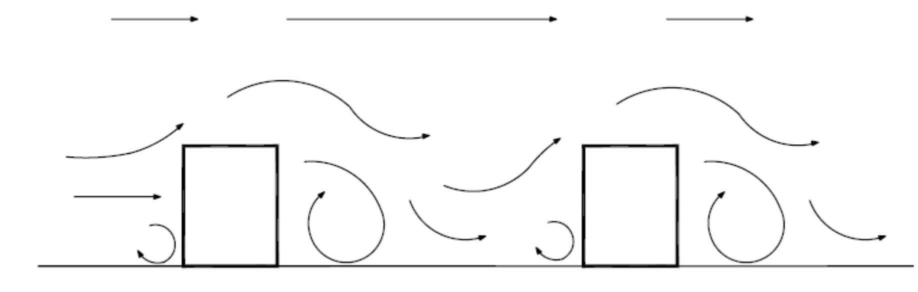


Figure B.1 Isolated roughness flow

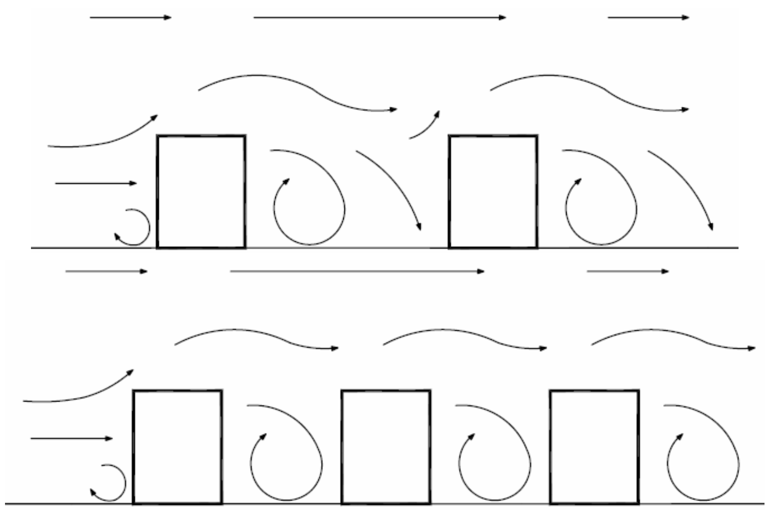


Figure B.2 Wake interference flow (top) and Skimming flow (bottom)

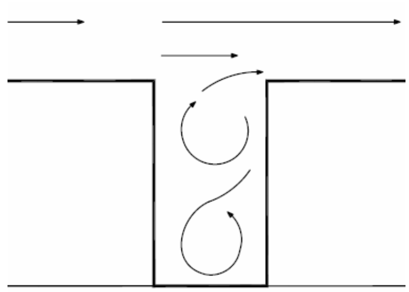


Figure B.3 Flow pattern in the street canyon with W/H=0.5

Ghiaus et al. (2005) presents the algorithm estimating the wind in urban street canyons [41]. The algorithm consists of several existing models. These models were validated by experiments conducted in five street canyons in Athens, Greece, under the conditions of hot weather and low wind velocity. Detailed description of the models including inputs, equations, and outputs can be found in *Urban Environment Influence on Natural Ventilation Potential,* by Ghiaus et al.,in Building and Environment, 2005. The flow chart for the models is shown in Figure B.4. A computer tool has also been developed based on these models.

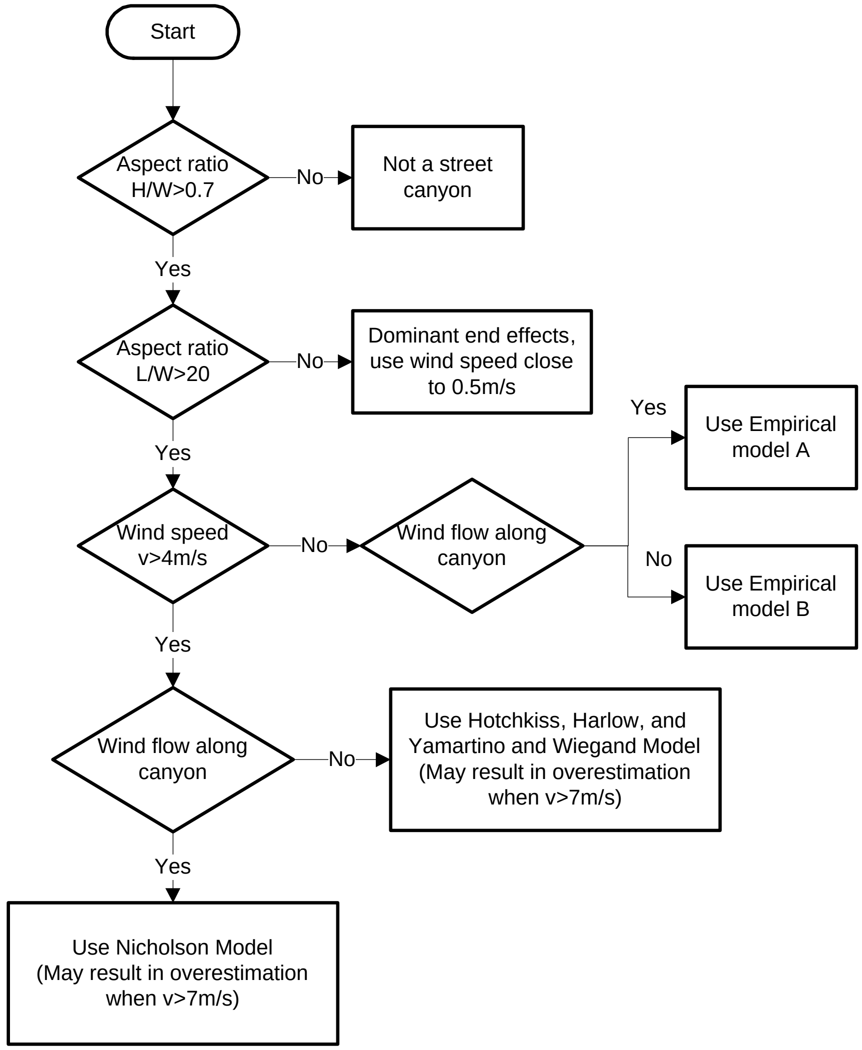


Figure B.4 The flow chart for estimating wind in a street canyon

1-1-C Wind speed reduction by trees (Reed 1964) [57]

$$R=\begin{bmatrix} 62\% \sim 78\%, d \le 5h \\ 24\% \sim 62\%, 5h < d \le 10h \\ 13\% \sim 24\%, 10h < d \le 15 \\ 10\% \sim 13\%, 15H < d \le 20h \end{bmatrix},$$

Where

R= Percentage of speed reduction

d = the distance between the trees and building

h = the height of the trees

1-1-D Basic principles of corrections for wind direction [57]

Corrections for wind direction may refer to the air movement principles of typical topographies

"When wind meets an object like a building or hill, it creates a high pressure zone of increased velocity on the windward side of the object and a low pressure zone of lower velocity on the leeward side of the object."

"Wind striking a landform, such as a hillside, is deflected, but not stopped."

"Wind is accelerated when constricted, according to the Venturi effect, such as when it flows through a gap between buildings, or through a saddle between two knolls, or when it is channeled by flowing parallel to the ridges of a canyon."

"Wind diverted by a land form will increase in turbulence and decrease in velocity behind the obstruction. Wind moving crosswise over a depression will tend to carry over narrow valleys and gradually fall into wider ones."

Near bodies of water, the breeze typically blows off the water toward the land during the day. At night the flow is reversed.

In valleys, the wind blows uphill during the day. At night the air flow reverses. "Different orientations of valley profiles create complex thermal wind patterns. The phenomenon of cool air falling also results in cool air flowing down hills at night and collecting in pockets formed by topography or vegetation."

Module 1-2 Temperature and Humidity

1-2-A Evaporative cooling by nearby bodies of water (not available)

1-2-B Transpirative cooling by vegetation (not available)

1-2-C Warming of the air due to the heat island effect

Urban Heat Island Intensity (UHII) is the maximum difference between urban and background rural temperatures. Oke (1982) has correlated the heat island intensity to the size of the urban population: [16]

$$\Delta\theta \cong \frac{\phi^{1/4}}{\bar{u}_r^{1/2}}$$

Equation B-2

where $\bar{u}_r$ is the regional speed of the wind, ϕ is the population of the city and $\Delta\theta = T_U - T_C$, where TU is the urban temperature and TC is the temperature of rural area.

The wind velocity threshold for the development of a heat island is:

$$u_{\lim} = 3.4\lg\phi - 11.6 \text{ (m/s)}$$

Equation B-3

He proposed two different regression lines for North American and European cities. The expected heat island intensity for a city of one million inhabitants is close to 8°C and 12°C in Europe and the USA respectively. Higher values for the American cities are because the centers of North American cities have taller buildings and higher densities than typical European cities [92].

Various studies on the intensity of heat island have been performed for many European cities. For example, heat island studies in Athens found high temperature difference (5°C -17°C) between suburban and urban stations in the daytime, and temperature difference up to 4°C in the night time. Both daytime temperature and night time temperature are important for ventilation potential. Higher night temperature limits the cooling capability of thermal mass with night ventilation. The impact of the heat island effect on summer cooling and night ventilation in London is investigated by Kolokotroni et al.[46]. They observed that the central London station was warmer than the rural reference station, especially during the night. Minimum temperatures were always higher in London when compared to a rural reference station. UHI intensities have been observed at their highest during hot clear and calm days. Since stack ventilation is often used for daytime and night cooling in England, the results from their work indicate that increased urban temperatures (especially those during the night when) should be considered as result in "significant deviations" from using standard meteorological weather data. They state the necessity and importance to develop a prediction model to estimate the urban heat island intensity from a standard meteorological station or weather data in typical urban environments of large urban centers.

1-3-D Temperature distribution in street canyons

No specific temperature distribution pattern relative to the canyon height has been found. The temperature homogeneity may be explained with advection, shadow, and big aspect ratio. Thus the input temperature need not be fixed.

Module 1-3 Noise Intensity levels

1-3-A Federal Transit Administration (FTA) noise impact assessment guidelines for transit and rail projects

The FTA guidelines provides detailed prediction methods for ambient noise based on "computation from partial measurement" of Leq or Ldn, and a tabular look-up for general assessment (Table 5-7, FTA Guidance Manual). (FTA Guidance Manual, http://ntl.bts.gov/data/rail05/rail05.html)

1-3-B Federal Highway Administration (FHWA), Highway Traffic Noise Model (HTNM)

The highway traffic noise model is a computer-based tool [93].

1-3-B1 British standard method for road traffic noise calculation [48]

The calculations are based on road traffic counts. Traffic flow count data q can be obtained from the local agency, or by sampling. The basic noise level hourly is predicted at 10 meters away from the nearside carriageway according to the following equation,

$$L_{10} = 42.2 + 10\lg q \text{, dBA}$$

Equation B-4

q = hourly traffic flow, veh/h

Then a series of corrections are done to the basic noise level, such as correction for mean traffic speed, for percentage of heavy vehicles, for gradient, for road surface, and for propagation that includes distance correction, ground cover correction and obstructed propagation correction. The reflection effect by the construction near the road, and the combined effect of several road segments are also included if applicable. Examples of calculating noise levels in some typical scenarios such as propagating over mixed ground cover, screening by flat-topped buildings and noise levels at street junctions surrounded by buildings can be found in Appendix, Calculation of Road Traffic Noise, the Department of Transport, London, 1988.

1-3-C Integrated Noise Model (INM) for aircraft noise, by the Federal Aviation Administration (FAA)

The INM is a computer-based tool. "The INM has been FAA's standard tool since 1978 for determining the predicted noise impact in the vicinity of airports"[94].

1-3-D GIS tool integrated with noise models [49]

For example, a GIS tool with INM.

1-3-E Noise in street canyons

Ghiaus, et al [44] provide a monogram for decisions in the initial stages of the design, by assuming that traffic intensity is dependent on street width (Figure B.5). They also found the following rules:

- High levels of noise can be found in these canyon type streets and low frequency end of the noise spectrum is predominant.
- The noise level decreases with height above the canyon floor. The attenuation in noise level decreases with increasing street width.

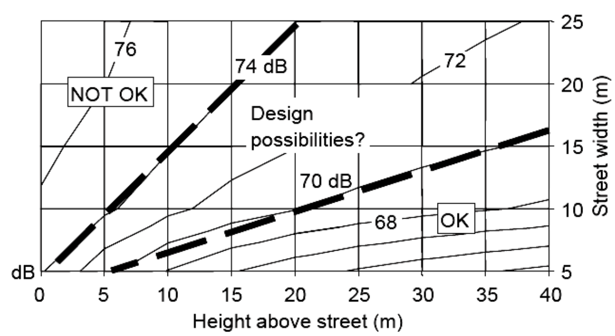


Figure B.5 Contours of noise level at different heights above the street and street widths. Configurations in which natural ventilation is possible are indicated (OK), as are those in which it is ruled out (NOT OK) for offices. Between these two extremes is a region in which there are possibilities for design solutions. [44]

1-3-F. Rule-of-thumb estimating background noise levels (British Standard 4142:1967) [59]

Table B.3 can be used for estimating the ambient background noise level outside residential buildings, which cannot be measured in the absence of noise.

Table B.3 Rule-of-thumb estimating background noise levels

1.	Basic level	50 dBA
2.	Corrections to be added to basic level	
(a)	Type of installation cause noise	
	New factory	0 dBA
	Existing factory in which noise radiated outside is changed by alteration to the building, or the installation of new plant	0 dBA
	Existing factory not typical of area, or obviously not in any of the other categories	+5 dBA
	Old established factories completely in character in well established industrial areas	+10 dBA
(b)	Type of area (select one only)	
	Rural (residential)	-5 dBA
	Suburban, little traffic	0 dBA
	Urban residential	+5 dBA
	Predominantly residential urban, but with some light industry or road traffic	+10 dBA
	General industrial area	+15 dBA
	Predominantly industrial area	+20 dBA
(c)	Time of the day	
	Weekdays only 9am to 6pm	+5 dBA
	Night 10pm to 7 am	-5 dBA
	All other times	0 dBA
(d)	Season	
	If it is known that noise occurs only during the winter	+5 dBA

1-3-G Rule-of-thumb estimating industrial noise attenuation

Table B.4 can be used to estimate industrial noise attenuation. a and b are the façade dimensions of a industrial building, where b>a. D is the distance from the point of interest to the building.

Table B.4 Rule-of-thumb estimating industrial noise attenuation

No attenuation	$D< a/\pi$ from the façade of the industrial building
3dB per doubling of distance	$a/\pi <D<b/\pi$ (The building is taken as plane–source)
6dB per doubling of distance	$D>b/\pi$ (The building is taken as point–source)

Module 1-4 Outdoor Air Quality

1-4-A Downwind from a point source (normal distribution model)[50]

(1) Concentration without ground-level reflection

The pollutant concentration at location C (x, y, z) can be estimated with Equation B-5.

$$C(x, y, z) = \frac{Q}{2\pi\mu\delta_y\delta_z}\exp\left(-\frac{1}{2}\left[\frac{y^2}{\delta_y^2}+\frac{(z-H)^2}{\delta_z^2}\right]\right)$$

Equation B-5

H = the effective stack height, m

δ_y, δ_z = dispersion coefficient, m, can be obtained from [50], Figure 4-6, p. 153 and Figure 4-7, p.154 . The stability class can be found in [50], Table 4-1, p.155.

Q = emission rate, g/s

μ = wind speed at stack height, should be adjusted by height, m/s

y , z = relative distance in y and z direction to the stack (center line of the plume), m

(2) Ground level concentration considering ground-level reflection (Z = 0)

The pollutant concentration at a ground location C(x, y, 0) can be estimated with Equation B-6.

$$C(x, y, 0)=\frac{Q}{\pi\mu\delta_y\delta_z}\exp\left(\frac{-H^2}{2\delta_z^2}\right)\exp\left(\frac{-y^2}{2\delta_y^2}\right)$$

Equation B-6

1-4-B: Downwind from a line source [50]

In the situations such as a series of industries located along a river or heavy traffic along a straight highway, the pollution is modeled as a continuous emitting infinite line source. When the wind direction is normal to the line of emission, the ground-level concentration downwind is:

$$C(x, 0) = \frac{2q}{(2\pi)^{1/2}\delta_z\mu}\exp\left[-\frac{1}{2}\left(\frac{H}{\delta_z}\right)^2\right]$$

Equation B-7

q = the source strength per unit distance, $g/s\cdot m$

When the wind direction is not perpendicular to the line source, Equation 33 is dividend by $\sin\vartheta$. ϑ is the angle between the line source and the wind direction, and the correction should not be used when ϑ<45.

If the line source is short, the edge effect should be counted, but may not be necessarily included in the framework.

$$C(x, 0, 0) = \frac{2q}{(2\pi)^{1/2}\delta_z\mu}\exp\left[-\frac{1}{2}\left(\frac{H}{\delta_z}\right)^2\right]\int_{p1}^{p2}\frac{1}{(2\pi)^{1/2}}\exp(-5p^2)dp$$

Equation B-8

Where $p_1 = y_1/\delta_y$, $p_2 = y_2/\delta_y$.

This is an example used by Wark et al. ([50], p. 172) to explain the calculation procedures.

Estimate the total hydrocarbon concentration at a point 300m downwind from an expressway at 5:30 P.M. on an overcast day. The wind is perpendicular to the highway and has a speed of 4m/s. The traffic density along the highway is 8000 vehicles per hour, and the average vehicle speed is 40mi/hr. The average vehicle emission rate of hydrocarbons is $2\times10^{-2}\,g/s$.

Assuming a reasonably straight section of highway, we will consider the pollutants emanating from a continuous infinite line source. The emission rate per unit length, q, is determined from the product of the emission rate per vehicle times the number of vehicles per unit length. Hence,

$$\frac{Vehicles}{m} = \frac{8000(vehicles/hr)}{40(mi/hr)}(\frac{mi}{1600m}) = 0.125$$

Therefore, $q = 0.125 vehicles/m \times 2\times10^{-2} g/vehicle = 2.5\times10^{-3} g/sm$

For an overcast day, the stability class is D. Thus at a downwind distance of 300m, the value of δz is 12m.

For a ground-level source, H = 0,

$$C(300,0,0) = \frac{2(2.5)(10^{-3})}{(2\pi)^{1/2}(12)(4)} = 42\mu g/m^3$$

1-4-D Traffic-induced pollution in street canyons

Traffic-induced emissions are major sources of air pollutants in urban areas.

An algorithm is available for calculating pollution levels in a urban street canyon with skimming flow. If wind velocity is normal to the vehicle motion and $H_s / D_s \approx 1$, the pollutant concentrations from streets at its lee ($q_a^{'}$) and windward ($q_a^{''}$) sides are: [51]

$$q_a^{'} = \frac{v_1 M}{(0.5+\mu)(2+\sqrt{x^2+z^2})} + q_b$$

Equation B-9

$$q_a^{''} = \frac{v_1 M(H_s - r)}{(0.5+\mu)H_s D_s} + q_b$$

Equation B-10

M = emission capacity of a linear source, g/ms

μ = wind speed over buildings, m/s

H_s, D_s = vertical and horizontal dimensions of a cross-section of the canyon, m

q_b = Background concentration

x, z = coordinates of the calculation point

v_1 = non-dimensional constant, when $H_s / D_s \approx 1$, $v_1 \approx 7$

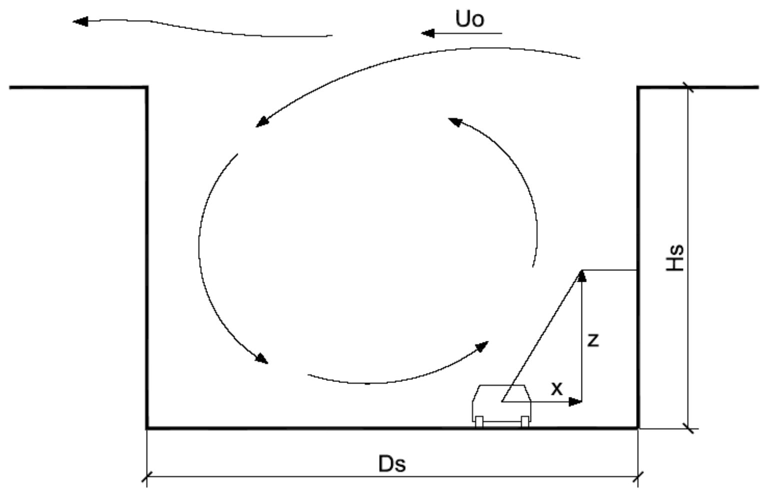


Figure B.6 Pollution in a street canyon

APPENDIX C SOUND INSULATION OF A DOUBLE-ENVELOPE WITH BOTH LAYERS PARTIALLY OPENED

(Module 2-2-E)

Oesterle et al.(2001) introduced a method for estimation sound insulation of a double-envelope with both layers partly opened and test it with measured data in two buildings with double-skin facades in Germany.

Step1. Make sure the geometry of the façade intermediate space and the design of the surface areas result in a largely diffuse sound field.

The direct sound field will be significant where the façade intermediate space is very shallow and where the openings in the inner and outer skins are close together.

$$r_g = \sqrt{A/25}$$

Equation C-1

Where r_g = boundary radius, m

A = the equivalent sound-absorption area, m^2

$$A = K\frac{V}{T_N}$$

Equation C-2

Where V = the volume of the façade space, m^3

T_N = reverberation time, s

K = a constant, equal to 0.05 when measurements are in feet and 0.163 when in meters

The depth of the façade intermediate space d should be much larger than r_g.

E. Oesterle et. al. (2001) measured T_N = 1.2s in the intermediate space of a corridor façade with the external layer open, in the City Gate building, Düsseldorf. It can be a useful reference for the framework. The values of T_N for frequencies 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz are 1s, 1.3s, 1.5s, 1.3s, 1.1s, and 1.1s, respectively.

Step 2. Where a diffuse sound field clearly exists, the method of Equation 6-9 can also be used to calculate the sound reduction by an exterior layer with respect to the intermediate space of the double envelope.

$$\Delta R = -10\log\left[\frac{f(1-10^{-0.1R1})+10^{-0.1R1}}{A}\right]$$
$$= -10\lg\left[f(1-10^{-0.1R1})+10^{-0.1R1}\right]+10\lg A$$

Equation C-3

Where ΔR = the sound transmission reduction, dB

f = the proportion of the open area to the total area of the facade

R_1 = sound insulation of the closed element, dB

Step 3. Calculate the sound reduction by an interior layer with respect to the receiving room.

$$NR = TL - 10\log\frac{S}{A_R}$$

The sound reduction in the receiving room is:

$$NR = -10\lg\left[f(1-10^{-0.1R}) + 10^{-0.1R}\right] + 10\lg\frac{A_R}{S}$$

Equation C-4

APPENDIX D SIZING BUILDING COMPONENTS

D.1 The explicit method of the CIBSE for sizing openings for combined stack and cross ventilation (Module 5-1-1-D)

Step 1. List the flow paths of the ventilation approach, such as in Figure D.1.

Step 2. Size the openings based on the stack effect.

2-1. Calculate the pressure with Equation D-1 at the top of each “slice” of the stack relative to a pressure of zero at grade level.

$$\Delta P_s = -\rho_{in} g T_{in} (h_2 - h_1) \left(\frac{1}{T_{out}} - \frac{1}{T_{in}} \right)$$

Equation D-1

ΔP_s= stack pressure difference, Pa

h_1 = height of the top of the slice, m

h_2 = the height of the grade level, m

T_{in} = absolute indoor air temperature, K

T_{out} = absolute outdoor air temperature, K

ρ_{in} = density of air inside the stack, kg/m^3

2-2. Set the desired neutral pressure level; make sure the stack effect works for every flow path (Figure D.1).

2-3. The stack pressure difference across the inlet is given by the difference in stack pressure at the window/opening and at the neutral pressure level.

2-4. The opening area is sized by applying Equation 8-10 with the required flow rate of this flow path and the pressure difference calculated in step 2-3.

2-5. The process can be repeated for each opening. For the outlet, use the sum of the inlet flow which flows to the outlet.

Step 3. Adjust the opening size with the mode of combined wind and stack effect. The difference of wind pressure from inlet to outlet can be calculated using Equation 34. Add it to the stack pressure difference across the inlet and outlet, and deduct the pressure loss across the outlet. Maintain the size of the outlet and size the inlet area of each flow path with the pressure difference calculated.

Step 4. Adjust the opening size of single-sided ventilation with the wind effect if applicable.

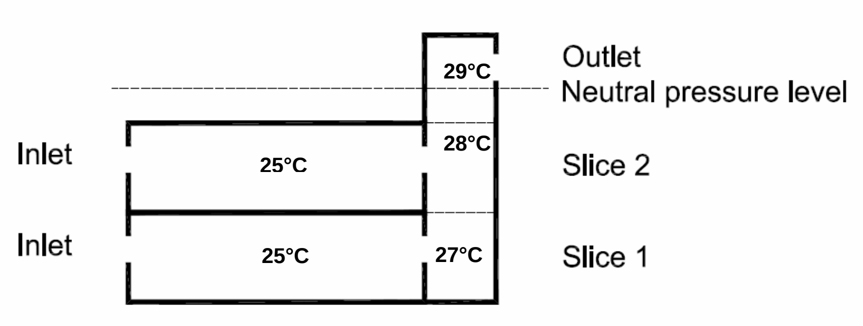


Figure D.1 An example for sizing openings for combined stack and cross ventilation

D.2 Rule-of-thumb approach for sizing thermal mass (Module 5-5-1)

Design inputs are simplified to two categories:

(1) Average mass:1 ft^2 of surface exposed per ft^2 of floor area, of a 4-inch ordinary-density concrete slab; no other thermal mass is included.

(2) High mass: 2 ft^2 of surface exposed per ft^2 of floor area, of a 3-inch ordinary-density concrete slab (or, both side of a 6-in. concrete wall or slab exposed); no other thermal mass is included.

With the building heat gain rate (q) known, if $qh < Q$, the thermal mass is adequate, where:

Q = Mass heat storage capability, Btu/day-ft^2 or W/day-m^2

q = Building heat gain rate, Btu/h-ft^2 or W/m^2

h = Hours occupied in “closed’ mode in the day

Figure D.2 can be used for fast estimation of mass heat storage capability with the inputs of summer design outdoor temperature, mean daily range, mass type (simply high or average), and area.

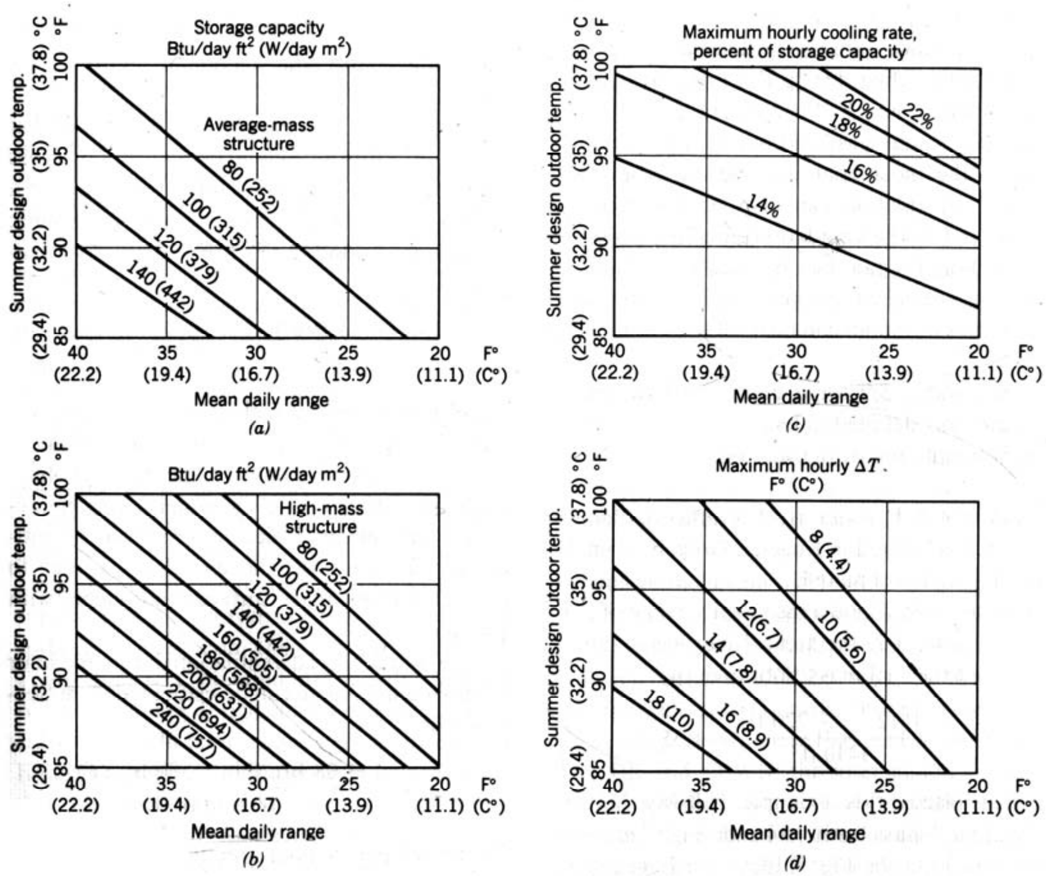


Figure D.2 Sizing thermal mass [56]

D.3 Spreadsheet method for sizing thermal mass (Module 5-5-2)

This procedure can be summarized as:

1. Calculate mass temperature hour by hour, until the mass temperature reaches the outdoor air temperature. As a rule-of-thumb, the final mass temperature is likely to be at least 5F above the lowest air temperature of the night.
2. Add all the hourly cooling to obtain the total mass cooling storage.
3. If the mass temperature is too high, consider more exposed mass area.
4. Determine the approximate flow required for night ventilating air.

Five sub-modules are included in the module.

Module A: Calculating mass heat capacity

The mass heat capacity C can be calculated with the following equation:

$$C = V\rho Cp$$

Equation D-2

C = Mass heat capacity, Btu/F

V = Mass volume, ft^3

ρ = mass density, lb/ft^3

Cp = mass specific heat, Btu/lb·F

Module B. Calculating mass heat storage capacity Q:

$$Q = (T_{mass-p} - T_o) A_{mass} h$$

Equation D-3

Q = mass heat storage capacity, Btu/h

T_{mass-p} = Previous hour mass temperature, F

T_{air} = Outdoor air temperature, F

A_{mass} = Mass surface area, ft^2

h = surface conductance, $Btu/h \cdot ft^2 \cdot F$

Module C. Calculating mass temperature T_{mass}:

$$T_{mass} = T_{mass-p} - \frac{Q}{C}$$

Equation D-4

Module D. Supplementary cooling

If the space has exposed concrete ceilings, walls, and floors, all already accounted for thermal mass, no supplementary area is added. If the entire ceiling is thermal mass but the walls or floors are not, add half the floor area. If the entire ceiling is thermal mass, but the walls are not and there are few walls, add 1/3 to 1/4 of the floor area.

Equation D-3 is used to calculate supplementary cooling due to surfaces other than those of the principle thermal mass. This should be applied for spaces with a significant amount of roof, wall, or floor area in addition to the thermal mass areas counted in the equation above.

$$Q_{sup} = 2.25 \lfloor 80 - T_{mass-f} \rfloor A_{floor}$$

Equation D-5

Q_{sup} = Supplementary cooling, Btu

T_{mass-f} = Final mass temperature, F

A_{floor} = Floor area, ft^2

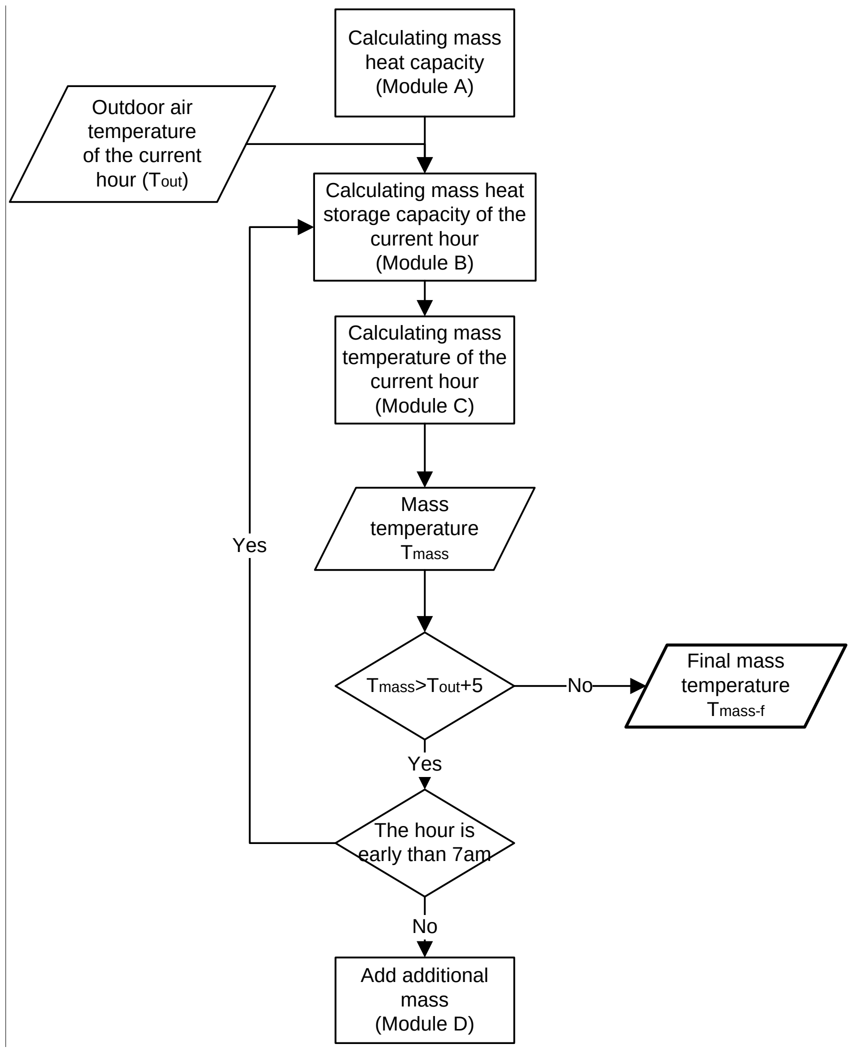


Figure D.3 Flow chart for sizing thermal mass for night ventilation

Module E: Determine the approximate flow required for night ventilating air:

$$cfh = \frac{Q_{\max}}{0.018\Delta T}$$

Equation D-6

Q_{max} = the cooling Btu for the hour of maximum cooling during the night, Btu/h

ΔT = the temperature difference between the final mass temperature and outdoor air for that same hour as maximum cooling.

The flow chart for sizing thermal mass is shown in Figure D.3. An example is given in Table D.1.

A. Mass surface area		2,232 ft^2
B. Mass heat capacity		16,573 Btu/°F
C. Floor area (supplementary cooling)		360 ft^2
	Total building (bay) volume	22,900 ft^3

(I) Hour	*(II)* Outside Air Temperature *(F)*	*(III)* Cooling[a] *(Btu/h)*	*(IV)* Mass Temperature *(F)*
P.M.			
8	80	No heat removed	80
9	77	(80 − 77)2232 (line A) = 6,696	$80 - \frac{6696}{16{,}573 \text{ (line B)}} = 79.6$
10	74	(79.6 − 74)2232 = 12,499	$79.6 - \frac{12{,}499}{16{,}573} = 78.8$
11	71	(78.8 − 71)2232 = 17,410	$78.8 - \frac{17{,}410}{16{,}573} = 77.7$
12	68	(77.7 − 68)2232 = 21,650	$77.7 - \frac{21{,}650}{16{,}573} = 76.4$
A.M.			
1	65	(76.4 − 65)2232 = 25,445	$76.4 - \frac{25{,}445}{16{,}573} = 74.9$
2	62	(74.9 − 62)2232 = 28,793	$74.9 - \frac{28{,}793}{16{,}573} = 73.2$
3	60	(73.2 − 60)2232 = 29,462	$73.2 - \frac{29{,}462}{16{,}573} = 71.4$
4	58	(71.4 − 58)2232 = 29,909	$71.4 - \frac{29{,}909}{16{,}573} = 69.6$
5	60	(69.6 − 60)2232 = 21,427[b]	$69.6 - \frac{21{,}427}{16{,}573} = 68.3$
6	62	(68.3 − 62)2232 = 14,062	$68.3 - \frac{14{,}062}{16{,}573} = 67.5$
7	65	(67.5 − 65)2232 = 5,580	$67.5 - \frac{5580}{16{,}573} = 67.2$
8	68	Stop flush: mass temperature is now below outdoor temperature	

D. Total mass cooling	212,933 Btu
E. Final mass temperature	67.2 F
F. Supplementary cooling	10,368 Btu
G. Total cooling (212,933 + 10,368)	223,301 Btu
H. Compare to 24-h heat gain	196,344 Btu
I. Flow rate required for night ventilation	About 5.5 ACH

[a] A surface conductance of 1.0 Btu/h-ft^2-°F is assumed in this calculation.

[b] At this point, enough heat has been removed to meet the typical bay's design-day heat gain.

Table D.1 Cooling by night ventilation of thermal mass of a typical bay in the Oregon office building [56]

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