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Dynamic Metrics of Natural Ventilation Cooling Effectiveness for Interactive Modeling

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Color should be used for Figures 5-7 in prints.

Abstract

The evaluation of natural ventilation potential for cooling indoor spaces during the early design phases is of great interest to researchers and practitioners. Among various definitions and usages for natural ventilation potential (NVP) in early design evaluation, this paper reviews and identifies the key performance indicators, and proposes two new dynamic metrics—natural ventilation cooling effectiveness (NVCE) and climate potential utilization ratio (CPUR). The metrics are dynamically responsive to various design options, in both steady and transient states, allowing consideration of thermal mass. Assisting in design development processes, the metrics quantify how well indoor spaces make use of natural ventilation’s cooling capacity. Case studies are presented to demonstrate how NVCE and CPUR enable designers to evaluate the predicted performance and how to apply the information to improve building design. The results of the design iterations showed that the relationship among various design parameters should be dynamically understood in order to evaluate the performance of natural ventilation, confirming that “the more the airflow, the greater the potential,” and “the heavier the thermal mass, the greater the energy saving” were not always true.

Keywords: natural ventilation; key performance indicators; interactive modeling; building simulation; ventilative cooling; thermal mass

1. Introduction

Building analyses using natural ventilation as an alternative cooling source have reported meaningful energy reductions world-wide. For instance, natural ventilation helped meet thermal comfort criteria in Bangkok, Thailand, with a steady airflow of 0.4 m/s [1]. Simulations of a building with a natural-ventilation-dedicated component in Tokyo, Japan, demonstrated a 35% reduction in electricity energy demand for cooling [2–4]. Also, analysis of a traditional Italian building reported that natural ventilation would save 43 – 53% of cooling energy depending on Italian local climates [5]. Some climates offer better opportunities than others. For example, a building in a hot and dry climate in Mexico would utilize more of natural ventilation’s potential than one in a hot and humid climate in the same country [6].

In addition to climate conditions, the benefits from natural ventilation could be increased or decreased via a combination of various design strategies. For example, two identical buildings in a hot and humid climate could lead to different thermal environments depending on heat capacities of building materials [6]. Thermal mass is known to have significant impact on natural ventilation's cooling potential [7–9], and alternating cooling modes, namely mixed-mode, is an effective way to utilize natural ventilation [10–13]. Window operation controlling the timing of the use of natural ventilation is another significant element in natural ventilation [14–16]. Particularly, night-time ventilation, or night-time cooling, utilizes the lower air temperature during the night to help cool the space and mitigate the peak cooling demand during the day with the help of thermal inertia [17,18].

These multifaceted factors influencing natural ventilation's cooling potential make it important to consider the interrelationship among building design decisions. This paper aims to quantify natural ventilation's cooling performance of a building with such factors, assisting in design iterations during early design phases. It explores relevant metrics that indicate natural ventilation's cooling potential, proposes new metrics to be used in early building design phases, and investigates how these metrics inform the dynamics of various design strategies combined with natural ventilation.

1.1. Natural ventilation potential (NVP)

Numerous studies have used a general term, natural ventilation potential (NVP), to indicate natural ventilation's usage in buildings and sites. One major purpose of these studies was to evaluate the suitability of using natural ventilation at given sites or under given climates [19–26]. Researchers examined local conditions including meteorological, morphological, environmental, and thermal information to evaluate NVP. Researchers could then compare NVPs of various regions, countries, or worldwide. Another major purpose served by NVP evaluation was to describe a building's potential to utilize natural ventilation with a given set of a building design options (for example, window location or opening areas) [27–29]. The foci of these studies were on building design or building components to identify better solutions utilizing natural ventilation. Previous studies on NVP of sites and buildings are listed in Table 1.

Table 1. Previous work on Natural Ventilation Potential (NVP) research on climates

	Location	**Category**	**Evaluation purpose**	**NVP Metric**
[20]	USA	Site	NVP of the US	Target ACH and potential cooling effect
[21]	Mediterranean coastal zones	Site	Climate comparison	Statistical wind rose and radar plot
[22]	Warm-humid climates in Asia	Site	City comparison	Thermal comfort improvement
[23]	European climates	Site	City comparison	Very high/ high/ medium/ poor
[24]	Sheffield District, UK	Site	NVP and urban morphology	Urban morphology indices (rugosity, porosity, sinuosity) and pressure coefficients
[26]	Geneva, Switzerland	Site	Site NVP	Good/medium/poor
[30]	Australia	Site	NVP comparison of Australian climates	NV hour and satisfied natural ventilation hour

				(SNVH)
[31]	China	Site	NVP of China	Annual cooling energy savings (kWh/m^2-year)
[32]	Canada	Site	Weather data set comparison	NV hour
[33]	China	Site	Re-evaluation of city's NVP with a more realistic building setting	Airflow rates
[17]	European climates	Site	Night-time cooling	Climate cooling potential
[25]	China	Site	City comparison	NV hour and pressure difference pascal hours (PDPH)
[34]	China	Site	City comparison, revised from [25]	PDPH
[35]	India	Site	NVP of India	PDPH
[27]	Turkey	Building	Indoor partitions	Air velocity
[28]	Hong Kong	Building	Various window opening degrees	ACH
[29]	General	Building	Window opening design	Natural ventilation effectiveness (NVE)
[36]	General	Building	New equation	Airflow rates
[37]	General	Building	Building design	NVE
[38]	Elblag, Poland	Building	Multiple chimneys and window tilts	ACH
[39]	California, USA	Building	Validation with occupants' window use, local weather conditions, indoor environmental conditions	ACH
[40]	General	Building	Window opening design	PMV and extended PMV measures
[41]	General	Building	Window opening size and atria	Ventilation performance indicator (VPI)

As revealed from the above literature, NVP has referred to various quantities depending on the focus of the research. Some used conventional quantities including airflow rates, air speeds, air changes per hour (ACH), and the total number of hours in a year during which natural ventilation provides acceptable air conditions (NV hour). Others proposed new metrics to nondimensionalize or otherwise describe a certain aspect more effectively to suit their research objectives. Such customized metrics include climate potential for natural ventilation (CPNV) [19], pressure difference Pascal hours (PDPH) [25,34,35], climate cooling potential (CCP) [17], ventilation performance indicator (VPI) [41], satisfied natural ventilation hour (SNVH) [30], and natural ventilation effectiveness (NVE) [29,37].

1.2. Evaluation metrics for an interactive design process

This study proposes NVP metrics that can be used during early design but later than a site evaluation phase—namely, the design development (DD) phase. The DD phase is an important design phase where multidisciplinary issues, including energy-conscious design, acoustic design, lighting design, envelope design, indoor environmental design and more, are addressed. For this reason, partnership and arrangements among various disciplines are critical, and vigorous design efforts are ideally made during the DD phase [42]. The evaluation metrics, therefore, should not only consider site information but also reflect design specifics. The desired criteria of such metrics would include:

- Dynamic response to design alternatives, such as materials, room design, window design, etc.;
- Ability to consider both steady-state and transient thermal behavior of a building; and
- Information that directly gives design feedback.

1.3. Research scope and methodology

Among various purposes for using natural ventilation, including controlling air quality, increasing work productivity, and cooling, this paper focuses on its cooling effectiveness. The paper reviews existing NVP metrics and consolidates their key characteristics into two new metrics—natural ventilation cooling effectiveness (NVCE) and climate potential utilization ratio (CPUR)—in order to meet the criteria described in Section 1.2. Lastly, the paper demonstrates the usage of NVCE and CPUR in design phases, and how these metrics incorporate and characterize design decisions as well as various climate zones.

2. Review of natural ventilation performance metrics

2.1. Commonly used metrics in natural ventilation prediction

2.1.1. Volume airflow rates

As direct measures of airflow, volume airflow rates (m^3/s) and air speeds (m/s) are often used in natural ventilation evaluation. Such metrics were determined in experiments by using the tracer-gas decay method [43] and conducting wind tunnel tests [44], as well as in numerical models including airflow network (AFN) and computational fluid dynamics (CFD) [36,38,45–47].

For example, ASHRAE Standard 62.1 [48] requires a breathing zone to meet a certain ventilation rate (V_{bz}) depending on the zone’s population (P_z), floor area (Z_z), and occupancy categories (e.g., bedroom, lobby, or office room). The calculation is given by:

$$V_{bz}=R_p P_z+R_a A_z,$$

where R_p is outdoor airflow rate required per person, P_z is zone population, R_a is outdoor airflow rate required per unit area, and A_z is zone floor area. R_p and R_a for different occupancy categories are listed in [48].

2.1.2. Air changes per hour

Air changes per hour (ACH) is another popular metric for natural ventilation evaluation ranging from indoor ventilation [20,28,49,50] to urban wind studies [51,52]. It measures the ratio of incoming airflow volume for an hour to the room volume, written as:

$$ACH = \frac{3600(s)\dot{V}}{vol},$$

where $\dot{V}$ is the airflow rate (m^3/s) and vol is the room volume (m^3). In experimental settings, an ACH can also be calculated by using the tracer-gas decay method [39,53]. The ACH in this method is computed as:

$$ACH = 3600 \ln \frac{C_0}{C_r} \frac{1}{\tau},$$

where C_0 is the initial CO_2 concentration, C_r is concentration at the time τ.

2.2. Customized metrics suggested by researchers

2.2.1. Natural ventilation evaluation by site and climate conditions

Ref. [26] defined natural ventilation potential (NVP) as “the possibility to ensure an acceptable indoor air quality by natural ventilation only” and passive cooling potential (PCP) as “the possibility to ensure an acceptable indoor thermal comfort using natural ventilation." They described NVP levels of local districts of Geneva, Switzerland, with good, medium and poor NVP and visualized them on a map using GIS. No building information was considered since the purpose was to evaluate NVP of a site rather than of a building. Criteria of NVP included but were not limited to meteorological data, including wind speed, direction, and air temperature; mean height of buildings; mean orientation of the streets; and buildings' adjacency with neighbors.

Similarly, but with different criteria, [23] evaluated NVP of five sites. Their criteria included undisturbed wind, local wind, stack effect, noise levels, and pollutant levels, as well as urban fabric and experts' ratings. NVPs were rated as very high, high, medium and poor. In another study, the NVPs of Basel, Switzerland, were evaluated and categorized as highest, intermediate, and lower NVPs [54]. The study created maps for pollution hours, noise hours, stack hours, as well as wind hours and analyzed them to yield NVP.

A metric named climate potential for natural ventilation (CPNV) quantified a climate's suitability for natural ventilation based on air temperature and humidity ratio [17]. The lower and the upper temperature criteria were determined by the adaptive model of ASHRAE Std. 55 [55], although the author indicated that other adaptive models might also be used, such as CEN Std. EN 15251 [56]. The lower and the upper humidity ratios were determined by the relative humidity of 30 % and 70 %. The CPNV was then calculated by the sum of the hours, during which climate condition met the criteria, divided by the total number of hours in a year. The metric is given as:

$$CPNV = \frac{\Sigma_{i=1}^{n} h_{NV,i}}{h_{tot}},$$

where h_{tot} is total number of hours in a year, and $h_{NV,i}$ is 1 if the climate condition at the i^{th} hour of the year meets thermal criteria, and 0 otherwise.

2.2.2. Natural ventilation evaluation by pressure difference

A natural ventilation performance indicator using pressure differences was proposed by [25]. The authors suggested the pressure difference Pascal hours (PDPH) as a means to predict NVP. The equation for the 'effective pressure difference (ΔP_{eff})' was calculated by the building's ventilation rate due to stack and wind effects, using the orifice flow equation.

Also, the 'required effective pressure difference (ΔP_R)' to meet the minimum ventilated rate per ASHRAE Std. 62.2P [57] was calculated. The PDPH is an index for air pressure semi-analogous to degree-days for temperature, which can be expressed as:

$$PDPH = 1\,hr * \sum_{hours} \left(\Delta P_{eff} - \Delta P_R \right), \text{if } \Delta P_{eff} - \Delta P_R > 0.$$

This metric is counted only when $\Delta P_{eff} - \Delta P_R > 0$ as noted in the equation. In their study, the PDPHs of four cities in China were calculated with several assumptions: south-facing buildings, identical openings on the south and the north facades, and uniform indoor air temperature at 22 degrees Celsius. The required effective pressure difference was determined by the minimum requirements from ASHRAE Std. 62.2P neglecting possible internal loads. The approach using the pressure difference gave useful information about NVP at a city scale. Ref. [35] also used PDPH as an NVP metric.

2.2.3. Natural ventilation evaluation by temperature difference

A metric named climate cooling potential (CCP) was suggested to explain degree-hours for the difference between indoor and outdoor air temperature [17]. Defined as “a summation of products between building/external air temperature-difference and time interval,” the CCP represented the cooling potential of a climate and its impact on a building. The value of CCP was 1 if the temperature difference was the same or larger than the critical temperature difference for night-time ventilation, and the value was 0 otherwise. The metric is written as:

$$CCP=\frac{1}{N}\sum_{n=1}^{N}\sum_{h=h_i}^{h_f} m_{n,h}\left(T_{b,n,h}-T_{e,n,h}\right)\begin{cases} m=1\,hr\,, if\, T_b-T_e \wedge \geq \Delta T_{crit} \\ m=0\,, if\, T_b-T_e<\Delta T_{crit}\,, \end{cases}$$

where h is the time of a day (h = 0, …, 23), H_i and H_f are the initial and the final hour of the night-time ventilation respectively, T_b is building temperature, T_e is external temperature, and ΔT_{crit} is critical temperature difference for night-time ventilation, for which the authors used 3 K.

2.2.4. Natural ventilation evaluation by buoyancy effect

An indicator for stack ventilation in multi-story buildings, the ventilation performance indicator (VPI), was suggested by [41]. The authors provided a dimensionless metric that informs designers how to meet the ventilation rate and indoor temperature requirements via an atrium. VPI is defined as:

$$VPI=\left(\frac{Q^2}{g^{'}H^5}\right)^{\frac{1}{2}},$$

where Q is airflow rate through the room (m^3/s), g' is reduced gravity due to buoyancy (m/s^2), and H is the height of a story (m). The term, g', is interchangeable with the measure of temperature, as in, $g^{'}=g\beta\left(T-T_o\right)$, where g is gravitational acceleration, β is the thermal expansion coefficient, and T and T_o are indoor and outdoor temperatures. Therefore, VPI can compare ventilation requirements to the stack effect resulting from the temperature difference and building height. The authors suggested that designers identify the “per-person VPI” per requirements, assign occupancy in a multi-story atrium building, and then determine the opening sizes to meet the designed VPI in each zone.

2.2.5. Natural ventilation evaluation of building design

To evaluate the natural ventilation potential of a customized building design, a metric called natural ventilation effectiveness (NVE) was suggested [37]. The metric compared the hourly airflow rate of a customized building to the airflow rate that was required to offset the cooling and ventilation load. The ratios of these two airflow rates were added for the hours of the test period and then divided by the total hours. The NVE was calculated as:

$$NVE=\frac{\Sigma\alpha}{n}\begin{cases}\alpha=1 & \text{, if } ACH_{avail}\geq ACH_{req}\\ \alpha=1 & \text{, if } ACH_{req}=0\\ \alpha=ACH_{avail}/ACH_{req} & \text{, otherwise,}\end{cases}$$

where ACH_{avail} is the available air changes per hour to be provided through openings, and ACH_{req} is the required air changes per hour, and n is the number of hours in the simulation period. This equation works for a steady-state condition. The authors retrieved the calculation of ACH_{req} from an energy simulation result.

3. Proposed and revised metrics to evaluate the effectiveness of natural ventilation's cooling performance

3.1. Three key metrics: CPNV, NVCE and CPUR

To suit the design procedure, this project focused on three key metrics, including two existing metrics from literature. One of the two existing metrics is climate potential for natural ventilation (CPNV), and the other is natural ventilation effectiveness (NVE). CPNV is useful since it offers the baseline information of the site based only on climate data, and is minimally revised in this paper to allow for customized simulation periods and criteria. NVE is helpful to investigate building design components as the formulation is influenced not only by climate conditions, but also by building materials, window configurations, internal and solar heat gains, and room sizes.

In this paper, we revise the NVE for three purposes. First, the metric needs mathematical expressions to represent the above-mentioned building components. Because the original NVE calculation depended solely on energy simulation results, the effect of having different design options on the metric would be shown only at the end of simulations. To overcome this limitation and offer users a clearer preview, we provide explicit equations to calculate the metric in this paper. The equations will also allow analytical approaches. Second, this paper develops the formulation of the metric to work with thermal mass, and thus, transient conditions; whereas the original NVE worked for steady-state conditions only. Lastly, while the original NVE has taken the minimum ventilation requirements and cooling demands into consideration, we name this revised metric Natural Ventilation Cooling Effectiveness, or NVCE, to clarify the purpose of the evaluation and focus on cooling performance.

With NVCE referring to a building's potential and CPNV a site's potential, a new supplementary metric that compares the NVCE and CPNV is also proposed, which we name Climate Potential Utilization Ratio, or CPUR. This metric indicates how well a building design has utilized the natural ventilation potential of the climate.

3.2. Proposed metric: natural ventilation cooling effectiveness (NVCE)

3.2.1. Definition of natural ventilation cooling effectiveness

Ranging from 0 to 1, the revised NVCE measures the effectiveness of natural ventilation as a cooling resource within a timestep. The NVCE of a single time step ($NVCE_{ts}$) is defined as:

$$NVCE_{ts} \equiv q_{avail} / q_{req} \tag{1}$$

where q_{avail} is the cooling power available through natural ventilation, and q_{req} is the required cooling power that would bring the indoor temperature to a desirable temperature. Unlike the original NVE, the proposed NVCE adopts cooling power, q, instead of ACH to consider transient cases more conveniently, as we elaborate in Section 3.2.3. The NVCE of a desired duration (a year, a season, or a month) is then defined as an average of each $NVCE_{ts}$ within the duration, as in Eq. (2):

$$NVCE = \frac{\Sigma_{n_{ts}} NVCE_{ts}}{n_{ts}}, \tag{2}$$

where n_{ts} is the number of time steps of the simulation period, which is 8760 if a time step is an hour and the simulation period is a year.

3.2.2. NVCE in a steady state

The key variables in NVCE are the available cooling power (q_{avail}) and the required cooling power (q_{req}¿. Equation (3) defines q_{avail} as below:

$$q_{avail} \equiv \begin{cases} 0, \wedge \text{if } T_{target} - T_{out} < 0 \\ -\rho c \dot{V}_{avail} \left(T_{target} - T_{out} \right), \wedge \text{otherwise}, \end{cases} \tag{3}$$

where ρ is air density, c is the specific heat of air at constant pressure, $\dot{V}_{avail}$ is intake airflow rate through natural ventilation obtained by simulations, calculations, or measurements, and T_{target} and T_{out} are target and outdoor temperatures. The indoor temperature ($T_{¿}$) under a steady state can be calculated as in Eq. (4):

$$T_{¿} = \frac{q_{gain}}{UA + \rho c \dot{V}_{avail}} + T_{out}, \tag{4}$$

where U is the thermal transmittance of the building envelope, A is the area of building envelope, and q_{gain} is the sum of heat gains from solar heat gain, occupants, lightings, and various home appliances, excluding the heat gains or losses through the envelope. However, if q_{avail} is not sufficient, such that

$T_{\text{¿}} > T_{target}$, there must be supplementary cooling power ($q_{\text{¿}}$) to achieve T_{target} as in Eq. (5).

$$T_{target} = \frac{q_{gain} + q_{\text{¿}}}{UA + \rho c \dot{V}_{avail}} + T_{out} \tag{5}$$

We define q_{req} as the sum of available and supplementary cooling powers as in Eq. (6). $NVCE_{ts}$ can then be written as in Eq. (7).

$$q_{req} \equiv q_{avail} + q_{\text{¿}} \tag{6}$$

$$NVCE_{ts} = \frac{q_{avail}}{q_{avail} + q_{\text{¿}}} = \frac{-\rho c \dot{V}_{avail} \left(T_{target} - T_{out}\right)}{-\left\{q_{gain} - UA\left(T_{target} - T_{out}\right)\right\}} \tag{7}$$

In a steady state, NVCE can also be expressed as Eq. (8).

$$NVC\,E_{ts} = \frac{q_{avail}}{q_{req}} = \frac{\dot{V}_{avail}}{\dot{V}_{req}} = \frac{ACH_{avail}}{ACH_{req}} \tag{8}$$

Equation (7) is elaborated from the original NVE, yet it still holds the same formula as NVE. Detailed steps from Eq. (4) through Eq. (8) are explained in Appendix A.

3.2.3. NVCE in a transient state

When thermal mass is present, Eqs. (4-(5) need to be modified to consider the heat storage of the mass as in Eqs. (9-(10):

$$T_{\text{¿},n+1} = T_{\text{¿},n} e^{\frac{-t}{\tau_n}} + \left(T_{out,n} + R_n q_{gain,n}\right)\left(1 - e^{\frac{-t}{\tau_n}}\right) \tag{9}$$

$$T_{target,n+1} = T_{\text{¿},n} e^{\frac{-t}{\tau_n}} + \left(T_{out,n} + R_n\left(q_{gain,n} + q_{\text{¿},n}\right)\right)\left(1 - e^{\frac{-t}{\tau_n}}\right) \tag{10}$$

$$R \equiv \left(UA + \rho c \dot{V}_{avail}\right)^{-1} \tau \equiv R\,C,$$

where $T_{\text{¿},n+1}$ and $T_{target,n+1}$ denote the indoor and target temperatures of the next time step, and t is the length of a time step in seconds. A target temperature is a desired temperature, which could be either fixed or varying, and supplemental cooling ($q_{¿}$) is varied each time step to maintain the target in a hypothetically conditioned building. The heat gain (q_{gain}) is varied throughout the day as solar gain changes and occupancy varies. As $\dot{V}_{avail}$ may vary each time step, so do R and τ. With these variables, NVCE can be written as below.

$$NVCE_{ts}=\frac{q_{avail}}{q_{avail}+q_{¿}}$$

$$¿\frac{-\rho c\dot{V}_{avail}\left(T_{target}-T_{out}\right)}{-\rho c\dot{V}_{avail}\left(T_{target}-T_{out}\right)-\left\{q_{gain}-\left(\frac{T_{target,n+1}-T_{¿}e^{\frac{-t}{\tau}}}{1-e^{\frac{-t}{\tau}}}-T_{out}\right)\frac{1}{R}\right\}} \tag{11}$$

In Eq. (11), all variables except $T_{target,n+1}$ are of the current time step, n. As Eqs. (3)(7),(11) indicate, $NVCE_{ts}=0$ when no cooling power is available from natural ventilation ($q_{avail}=0$), and $NVCE_{ts}=1$ when no supplemental cooling is needed ($q_{¿}$= 0). If NVCE is between 0 and 1, it is the fractional cooling capacity that natural ventilation can provide compared to the cooling capacity required to meet the target indoor temperature.

3.3. Proposed metric: Climate potential utilization ratio (CPUR)

While NVCE indicates the status quo of the current design in terms of natural ventilation's cooling performance, Climate Potential Utilization Rate (CPUR) is introduced to quantify how much room for improvement is left under the given climate. A CPUR is simply the ratio of NVCE to CPNV as described in Eq.(12). To use the metrics correctly, the duration, time step, and thermal criteria of NVCE and CPUR must be the same.

$$CPUR \equiv NVCE / CPNV \tag{12}$$

3.4. Understanding NVCE and CPUR together

The metrics dynamically respond to building design and climate conditions as explained in Table 2. The combination of the two metrics of NVCE and CPUR can then provide useful information in interactive design and energy modeling.

Error: Reference source not found illustrates the conceptual workflow as to how the metrics may be used during an early design phase. For example, architects set a goal to achieve NVCE of 1 to replace mechanical cooling with natural ventilation entirely. While evaluating the site, they notice that the given climate has CPNV of 0.8. An initial design option may turn out to have an NVCE of 0.4, which architects know it is only the half of what the climate has to offer, as CPUR is 0.5. Through numerous design iterations, they keep track of NVCE to identify the best design option. A CPUR that is greater than 1 may be achieved by using thermal mass strategically. This is because a properly calculated thermal storage amount may help a room remain at a comfortable level, even when the outdoor air is warmer than the comfort criteria.

Figure 2 explains the interpretation of the combination. For example, a low NVCE and a low CPUR indicate that natural ventilation cannot offer as much cooling power as the specific building needs, but there still is room to improve the NVCE since the building has not utilized the climate potential very well. A low NVCE and a high CPUR may not be encouraging, as this combination implies that the building requires significant mechanical cooling despite a high utilization ratio of its climate resources. Having this information while developing a building design would allow architects to revise their design to better utilize natural ventilation.

Table 2. Dynamic nature of CPNV, NVCE, and CPUR.

		CPNV	**NVCE**		**CPUR**
			q_{avail}	q_{req}	
Site	**Influenced by local climate**	×	×	×	×
	Influenced by intake airflow (window sizes, single-sided ventilation, cross-ventilation, displacement ventilation, etc.)		×	×	×
	Influenced by heat gain and loss (Building materials, internal and solar heat gains, etc.)			×	×
	Influenced by thermal mass			×	×

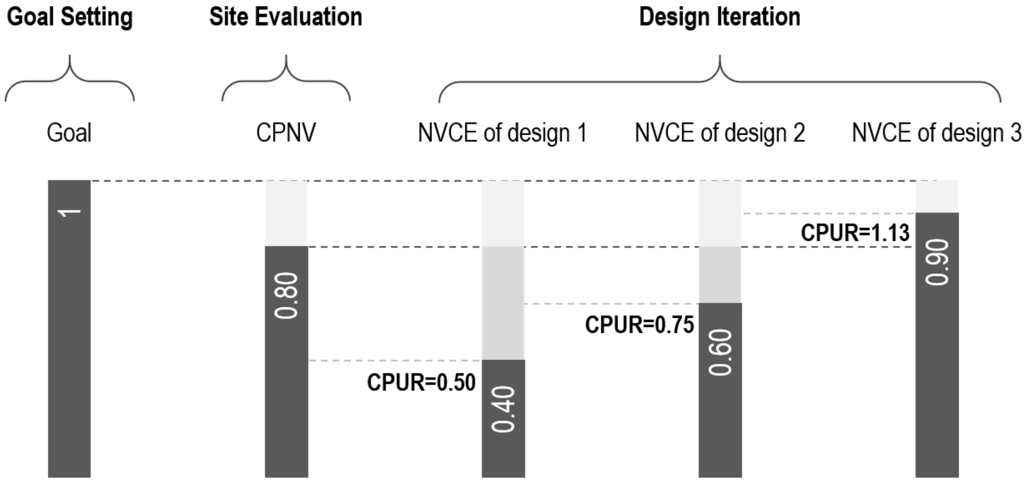


Figure 1. Conceptual diagram of the usage of CPNV, NVCE, and CPUR.

Figure 2. Understanding NVCE and CPUR together.

4. Interactive modeling in a design process using NVCE and CPUR

4.1. Feasibility study description

A feasibility study was conducted to demonstrate a way to harness the dynamic metrics within an interactive design framework, and to understand building design options that influence the NVCE in various climates. Three cities were examined: Phoenix, AZ; Fresno, CA; and Denver, CO. The cities are located in the 2B, 3B, and 5B climate regions, respectively, per [58]. The study used a set of 3D parametric design platforms including Rhino 3D [59], a computer-aided design application, and Grasshopper [60], a visual programming language, to allow an interactive design procedure. Two Grasshopper plug-ins, Ladybug [61] and Honeybee [62], were used to import weather data and run building energy simulations using EnergyPlus within the Grasshopper environment.

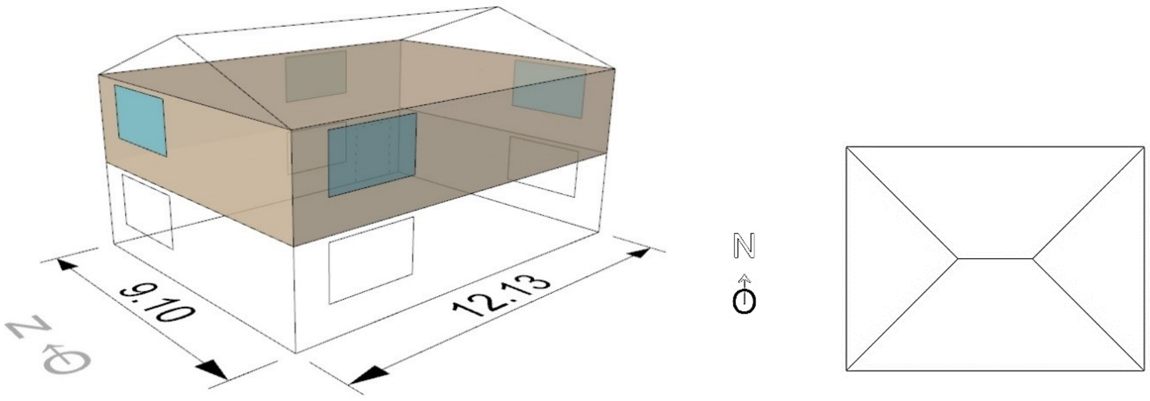
4.2. A base case model description and variations to consider

The base case building (Figure 3 (A)) was the prototypical single-family detached house model developed by the Pacific Northwest National Laboratory

(PNNL) [63]. Originally intended for the U.S. Department of Energy's Building Energy Codes Program, the residential prototype building models for various climate regions have been widely used in simulation research by either using the building properties only and/or using building geometries [64–71]. We downloaded EnergyPlus Input Files (IDF) for the three climate zones (2B, 3B, and 5B) from [63]. These files included building properties in compliance with the 2018 International Energy Conservation Code (IECC). The settings applied in this study are detailed in Appendix B.

For natural ventilation, this test used the ZoneVentilation:WindandStackOpenArea class of EnergyPlus made available through Honeybee. This model automatically decided a ventilation mode between buoyancy-driven or wind-driven ventilation modes, depending on window's height and angle towards the wind direction. All windows created in this test were at the same heights, therefore, no stack effect was considered. Users may choose other ventilation models offered in Honeybee, including a custom ventilation type for chimneys or cowls, and a fan-driven ventilation with a fixed airflow rate. Integration into the proposed workflow of models not yet supported by Honeybee, including the airflow network model of EnergyPlus or customized analytical models, would require further development.

The reference IDF data consisted of only two zones for a three-story house: an attic zone and a living unit zone. Two floors were bundled as a living unit zone, so we separated the floors to represent the ground floor and the second-floor. Thermal zoning and distributions of internal heat gains should be determined by the floor plans of a specific building. However, since this feasibility study focuses on the demonstration of the workflow, we used the traditional core-perimeter zoning method of EnergyPlus. Since the room is not as large as other reference commercial buildings and a core zone would not have any natural ventilation, only perimeter thermal zones were created with a zone depth of 4.55 [m], which is a reasonable size for perimeter zones [72].



(A) (B)

Figure 3. (A) A simulation model for a single-family detached house developed by the Pacific Northwest National Laboratory (PNNL) for U.S. Department of Energy's Building Energy Codes Program; and (B) Thermal zoning of the second-floor. The whole building was simulated, from which the second-floor (highlighted in (a)) was analyzed.

Based on the base case, various design options listed in Table 3 were explored to reveal their impacts on natural ventilation metrics under different climates, and thus demonstrating how these metrics help make design decisions. Two simulation periods, one from January to December and the other from May to October, were chosen to represent seasonal impacts.

Table 3. Model set-ups for Study.

Design factors	Variables
(1) Climates	Fresno, CA Phoenix, AZ Denver, CO

(2) Simulation period	Annual (Jan-Dec) Seasonal (May-Oct)
(3) Operable window area	5 %, 25 %, 50 %, and 75 % airflow rates of base case
(4) Shading devices, glazing sizes, occupancy, light fixture efficiency, appliances, etc.	5 %, 25 %, 50 %, and 75 % solar and internal heat gains of base case
(5) Thermal mass	5 %, 25 %, 50 %, and 75 % thermal capacity of base case

After obtaining NVCE of each city for a base-case building, other variables including airflow rates, solar and internal heat gains (hereinafter heat gains), and thermal capacities were tested with reduced values to represent different design options. For example, the reduced airflow rates may represent reduced opening areas, and the reduced heat gains may represent enhanced shading strategy or reduced occupant density. With a combination of variations in Table 3 (3)-(5), 125 cases for each city were examined by post-processing the simulation results in Python codes, which led to 375 cases for each simulation period. The target temperature, T_{target}, for CPNV and NVCE calculations was set monthly according to the adaptive model proposed by [73]. Humidity is not of a major concern in the chosen cities, and was not considered in the criteria.

4.3. Simulation work flow

The non-design metric, CPNV, was calculated based on thermal criteria (target temperatures only in this case) and weather data imported through Ladybug. Honeybee translated the 3D Rhino geometry into a thermal zone for energy simulation, and read climate information via Ladybug. Then the energy simulation results including zone air temperature, total heat gains, and airflow rates were plugged to a customized component written in Python. The Python component extracted the total heat gains (q_{gain}) by summing up solar gain, and internal heat gains from lighting, equipment and occupancy. The airflow rates caused by infiltration and natural ventilation were summed to calculate the total airflow rates ($\dot{V}_{avail}$). This component used Eqs. (3)-(4, (10(11) to calculate NVCE and CPUR. Figure 4 describes the work flow.

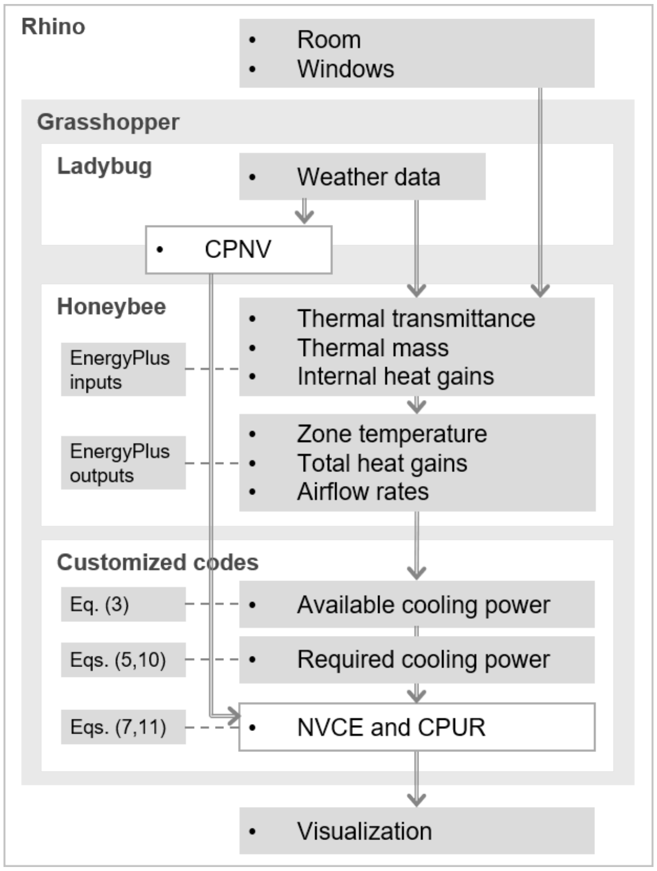


Figure 4. Parametric design frameworks.

5. Results and discussion

5.1. Climate Potential of natural ventilation (CPNV)

The climate potential of natural ventilation (CPNV) of each city was calculated using weather data, analysis period, and target temperatures, and is shown in Table 4. Unlike the original CPNV calculation [19], this study only considered outdoor dry bulb temperature in order to be consistent with NVCE's criteria.

Table 4. CPNV of three cities

City	Annual: Jan – Dec CPNV	Seasonal: May-Oct CPNV
Phoenix, AZ	0.66	0.41
Fresno, CA	0.83	0.68
Denver, CO	0.94	0.88

5.2. Natural Ventilation Cooling Effectiveness (NVCE)

5.2.1. NVCE of base cases

Having followed the workflow (**Figure 4**) and applied building conditions (Appendix B, Table B1), the base-case tests of three cities yielded NVCEs and CPURs as listed in Table 5. As there were four zones on the second-floor, the numbers presented in this section are the average values of the floor. The results show that the cooling potentials of sites (CPNV) and buildings (NVCE) may disagree although the difference between these values can be small. In fact, the reason why CPURs of these cases were very close to 1 was due to the optimistic design assumptions including widely-open windows and high thermal storage.

Table 5. NVCE and CPUR of base cases.

City	Annual: Jan – Dec Base case NVCE (CPUR)	Seasonal: May-Oct Base case NVCE (CPUR)
Phoenix, AZ	0.63 (0.95)	0.36 (0.88)
Fresno, CA	0.81 (0.98)	0.65 (0.96)
Denver, CO	0.93 (0.99)	0.86 (0.98)

5.2.2. NVCEs of various design options

Different sets of design decisions led to wide ranges of consequences in NVCE as shown in Table 6. In Phoenix, the least airflow (5% of base case) with the highest heat gains (100% of base case) and thermal mass (100 % of base case) led to the minimum NVCE, while the most airflow with the lowest heat gains led to the maximum NVCE with little to no impact from thermal mass. In Fresno, the minimum NVCE was observed with the least airflow and the highest heat gains, regardless of thermal mass. The maximum NVCE of Fresno was achieved by the lowest airflow rate and the heat gains with the highest thermal mass. Lastly, in Denver, the least airflow and thermal mass with the highest heat gains resulted in the lowest NVCE; while the lowest airflow rate and heat gains with the highest thermal mass offered the maximum NVCE.

Table 6. Minimum and maximum NVCE and CPUR of various design options.

City	Annual: Jan – Dec		Seasonal: May-Oct	
	Minimum NVCE (CPUR)	Maximum NVCE (CPUR)	Minimum NVCE (CPUR)	Maximum NVCE (CPUR)
Phoenix, AZ	0.31 (0.46)	0.68 (1.04)	0.04 (0.09)	0.43 (1.04)
Fresno, CA	0.44 (0.53)	0.90 (1.08)	0.09 (0.13)	0.79 (1.17)
Denver, CO	0.68 (0.73)	0.99 (1.06)	0.43 (0.49)	0.99 (1.13)

The correlation between the tested variables and NVCE varied, too, suggesting that natural ventilation cannot be evaluated by a single factor, i.e., airflow. Below we describe how this metric helped identify better design options among various alternatives in detail. Figures 5-7 present the results of the test cities.

Each plot presents 125 test results with variations listed in Table 3 (3)-(5), in which results with extreme settings are highlighted.

5.2.2.1. Airflow rate

Airflow rate impacted NVCE in most cases as shown in Figures 5-7 (A). Generally, higher airflow rates yielded higher NVCE. For Fresno and Phoenix, securing a certain level of airflow was critical when heat gains were at base-case, high values (Figures 5-6 (A) red and orange lines). In all test cities, airflow did not significantly impact NVCE when both heat gains and thermal heat capacity were reduced to 5% of the base case (Figures 5-7 (A) blue dashed lines). This indicates that if a building is equipped with highly effective shading devices, highly efficient light fixtures, and light thermal mass, sizing airflow openings may not be an important decision to make.

On the other hand, some cases showed that higher airflow rates could have an adverse effect on NVCE. For example, in Fresno and Denver, the maximum NVCE was observed with the least airflow given low heat gains and base-case thermal mass as shown in Figures 6-7 (A), green dashed lines. This means that the indoor air can stay cooler than the outdoors and having more airflow from outside can diminish the effect of the thermal delay and reduce NVCE.

5.2.2.2. Solar and internal heat gains

In some cases, controlling heat gains was found to be the most significant factor in NVCE, and the impact range of reducing heat gains was at maximum with low airflow rates and base-case mass (Figures 5-7 (B), green dashed lines). In other cases, the impact was minimal when the base case, high airflow was provided (Figures 5-7 (B), red and orange lines). Unlike airflow rates or thermal mass, the impact of heat gains on NVCE was consistent: the higher the heat gains, the lower the NVCE in all tests. In design practice, this would mean that strategic building orientation, shading design, low occupancy rates, or highly reflective building envelopes would help enhance the cooling effect from natural ventilation.

5.2.2.3. Thermal mass

The influence of thermal mass on NVCE depended strongly on other settings, including climate, airflow rate, and heat gains. While most cases in Phoenix showed negative responses to the increased mass, most cases in Denver showed otherwise, as shown in Figures 5 (C) and 7 (C). Furthermore, the blue and green dashed lines of Figure 6 (C) reveal that NVCE may correlate positively or negatively with thermal mass even under the same climate. The results support many researchers' findings that thermal mass should be chosen after a close examination of other building and climate conditions to avoid overly warm situations [59–61]. The cases which showed negative correlations of NVCE with thermal storage, as mostly found in Phoenix (Figure 5 (C)), indicate that the building would require more cooling power with an increased mass when mechanical cooling is used in addition to natural ventilation.

However, it should not lead to a misunderstanding that thermal mass would not be beneficial in such climates. For example, if the building in Phoenix relied solely on natural ventilation and the goal was to mitigate the peak temperature during a hot day, one should look at the temperature profile in addition to NVCE to make the right decision. As shown in the temperature graphs of Phoenix (**Figure 8**), heavy mass could be a better option, if avoiding heat exhaustion due to high indoor temperature was more important than having greater number of hours that met the target temperature.

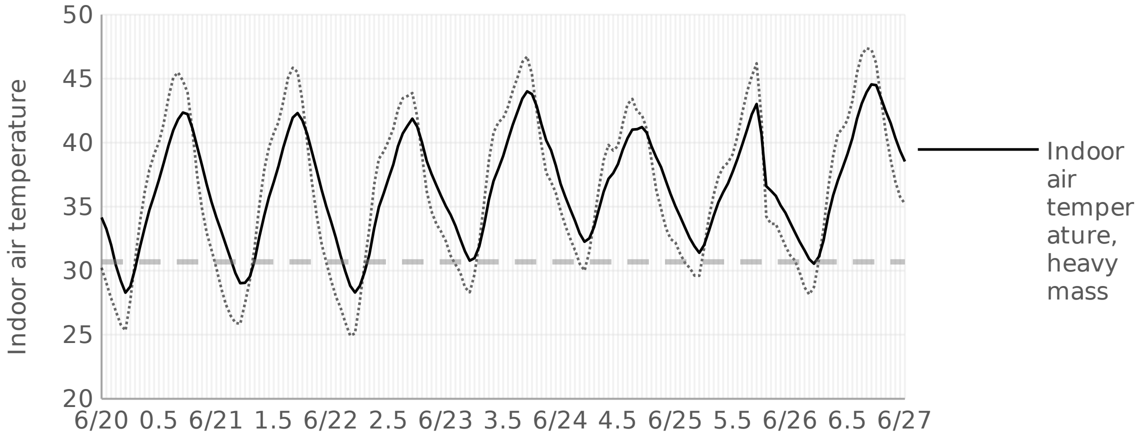


Figure 8. Indoor air temperature graphs with heavy and light mass in Phoenix, AZ, June 20-June 27.

5.3. Climate Potential Utilization Ratio (CPUR)

During the iterations of test cases, CPUR provided a sense of scale as to how far the case is from what was expected from the climate condition. For example, when the case in Phoenix had 95% airflow rate reduction with high heat gains and high heat capacity (Figure 5 (A), red line), its seasonal NVCE was merely 0.04 and CPUR was 0.09. Without looking at other case results for comparison, a CPUR of 0.09 indicated that the there was still a chance to improve NVCE if a different option was selected.

In a steady state, in which no mass is considered, CPUR is always less than or equal to 1, as indoor temperatures would be always higher than the outdoors as long as internal heat gains exist. However, results from this study showed that a CPUR that is greater than 1 (NVCE > CPNV) would be possible through choosing the right thermal capacity, thanks to the thermal lag it carries.Error: Reference source not found

5.4. Limitation and future work

As the name of the metric indicates, NVCE focused on the cooling effect only. A future step would be to consider the quality of the intake air, including humidity and air pollution, within an NVCE evaluation, as many researchers have addressed the importance of these factors [16,77–81]. Doing so would allow the use of various comfort criteria, such as Standard Effective Temperature (SET) and Heat Index (HI), in addition to dry bulb temperature.

Although the test cases used fixed building configurations, the results implied that operation strategies would also significantly influence the parameters of NVCE. One may bring up questions, such as “what time of a day will a smaller opening area benefit?” or “how do we incorporate this analysis when the space is not occupied, thus allowing overwarming during unoccupied times of a day?” Therefore, further studies should investigate how various building dynamics, including dynamic shading design, window operations, and occupancy, would determine NVCE.

In the workflow of a feasibility case study, the calculation of the metrics was linked with EnergyPlus via custom programming, as solar and internal heat gains and airflow needed to be retrieved from energy simulations. In the EnergyPlus model, we applied building settings as close as possible to the assumptions of the NVCE equations discussed in Section 3.2, which limited the choice in test buildings and settings. To apply this approach in a more complex building, it would be desirable to incorporate the NVCE equations within EnergyPlus. This would reduce calculation errors as the equations can use the uninterpreted, native EnergyPlus values. The incorporation of NVCE into EnergyPlus would also make the NVCE analysis accessible to users who do not code.

6. Conclusion

A complex set of conditions in buildings, variations in occupancy, and weather conditions should be considered to evaluate the cooling capacity from natural ventilation, in addition to asking a simple question—"is there airflow?” This is why the “availability” of natural ventilation for a given building cannot solely represent its “effectiveness” in cooling the space. This study reviewed evaluation metrics used for natural ventilation in buildings, selected useful metrics for design procedures, and revised them to further include the transient behavior of thermal mass in the evaluation of natural ventilation’s performance. The three key performance indices identified in this paper were climate potential of natural ventilation (CPNV), natural ventilation cooling effectiveness (NVCE), and climate potential utilization ratio (CPUR). The study further demonstrated the applicability of such metrics within a design procedure as follows:

- During a site evaluation and schematic design phase, CPNV informs general ideas as to how much cooling potential the site can expect from natural ventilation.
- During a design development phase, in which various design options and specifications of a building are tested, NVCE provides the key information about cooling effectiveness of a given design solution. A supplementary metric, CPUR, explains how the building performs compared to the expected CPNV.

The main advantage of having these metrics is the interactive feedback they offer during numerous design iterations. In the feasibility study, we parameterized important building components in the 3D modeling environment, including thermal capacity, overall heat transfer coefficients, internal heat gains, climate conditions, and comfort criteria. We then linked the building parameters with NVCE calculation, such that NVCE and CPUR were calculated each time the 3D model or a criterion was changed.

The wide ranges of NVCE shown by the feasibility tests support the hypothesis that the relationship among various design parameters should be dynamically understood in order to evaluate the performance of natural ventilation, since “the more the airflow, the better,” or “the heavier the thermal mass, the better” are not always true. The newly proposed metrics, NVCE and CPUR, offer clearer perspectives on how the chosen settings influence natural ventilation’s performance. The equations can be easily incorporated into a spreadsheet and computer scripts for a simple case, and can be used in combination with energy simulations and additional scripting for more comprehensive studies.

Author contributions

Nari Yoon: Conceptualization, Methodology, Software, Formal analysis, Investigation. Writing – original draft, Writing – Review & Editing, Visualization, Funding acquisition. **Leslie Norford**: Methodology, Investigation, Writing – Review & Editing, Supervision. **Ali Malkawi**: Resources, Writing – Review & Editing, Supervision. **Holly Samuelson**: Writing – Review & Editing, Supervision. **Mary Ann Piette**: Writing – Review & Editing, Supervision.

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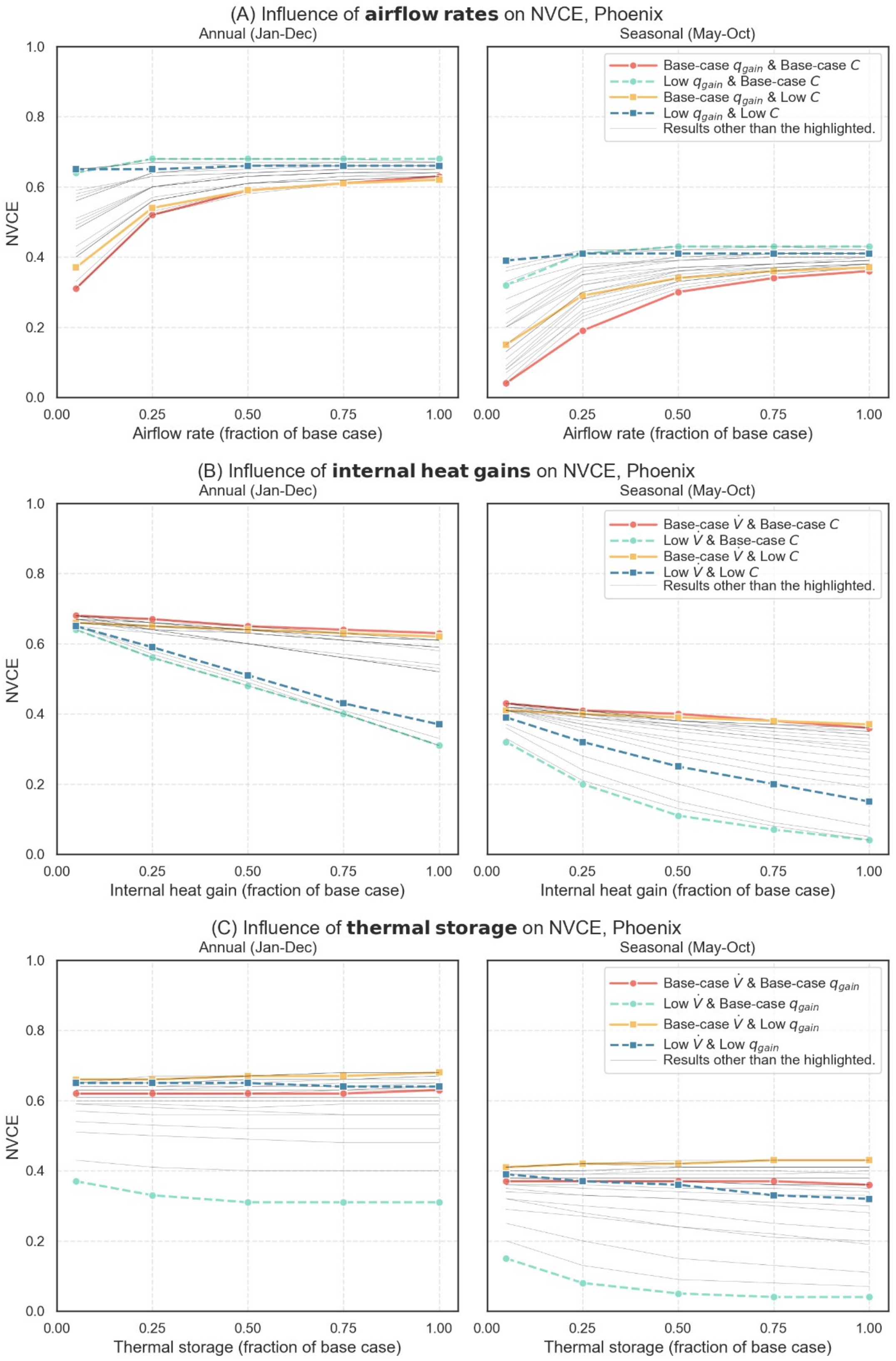
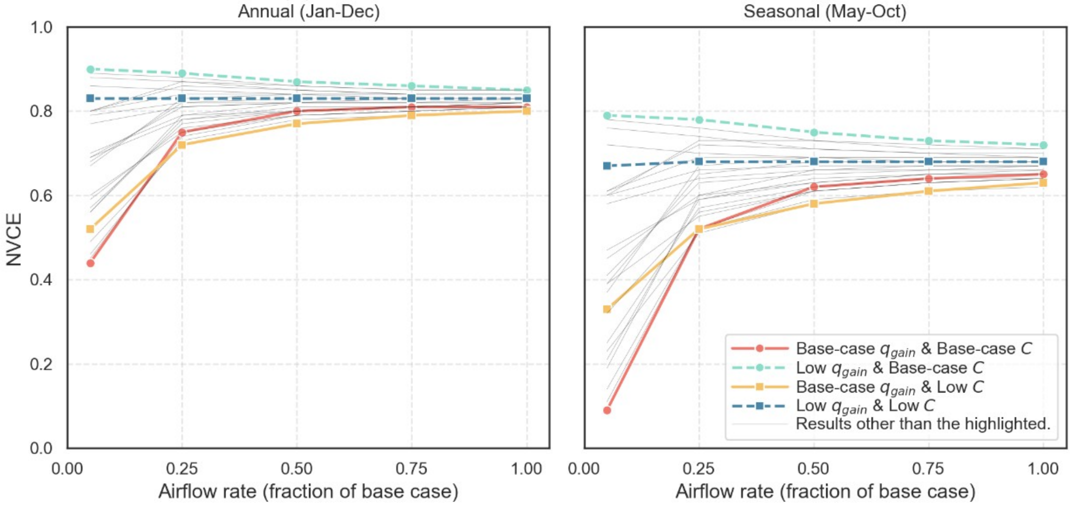
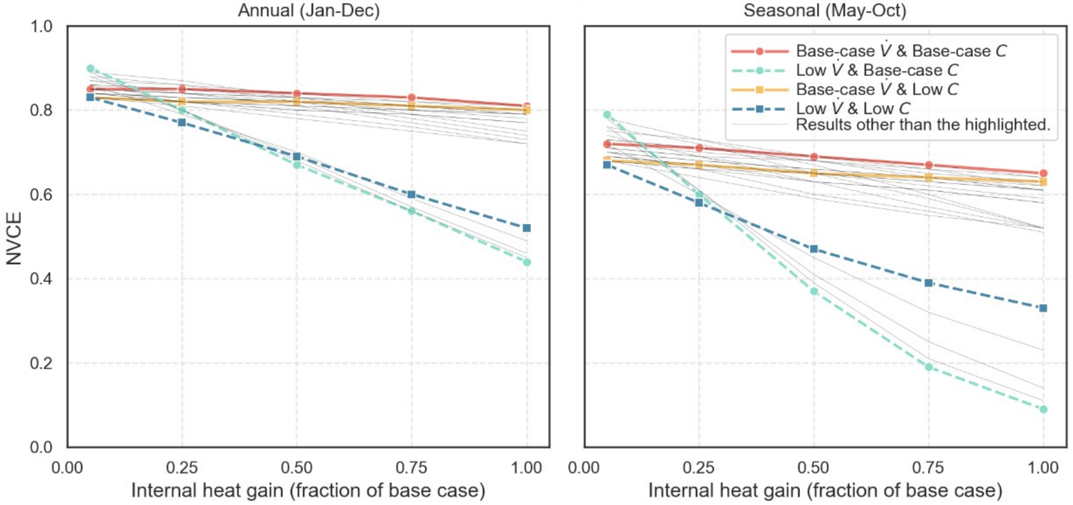


Figure 5. Results of Phoenix, AZ ($\dot{V}$, airflow rate; q_{gain}, internal heat gains; C, thermal storage).

(A) Influence of **airflow rates** on NVCE, Fresno



(B) Influence of **internal heat gains** on NVCE, Fresno



(C) Influence of **thermal storage** on NVCE, Fresno

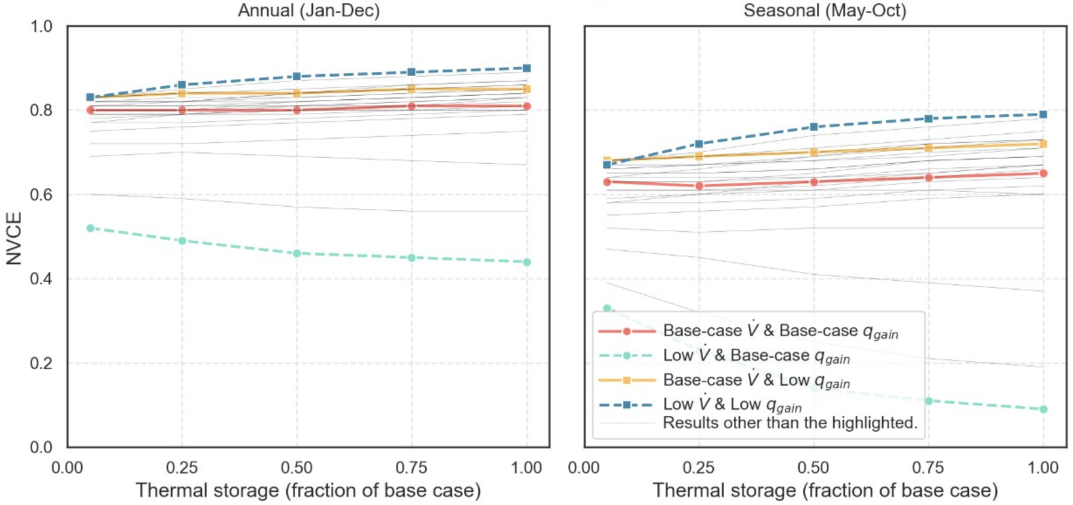


Figure 6. Results of Fresno, CA ($\dot{V}$, airflow rate; q_{gain}, internal heat gains; C, thermal storage).

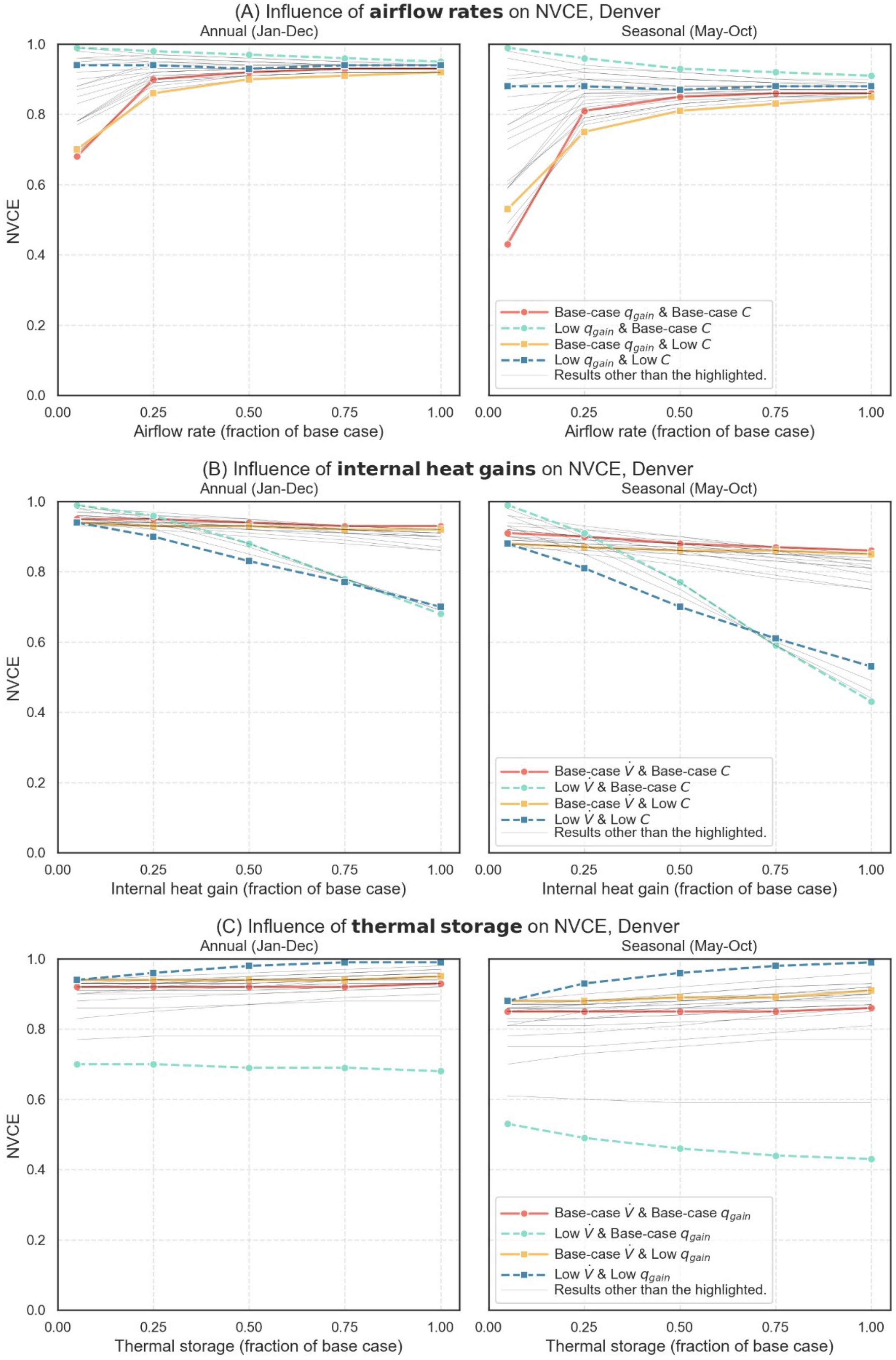


Figure 7. Results of Denver, CO ($\dot{V}$, airflow rate; q_{gain}, internal heat gains; C, thermal storage).

Appendix A. Detailed steps through Eqs. (4-8)

In a steady state, the total heat gains and losses is equal to zero as in Eq. (A.1):

$$0 \qquad ¿\, q_{solar}+q_{\int ¿+q_{wall}+q_{inf+vent} ¿} \tag{A.1}$$

where q_{solar} is solar heat gain, $q_{\int ¿¿}$ is internal heat gains from occupancy, lighting, appliances, etc., q_{wall} is heat loss through the overall wall (including opaque and glazing materials), and $q_{inf+vent}$ is heat loss through infiltration and ventilation. Defining $q_{gain}=¿\, q_{solar}+q_{\int ¿¿}$, we get Eqs. (A.2) and (4):

$$0 \qquad ¿\, q_{gain}+UA\left(T_{out}-T_{¿}\right)+\rho\, c\, \dot{V}_{avail}\left(T_{out}-T_{¿}\right) \tag{A.2}$$

$$T_{¿} \qquad ¿\, \frac{q_{gain}}{UA+\rho c \dot{V}_{avail}}+T_{out} \tag{4}$$

Starting from Eq. (5) in the main text, Eq. (7) was derived as in Eqs. (5), (A.3), (6), and (A.4):

$$T_{target} \qquad ¿\, \frac{q_{gain}+q_{¿}}{UA+\rho c \dot{V}_{avail}}+T_{out} \tag{5}$$

$$q_{¿} \qquad ¿\left(T_{target}-T_{out}\right)\left(UA+\rho c\, \dot{V}_{avail}\right)-q_{gain} \tag{A.3}$$

$$q_{req} \qquad \equiv q_{avail}+q_{¿} \tag{6}$$

$$\begin{aligned} &¿-\rho c \dot{V}_{avail}\left(T_{target}-T_{out}\right)+\left(T_{target}-T_{out}\right)\left(UA+\rho c \dot{V}_{avail}\right)-q_{gain} \\ &¿-\left\{q_{gain}-UA\left(T_{target}-T_{out}\right)\right\} \end{aligned} \tag{A.4}$$

$$NVCE_{ts} \qquad ¿\, \frac{q_{avail}}{q_{avail}+q_{¿}}=\frac{-\rho c \dot{V}_{avail}\left(T_{target}-T_{out}\right)}{-\left\{q_{gain}-UA\left(T_{target}-T_{out}\right)\right\}} \tag{7}$$

If we assume that the supplementary cooling power, $q_{¿}$, comes from natural ventilation,

$$q_{\text{¿}} \qquad \text{¿}-\rho c \dot{V}_{\text{¿}} \text{¿}), \tag{A.5}$$

where $\dot{V}_{\text{¿}}$ is the supplementary airflow rate from natural ventilation. Eqs. (6) and (7) can be expressed as Eqs. (A.6) and (A.7):

$$q_{req} \qquad \equiv q_{avail}+q_{\text{¿}} \tag{6}$$

$$\text{¿}-\rho c \dot{V}_{avail}\left(T_{target}-T_{out}\right)-\rho c \dot{V}_{\text{¿}}\left(T_{target}-T_{out}\right)$$

$$\text{¿}-\rho c\left(\dot{V}_{avail}+\dot{V}_{\text{¿}}\right)\left(T_{target}-T_{out}\right) \tag{A.6}$$

$$NVCE_{ts} \qquad \text{¿}\frac{q_{avail}}{q_{avail}+q_{\text{¿}}}\text{¿}\frac{-\rho c \dot{V}_{avail}\left(T_{target}-T_{out}\right)}{-\rho c\left(\dot{V}_{avail}+\dot{V}_{\text{¿}}\right)\left(T_{target}-T_{out}\right)}\text{¿}\frac{\dot{V}_{avail}}{\dot{V}_{req}}, \tag{A.7}$$

where $\dot{V}_{avail}$ is the available airflow rate from natural ventilation, and $\dot{V}_{req}$ is the ideal airflow rate ($\dot{V}_{avail}+\dot{V}_{\text{¿}}$) required from natural ventilation. Airflow rate is used to define air changes per hour (ACH) as:

$$ACH=\frac{3600(s)\dot{V}}{vol},$$

where vol is the volume of the room. Therefore, Eq. (A.7) leads to Eq. (8):

$$NVCE_{ts}=\frac{q_{avail}}{q_{req}}=\frac{\dot{V}_{avail}}{\dot{V}_{req}}=\frac{ACH_{avail}}{ACH_{req}}, \tag{13}$$

where ACH_{avail} is the available ACH from natural ventilation, and ACH_{req} is the required ACH.

Appendix B. Detailed settings used in the feasibility test

Table B1. Base case model settings for three cities.

		Phoenix, AZ (IECC Climate Region 2B)		Fresno, CA (IECC Climate Region 3B)		Denver, CO (IECC Climate Region 5B)	
		SI units [c]	IP units [d]	SI units	IP units	SI units	IP units
Fenestration	U-Factor [a]	2.271	0.400	1.817	0.320	1.703	0.300
Glazed fenestration	SHGC [a]	0.250	0.250	0.250	0.250	Not Required	Not Required
Ceiling	R-Value [a]	6.697	38	6.697	38	8.635	49
	Equivalent U-Factor [b]	0.170	0.030	0.170	0.030	0.148	0.026
Wood frame wall	R-Value	2.291	13	3.525	20	3.525	20
	Equivalent U-Factor	0.477	0.084	0.341	0.060	0.341	0.060
Floor	R-Value [a]	2.291	13	3.348	19	5.287	30
	Equivalent U-Factor [b]	0.363	0.064	0.267	0.047	0.187	0.033
Slab	R-Value [a]	0	0	0	0	1.762	10
	Depth [a]	-	-	-	-	0.610	2.000
Glazing area		4.13 [m^2] each					
Opening area		1.24 [m^2] each					
Thermal storage per area		25,200 [J/K- m^2] (Second-floor only)					
Equipment load per area		5 [W/m^2]					
Lighting power density		7 [W/m^2]					
Number of people per area		0.02 [ppl/m^2]					

[a] Value reference: IECC [82] Table R402.1.2, *Insulation and Fenestration Requirements by Component*.

[b] Value reference: IECC [82] Table R402.1.4, *Equivalent U-Factors*.

[c] SI units used are [$W/(m^2 \cdot K)$] for U-Factor, [$m^2 \cdot K/W$] for R-Value, [m] for depth. The values were converted from the IECC tables, which were originally

provided in the IP units.

[d] IP units used are [Btu/(h·ft^2·°F)] for U-Factor, [°F-ft^2-h/Btu] for R-Value, [ft] for depth.