

Preliminary design geometry for predicting natural ventilation performance in row houses

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ARTICLE INFO	ABSTRACT
<i>Article history:</i> Received June 16, 2026 Received in revised form July 16, 2026 Accepted August 11, 2026 Available online September 01, 2026 <i>Keywords:</i> Computational Fluid Dynamics (CFD) Initial design geometry Natural ventilation Predictive model linear regression Row houses *Corresponding author: Khotijah Lahji Department of Architecture, Faculty of Civil Engineering and Planning, Universitas Trisakti, Indonesia Email: khotijah@trisakti.ac.id	The Computational Fluid Dynamics (CFD) prediction tool has demonstrated a high degree of accuracy in modeling airflow velocity; however, its application requires comprehensive design data, making it more appropriate for use during advanced stages of the architectural design process. At the conceptual design stage, tools capable of predicting airflow velocity remain relatively limited. Therefore, this study aims to develop a geometry-based prediction tool that is simple, accessible, rapid, practical, and sufficiently accurate for early-stage architectural design. A quantitative research approach was employed, beginning with CFD simulations based on geometric or independent-variable indicators across 212 cases of two-story row house designs to obtain accurate airflow-velocity values as the dependent variable. The processed initial-design geometry data and CFD simulation results were subsequently analyzed using linear regression through the enter and stepwise methods in SPSS. The initial prediction equation was selected based on the model with the highest R^2 value and the smallest number of determining variables. The findings yielded an R^2 value of 0.738, determined by four geometric or independent variables: (1) building width (-), (2) number of doors on the second floor, (3) width of the window inlet on the front facade of the second floor, and (4) area of the vertical stair void. This prediction tool is effective for application during the conceptual design stage. A further model produced an R^2 value of 0.867 based on 16 geometric or independent variables; although this model provides a higher level of predictive accuracy, its greater complexity makes it more suitable for application during the advanced design stage. This study addresses the existing gap in early-stage prediction tools by introducing a novel building-geometry-based predictive approach in the form of a linear equation that is practical, rapid, straightforward, and sufficiently accurate for supporting natural ventilation assessment during the early design stage without compromising architectural design creativity.

Introduction

The rapid expansion of urbanized areas in Jakarta has generated increasing demand for high-density residential development, including housing typologies in the form of row houses (Gür and Dülgeroğlu Yüksel 2019). Such conditions

frequently result in restricted opportunities for natural ventilation because of the narrow spacing between adjacent buildings and inadequate spatial configurations. In humid tropical climates, residential architecture needs to optimize natural ventilation in order to promote thermal comfort while reducing dependence on mechanical



cooling systems (Djamila 2017; Iqbal et al. 2023). In architectural design practice, Computational Fluid Dynamics (CFD) is commonly employed to predict natural ventilation at relatively advanced design phases because the method requires detailed geometric information. Consequently, CFD analysis is generally undertaken during the design development or detailed design stage (Chew, Chen, and Gorlé 2022; Aeinfar and Serteser 2026; Lahji et al. 2026). Nevertheless, conceptual design is generally not supported by tools that can predict ventilation performance rapidly, simply, and in an integrated manner. As a result, performance assessment is frequently postponed until the advanced design phase, when more sophisticated simulation procedures can be implemented (Kim and He 2025).

The primary objective of this research is to formulate an airflow-velocity prediction tool that can be readily, rapidly, practically, and reasonably accurately applied during the conceptual design phase. This objective is pursued through an examination of the effects of initial design geometry variables on airflow velocity using the Computational Fluid Dynamics (CFD) approach combined with Linear Regression analysis in SPSS. The geometric variables examined include building dimensional characteristics, facade openings, opening configuration and orientation, room dimensions, voids, the arrangement of solid and porous partitions, and spatial connectivity.

The scope of this investigation is restricted to row house designs characterized by limitations in their ventilation design. Ventilation performance is not determined solely by building geometry; it is also affected by microclimatic contributions, including environmental wind speed, which plays an important role in determining airflow velocity within row house (RH) configurations.

Row house design in urban environments presents several challenges associated with natural ventilation performance, including: (1) constraints on natural ventilation and insufficient integration between building geometric design, ventilation strategies, and interior spatial design; (2) the limited availability of prediction tools that are both practical and sufficiently accurate for evaluating natural ventilation performance during the conceptual design phase; and (3) the use of CFD simulations at relatively advanced design phases, particularly during design development, which can make subsequent design revisions less efficient. These challenges constitute the principal

issues addressed by this research. Accordingly, the research questions are: (1) How can an initial design strategy integrate geometric design variables to generate favorable airflow velocity? (2) How can an airflow-velocity prediction tool be developed that is easy to calculate, rapid to use, and sufficiently accurate? (3) How can an early- or conceptual-stage prediction tool based on building geometry be formulated in the form of linear equations?

The anticipated contributions of this research are as follows: (1) contributing to the advancement of architectural science; (2) developing a geometry-based predictive tool with an accuracy of 70%; (3) providing an airflow-velocity prediction tool that can function as a reference for subsequent research; (4) assisting designers in evaluating natural ventilation strategies beginning at the conceptual design phase; and (5) supporting a design decision-making process that is simpler, faster, more efficient, and data-driven.

Extensive research has examined natural ventilation prediction using CFD methods, field measurements, and other simulation techniques. The research gap identified in this study comprises: (1) the limited availability of predictive approaches specifically intended for the conceptual or schematic design stage; (2) insufficient integration of more complex geometric characteristics in previous analyses of natural ventilation performance; and (3) the limited number of studies addressing row houses in tropical urban environments that experience significant ventilation design constraints. The novelty of this research is therefore positioned in the development of a natural ventilation prediction tool or formula based on the integration of building design geometry during the early design phase, with specific applicability to row houses located in dense tropical urban environments.

The research gaps and novelty were established through an analysis of the SOTA (State of the Art) matrix or tabulation developed from 40–50 reputable journals ranging from Sinta 1 to Q1. The SOTA analysis also provides the foundation for the literature review concerning natural ventilation performance. Natural ventilation in buildings represents a passive air-exchange process affected by wind pressure and temperature differentials, thereby contributing to improved indoor air quality, thermal comfort, and building energy efficiency (Ramezani and Reza

2026). The parameters governing natural ventilation are influenced by two principal aspects: (1) environmental climate, including local climatic conditions such as wind speed, wind direction, and turbulence patterns in the outdoor environment, as well as the presence of vegetation as a hybrid optimization strategy for outdoor cooling (Zhang, Weerasuriya, and Tse 2020; Xiong et al. 2024; Niu et al. 2026); and (2) building design geometry, which encompasses building orientation, massing configuration, spatial dimensions, opening design, voids, spatial organization, spatial connectivity, and obstructions created by interior components, all of which influence airflow distribution patterns within the building (Gökşen 2026).

Building geometry constitutes a critical factor that directly influences wind velocity, turbulence behavior, cross-ventilation effectiveness, and the quality of airflow distribution within an architectural space (Díaz-Calderón, Castillo, and Huelsz 2024; Sudirman et al. 2025). Building orientation determines how the facade receives and captures prevailing wind flows, thereby influencing pressure distribution and the effectiveness of cross-ventilation (Deng et al. 2023; Li et al. 2023). The configuration of inlet and outlet openings represents one of the most direct geometric determinants of natural ventilation because it establishes the pathways through which air enters and exits a space (Díaz-Calderón, Castillo, and Huelsz 2024; Li et al. 2023; Fu and Zhao 2025). Opening design, including the inlet-to-outlet opening ratio, opening position, and opening height, has been demonstrated to influence wind-velocity distribution and cross-ventilation effectiveness in both multistory buildings and row houses (Deng et al. 2023; Fam et al. 2024; Yi et al. 2023). Furthermore, combining horizontal and vertical openings can substantially enhance ventilation performance when compared with configurations that rely on openings oriented in only one direction (Díaz-Calderón, Castillo, and Huelsz 2024; Sudirman et al. 2025).

Voids, atria, and stairwells constitute vertical geometric elements that can contribute to the development of the stack effect, referring to the vertical movement of air generated by pressure and temperature differences between building levels (Yin et al. 2024; Sudirman et al. 2025; Mateus, Pinto, and Pereira 2024). The incorporation of a void has been shown to improve airflow distribution on upper floors while

assisting in the accelerated removal of accumulated hot air from the building interior (Omidi et al. 2026; Ibrahim et al. 2026). In two-story row houses, appropriately positioned stair voids can improve the stability of airflow patterns in comparison with building configurations that do not incorporate a void (Lahji et al. 2026; Yin et al. 2024).

Spatial layouts and interior partitions likewise constitute geometric components that directly influence natural ventilation because they determine spatial connectivity and airflow resistance between adjacent spaces (Rezadoost Dezfali et al. 2023; Kajjoba et al. 2025; Zhang, Weerasuriya, and Tse 2020). Solid partitions generally impede airflow and may generate stagnant zones, whereas porous partitions and more open spatial configurations facilitate a more uniform distribution of airflow (Fam et al. 2024; Yin et al. 2024). Interior geometry therefore functions not merely as an element for defining and organizing space, but also as a mechanism for controlling airflow pathways and determining the quality of natural ventilation within a building (Chu Yang, Muhammad Yazid, and Mohamad 2026; Sari, Chiou, and Sugianto 2025; Martínez Palmeth et al. 2026).

This research specifically investigates row houses in urban areas. Accordingly, an understanding of row house typologies is considered essential because they represent one potential response to housing requirements in densely populated urban environments (Gallagher 2026; Meshulam and Saxe 2026). Although row houses offer considerable spatial efficiency, their closely packed configuration and restricted facade width can inhibit the penetration of natural airflow, thereby diminishing indoor ventilation performance (Lahji et al. 2026). Within humid tropical climatic conditions, this issue becomes particularly significant because natural ventilation has an important role in maintaining thermal comfort and indoor air quality (Xiong et al. 2024).

Within architectural and interior design processes, ventilation planning is highly important for achieving thermal comfort and consequently requires a prediction tool that can be employed during the early or conceptual design phase. Prediction tools can be understood as analytical or computational systems used to estimate the behavior of a phenomenon on the basis of relationships among measurable variables (Alam and Abbasabadi 2026). In the context of

natural ventilation, prediction has increasingly developed toward simulation-based approaches capable of estimating air velocity, airflow distribution, and indoor air quality rapidly and accurately. Such approaches can support more adaptive design decisions in response to climatic conditions and building geometry (Pagano, De Filippi, and Simonetti 2026).

CFD and linear regression analysis in SPSS were employed as analytical instruments in the development of the proposed prediction tool. As a predictive technique, CFD provides a high degree of accuracy in estimating natural ventilation performance and airflow distribution, with results that are consistent with findings obtained from wind-tunnel experiments and field measurements. CFD also provides substantial flexibility for assessing multiple design alternatives and investigating different design scenarios (Hu, Kikumoto, and Ooka 2024; Hu et al. 2022; Sudirman et al. 2025). Moreover, CFD is appropriate for more detailed and complex evaluations of airflow performance during advanced design phases (Matour et al. 2021) and can retain satisfactory accuracy even when applied to reduced-scale studies and environments involving more complex thermal conditions (Jiang et al. 2024).

Linear regression is a quantitative statistical technique used to examine relationships between independent and dependent variables by constructing a linear mathematical equation through which the value of one variable can be predicted from another variable. In quantitative research within engineering, architecture, and environmental studies, an R^2 value of ≥ 0.60 is generally regarded as representing good and

adequate predictive capability for application as a prediction tool (Tan and Teoh 2026), and predictive significance and accuracy can be evaluated through the coefficient of determination, R^2 . Linear regression using the enter and stepwise approaches in SPSS is widely applied in quantitative research because these methods can transform complex relationships among variables into mathematical models that are more practical and easier to interpret (Umar, Rana, and Mokayed 2026; Yuanxi Han and Jin 2026). Consequently, linear regression functions not only as a statistical analysis technique but also as a methodological basis for developing predictive tools that facilitate data-driven decision-making in scientific research (Noramli et al. 2026).

Methods

The initial phase of the research involved CFD simulation using ANSYS Fluent 2024. This analysis functioned as the simulation instrument for obtaining accurate wind velocity (WV) values within the RD space, which simultaneously served as the dependent variable (Y). The dependent variable is affected by independent variables representing building design characteristics in the form of geometric parameters and is also influenced by microclimatic or local climatic conditions, particularly outdoor wind speed. The annual average wind velocity recorded in urban areas ranges from 1.5 m/s to 3 m/s, and in some circumstances is less than 3 m/s (BMKG 2024). The following figure presents the CFD workflow:

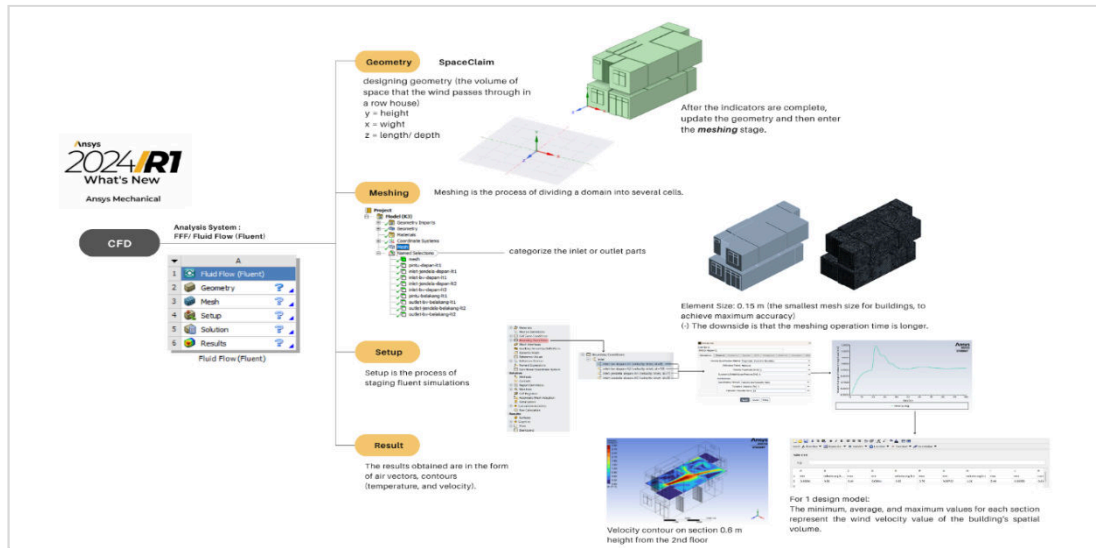


Figure 1. CFD operational scheme

The independent variables are represented as ($x_1, x_2, x_3, x_4 \dots x_n$) and comprise building geometric design parameters totaling 20 variables. The clustering process conducted in SPSS reduced the initial set of 33 variables to 20 variables with a significance value of 0.05 using the enter method. The variables are defined as follows: x_1 , building width geometry; x_2 , building length; x_3 , width of solid interior partitions; x_4 , width of porous partitions; x_5 , floor-to-ceiling height; x_6 , stair void area; x_7 , interior void; x_8 , courtyard; x_9 , number of doors located on the facade and within the interior of the first floor; x_{10} , number of doors located on the facade and within the interior of the second floor; x_{11} , width of the main door on the first floor; x_{12} , door height; x_{13} , door width; x_{14} , transom height; x_{15} , width of the inlet window on the first floor; x_{16} , width of the inlet window on the second floor; x_{17} , width of the outlet window on the first floor; x_{18} , width of the outlet window on the second floor; x_{19} , window position measured from the floor elevation or window height on the first floor; and x_{20} , window position measured from the floor elevation or window height on the second floor. These 20 variables were entered as inputs during the CFD simulation process. The role of SPSS simulation, employing linear regression analysis, was to derive a linear equation and establish the relationship between the dependent variable, namely velocity, and the independent variables based on the geometric characteristics of the row house design. The linear

regression equation is expressed as $Y = a_0 + a_1.x_1 + a_2.x_2 + a_3.x_3 + a_n.x_n$.

Nine dependent variables, represented by Y and expressed as wind speed (WV), were established from velocity measurements at different zones and spatial locations. These include the volume velocity across floors 1 and 2 (Y1), volume velocity on floor 1 (Y2), volume velocity on floor 2 (Y3), vertical-section velocity at the center inlet-outlet location (Y4), vertical-section velocity at the center of the stair void (Y5), horizontal-section or plan velocity at a height of 60 cm on floor 2 (Y6), horizontal-section or plan velocity at a height of 150 cm on floor 2 (Y7), horizontal-section or plan velocity at a height of 60 cm on floor 1 (Y8), and horizontal-section or plan velocity at a height of 150 cm on floor 1 (Y9). Each variable from Y1 through Y9 contains minimum, average, and maximum values, producing a total of 27 dependent variables.

To formulate a natural ventilation prediction equation based on building geometric design and incorporating 20 independent variables, a minimum of 212 cases was required to generate the prediction equation. In quantitative methods, a minimum sample size equivalent to at least 10 times the number of independent variables is required to establish a prediction equation or predictive tool (Sugiyono 2013; Kurniawan 2016; Anto et al. 2024).

The research procedure consisted of the following stages: (a) collecting design information for approximately 200 row house

cases; (b) identifying row house types with building widths ranging from 4 to 6.9 m and building lengths ranging from 7 to 17 m; (c) redrawing the row house designs using geometric dimensions generated from random values through the *RANDBETWEEN* function in Excel. This procedure was used to obtain random dimensions that more accurately satisfy the requirements for normally distributed data, as represented through the histogram generated in SPSS; and (d) producing three-dimensional row house design models in a format compatible with CFD analysis. The CFD-compatible models incorporated geometric dimensions generated through *RANDBETWEEN*, which subsequently served as the independent variables (x). The CFD

simulations generated WVm/s results, while the dependent variables comprised nine variables, Y1 through Y9, each containing minimum, average, and maximum values and therefore producing 27 dependent variables in total. Consequently, the 200 RH cases generated WV values represented by 27 variables for each case. As an illustration, CFD results for a 6×12 type row house included not only velocity contours used to identify minimum and maximum WV values, but also average WV values, airflow patterns represented through vectors, and average graphs illustrating the direction of inlet and outlet airflow. An example of one CFD case and its corresponding airflow pattern is presented below:

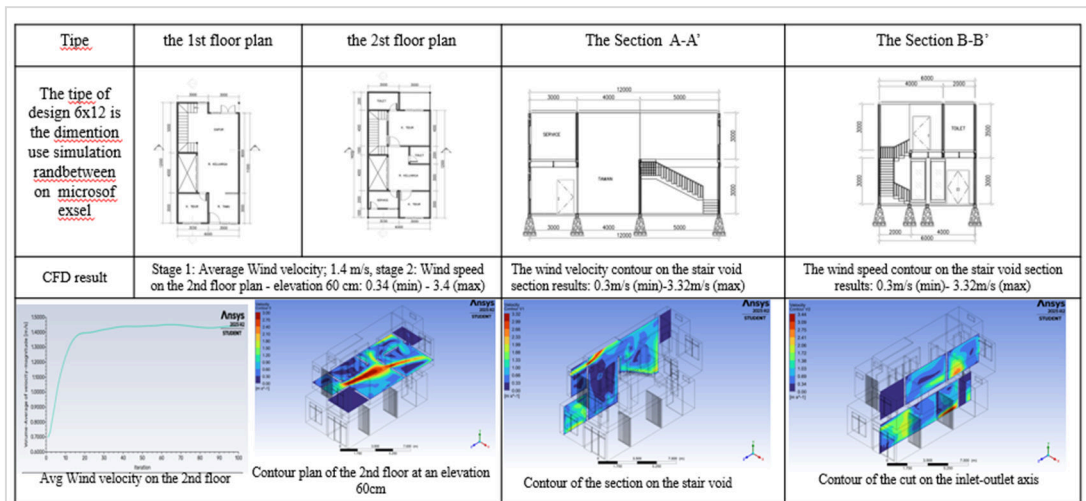


Figure 2. CFD results illustration for the airflow pattern on the 2nd floor at a height of 60 cm on RD

(e) The subsequent stage involved SPSS simulation using linear regression analysis with the stepwise method. The final output of this procedure was a natural ventilation prediction equation based on the parametric geometric characteristics of the building. The standard prediction equation was expressed as follows: each value $Y = f(x_1, x_2, x_3 + \dots X_{20})$. Within the SPSS statistical procedure, the dependent variable consisted of 27 variables, whereas the independent variable set consisted of 20 variables. (f) SPSS simulation was subsequently performed using linear regression analysis with the stepwise method across all Y values, namely independent variables 1–27, based on the 200 RD design cases. (g) To derive the velocity prediction equation ($Y = f(x)$), linear regression analysis was performed using the stepwise method. As a criterion for

establishing a natural ventilation prediction equation that could serve as generalized research finding, the resulting R^2 value was required to be ≥ 0.6 . If the linear regression simulation produced an R^2 value ≤ 0.6 , the resulting model was considered not to satisfy the standard required for establishing a natural ventilation prediction equation for RD. In such circumstances, the independent variables and the completeness of the random data would need to be reviewed to ensure that the data corresponded to the normal-data distribution represented by the bell-shaped histogram in SPSS.

The dependent variable (Y) generated from the CFD simulation consisted of three values: Y minimum, Y average, and Y maximum, defined as follows. Y1 represents the velocity measurement zone within the volume of floors 1

and 2 at the void section; Y2 represents the measurement zone within the volume of floor 1 only; Y3 represents the velocity on floor 2; Y4 represents the velocity at the inlet and outlet section; Y5 represents the velocity at the stair void; Y6 represents the velocity within the floor plan of floor 2 at a height of 60 cm; Y7 represents the velocity within the floor plan at a height of 150 cm; Y8 represents the velocity within the zone or plan of floor 1 at a height of 60 cm; and Y9 represents the velocity within the zone or plan of floor 1 at a height of 150 cm. The analysis incorporated 20 independent variables ($x_1, \dots, x_{20}$) with significant values. These variables were defined as follows: x_1 , building width geometry; x_2 , building length; x_3 , width of the solid interior partition; x_4 , width of the porous partition; x_5 ,

floor-to-ceiling height; x_6 , stair void area; x_7 , interior void; x_8 , courtyard; x_9 , number of doors on the facade and interior of floor 1; x_{10} , number of doors on the facade and interior of floor 2; x_{11} , width of the main door on floor 1; x_{12} , door height; x_{13} , door width; x_{14} , transom height; x_{15} , width of the inlet window on floor 1; x_{16} , width of the inlet window on floor 2; x_{17} , width of the outlet window on floor 1; x_{18} , width of the outlet window on floor 2; x_{19} , window position measured from the floor elevation or window height on floor 1; and x_{20} , window position measured from the floor elevation or window height on floor 2. From the 20 variables.

Research procedure

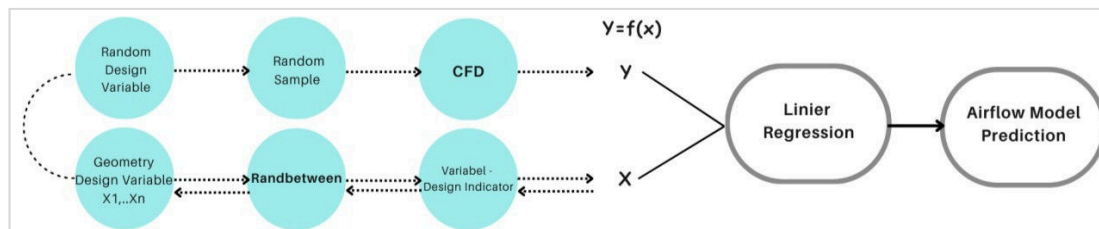


Figure 3. Research procedure

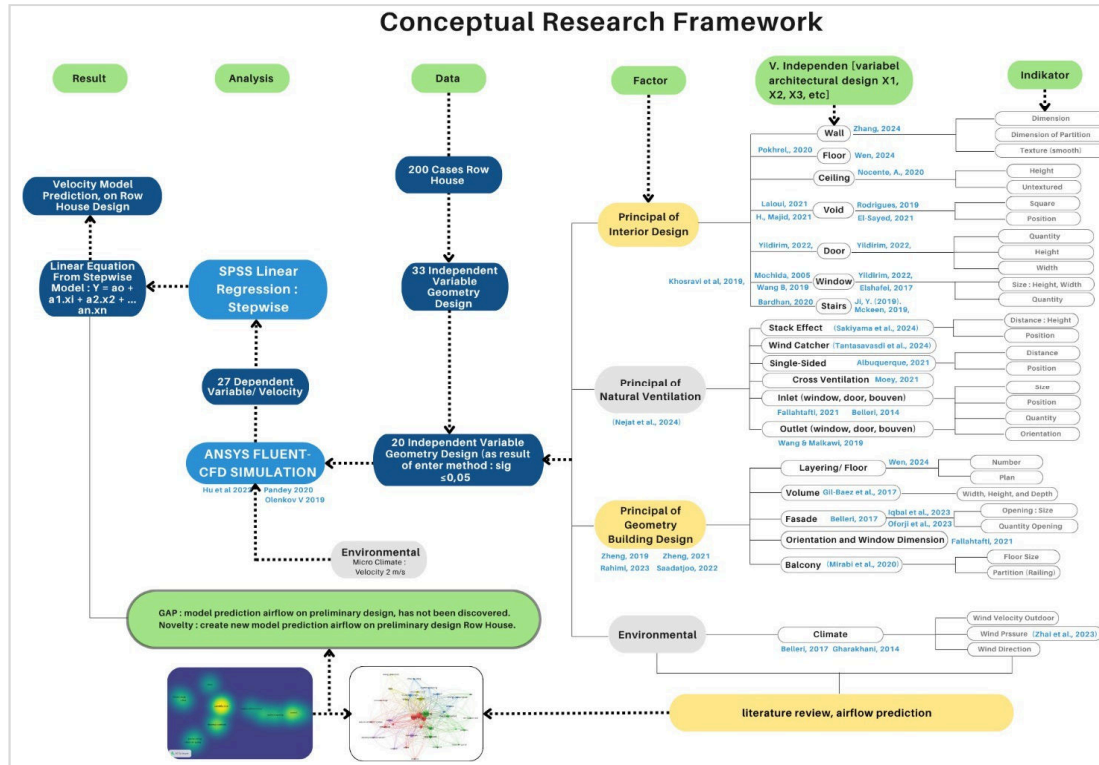


Figure 4. Research concept framework

Results and discussion

The research dataset comprises 212 cases of two-story row house designs collected from various housing developers operating in tropical urban areas. The design variations include building widths ranging from 4 to 6.5 meters and building lengths ranging from 7 to 17 meters, representing the general characteristics of row houses located

within densely populated tropical urban environments. All building geometry data were processed using the *RANDBETWEEN* method to generate a more randomized distribution of data and satisfy the normality requirements for statistical analysis in SPSS. The *RANDBETWEEN* outputs were subsequently used as the basis for establishing the geometric dimensions of each row house type across the 212 cases.

Table 1. Processing geometry data of row houses with randbetween from microsoft excel

Case	X1Geo_building width	X2Geo_building length	X3Geo_Width and length of a solid partition perpendicular to the	X4Geo_Porous/Hollow Wall Perpendicular to Wind Direction	X5Geo_Floor-to-ceiling height (1st & 2nd floors): 280, 290	X6Geo_Area of Vertical Stairwell Void (6-7) m ²	X7Geo_Area of Indoor Vertical Void (6-18) m ²	X8Geo_Void area (courtyard) with open roof: 0-5 m ²	X9Geo_Number of Doors_1st Floor (2-3)	X10Geo_Number of Doors_2nd Floor (3-4)	X11Geo_Main Door Width (0.9, 1.0)	X12Geo_Door Height	X13Geo_Interior Door Width (0.7, 0.8)	X14Geo_Window Header Height (0.4, 0.5)	X15Geo_Front Facade Inlet	X16Geo_Front Facade Inlet	X17Geo_1st Floor Outlet Window	X18Geo_2nd Floor Outlet Window	X19Geo_Window Position relative to	X20Geo_Window Position from Floor
1	6,10	10,00	9,00	0,00	3,20	6,00	0,00	0,00	50	30	14	24	08	06	16	16	00	32	02	09
2	5,30	12,30	12,30	0,00	3,00	6,00	6,00	0,00	20	30	14	23	08	05	21	21	14	28	02	09
3	6,10	14,00	10,10	0,00	3,05	6,00	0,00	0,00	50	40	10	24	08	04	08	17	25	17	00	10
4	4,10	7,10	6,40	0,00	3,05	6,00	0,00	0,00	30	30	12	24	07	06	19	06	06	13	02	08
5	5,00	9,00	9,00	0,00	3,00	8,40	0,00	0,00	30	50	10	21	08	05	08	08	08	08	02	02
6	6,40	10,40	9,40	0,00	3,20	7,00	7,20	0,00	60	40	10	22	07	06	21	14	14	14	00	10
7	4,00	10,00	8,00	2,00	3,15	6,00	0,00	1,07	30	30	09	23	07	06	22	15	00	00	02	08
8	6,00	17,00	14,85	0,00	3,00	7,00	0,00	4,78	60	50	10	22	08	06	28	21	21	35	02	08
9	5,40	12,40	12,40	0,00	3,20	6,00	4,20	0,00	20	40	14	22	08	06	24	32	16	16	02	09
10	6,20	12,20	11,20	3,20	3,20	7,00	0,00	5,00	30	50	14	23	07	06	21	21	14	14	01	08
Case 200									0	0	0	0	0	0	0	0	0	0	0	0

The use of 212 cases follows the quantitative research principle that the number of cases should be at least 10 times the number of independent variables, which in this study comprises 20 variables. This sample size was established to support the development of a predictive tool with potential for generalization (Sugiyono 2013; Kurniawan 2016; Anto et al. 2024).

The initial research phase consisted of CFD simulations conducted using ANSYS Fluent 2024 to obtain accurate airflow-velocity values that functioned as the dependent variable (Y). The ANSYS Fluent simulations were performed across nine observation zones, namely:

- Y1–Y3: velocity measurements within the volume of the first floor and/or second floor.
- Y4–Y5: measurements of the vertical inlet–outlet section and staircase void.
- Y6–Y9: horizontal sections measured at elevations of 60 cm and 150 cm on floors 1

and 2. These measurement heights were selected based on the comfort zone associated with sitting and standing activities (ASHRAE 2020)

- Each zone has minimum, average, and maximum velocity values, resulting in a total of 27 dependent variables (Y).

During the CFD simulation process, the constant environmental variable was the average wind speed within the urban residential area of Jakarta, which was approximately ± 2 m/s based on BMKG data for 2023–2025. This value was selected to approximate actual conditions in a tropical urban environment. The CFD simulation results indicate the average RD velocity across all conditions represented by Y1–Y9, as shown in figure 5.

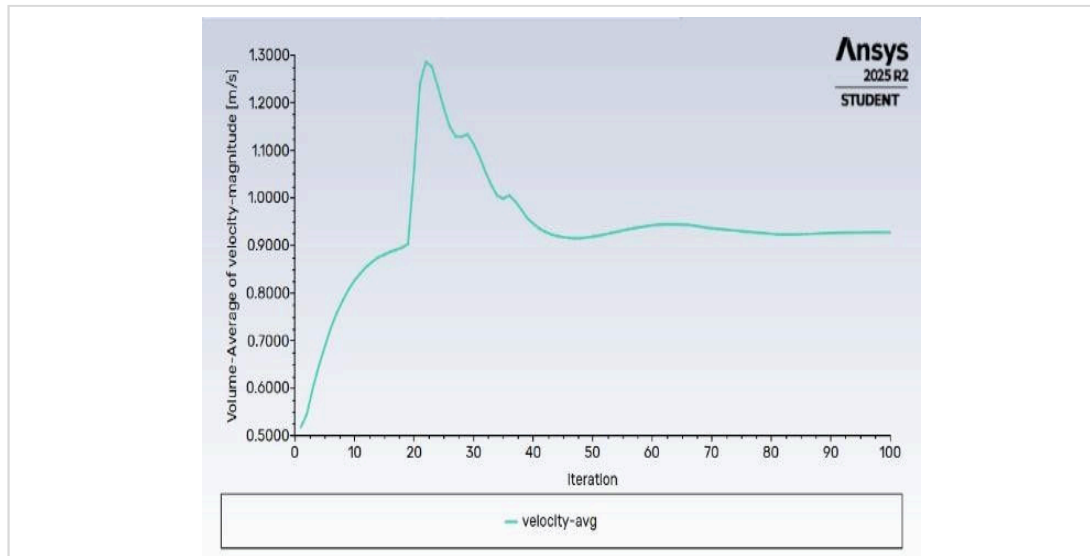


Figure 5. Average wind speed of 0.98 m/s from CFD results for 9 measurement zones

Following the determination of the average velocity value of 0.98 m/s, the minimum and maximum velocity values were identified through the ANSYS Fluent simulation using velocity contours. The magnitude of the minimum and maximum velocity values obtained from the CFD analysis is presented in table 2.

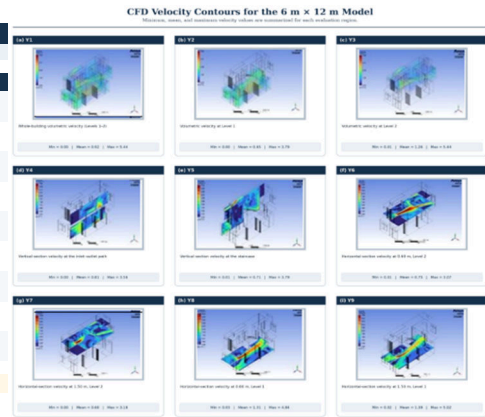
Among the 27 dependent variables, the highest velocity value was identified in the volume zones of the first and second floors (Y3), reaching 5.44 m/s within the combined volume of

the first and second floors. The average CFD velocity results are also presented graphically in figure 5. The velocity values obtained from the CFD simulation within the spatial zones consequently function as the dependent variable (Y). The subsequent analytical stage involved linear regression analysis using the stepwise method in SPSS to identify the relationships between building geometry variables and airflow-velocity values.

Table 2. CFD simulation results: Wind speed and wind speed contours

CFD Velocity Summary — 6 m × 12 m Model						
Journal-ready summary; minimum, mean, and maximum values are linked to the detailed dataset.						
Panel	Variable	Evaluation region	Minimum	Mean	Maximum	Unit
(a)	Y1	Whole-building volumetric velocity (Levels 1-2)	0.00	0.92	5.44	m/s*
(b)	Y2	Volumetric velocity at Level 1	0.00	0.65	3.79	m/s*
(c)	Y3	Volumetric velocity at Level 2	0.01	1.26	5.44	m/s*
(d)	Y4	Vertical-section velocity at the inlet-outlet path	0.00	0.81	3.56	m/s*
(e)	Y5	Vertical-section velocity at the staircase	0.01	0.71	3.79	m/s*
(f)	Y6	Horizontal-section velocity at 0.60 m, Level 2	0.01	0.75	3.07	m/s*
(g)	Y7	Horizontal-section velocity at 1.50 m, Level 2	0.00	0.60	3.18	m/s*
(h)	Y8	Horizontal-section velocity at 0.60 m, Level 1	0.03	1.31	4.84	m/s*
(i)	Y9	Horizontal-section velocity at 1.50 m, Level 1	0.02	1.39	5.02	m/s*

*Verify the final velocity unit against the original ANSYS/CFD export before journal submission.



The analysis demonstrated that most of the models produced coefficients of determination (R^2) of ≥ 0.60 . The model selected as the velocity prediction tool was determined by considering

both a high R^2 value and the smallest number of determining variables. This selection criterion was adopted to ensure that the resulting prediction tool could be practically applied during the design

process. The highest R^2 value was obtained for the Y6 average variable, representing airflow velocity in the horizontal section on the second floor at an elevation of 60 cm. This model produced an R^2 value of 0.738. Four principal variables determined this model: the floor-plan width, the

number of doors on the second floor, the width of the inlet windows on the front facade of the second floor, and the area of the vertical stair void. The R^2 values obtained for Y1–Y9 are presented in table 3. The analytical results used to determine the prediction tool are summarized below.

Table 3. CFD simulation results - wind speed - linear regression - R^2 value - number of dependent variables determining the speed prediction formula

CFD ANALYSIS + SPSS Linear Regression Simulation produced the R^2 values from the Stepwise Model and the number of independent variables affecting the 27 dependent variables.						
No.	Y	Velocity CFD	Dependent Variable	R^2 Value		Number of Independent Variables
				Minimum	Maximum	Selected Largest
1	Y1_minimal	0.00	Volume Velocity Lt 1 and Lt 2	-	-	-
2	Y1_average	0.92	Volume Velocity Lt 1 and Lt 2	0.628	0.785	8 13
3	Y1_maximum	5.44	Volume Velocity Lt 1 and Lt 2	0.640	0.702	3 -
4	Y2_minimal	0.00	Volume Velocity Lt 1	-	-	-
5	Y2_average	0.65	Volume Velocity Lt 1	0.604	0.675	7 10
6	Y2_maximum	3.79	Volume Velocity Lt 2	0.601	0.685	4 10
7	Y3_minimal	0.00	Volume Velocity Lt 2	-	-	-
8	Y3_average	1.26	Volume Velocity Lt 2	0.626	0.793	4 11
9	Y3_maximum	5.44	Volume Velocity Lt 2	0.640	0.699	3 9
10	Y4_minimal	0.00	Vertical Velocity at Inlet-Outlet	-	-	-
11	Y4_average	0.41	Vertical Velocity at Inlet-Outlet	0.643	0.744	3 10
12	Y4_maximum	3.56	Vertical Velocity at Inlet-Outlet	-	-	-
13	Y5_minimal	0.00	Vertical Velocity at Tangential	0.603	0.645	3 12
14	Y5_average	0.71	Vertical Velocity at Tangential	-	-	-
15	Y5_maximum	3.79	Vertical Velocity at Tangential	0.610	0.688	3 13
16	Y6_minimal	0.00	Horizontal Velocity 60cm Lt 2	-	-	-
17	Y6_average	0.94	Horizontal Velocity 60cm Lt 2	0.738	0.817	4 9
18	Y6_maximum	4.84	Horizontal Velocity 150cm Lt 1	0.710	0.888	3 13
19	Y7_minimal	0.01	Horizontal Velocity 150cm Lt 1	-	-	-
20	Y7_average	0.50	Horizontal Velocity 150cm Lt 1	0.663	0.855	3 12
21	Y7_maximum	3.18	Horizontal Velocity 150cm Lt 2	0.719	0.896	4 14
22	Y8_minimal	0.03	Horizontal Velocity 150cm Lt 2	-	-	-
23	Y8_average	1.13	Horizontal Velocity 150cm Lt 2	-	0.609	3 10
24	Y8_maximum	4.84	Horizontal Velocity 150cm Lt 2	-	-	-
25	Y9_minimal	0.90	Horizontal Velocity 150cm Lt 1	-	-	-
26	Y9_average	1.39	Horizontal Velocity 150cm Lt 1	0.602	0.618	11 12
27	Y9_maximum	5.02	Horizontal Velocity 150cm Lt 1	-	-	-

No.	Y	Dependent Variable	R^2 Value	
			Min	Max
1	Y1_average	Volume Velocity Lt 1 and Lt 2	0.628	0.785
2	Y1_maximum	Volume Velocity Lt 1 and Lt 2	0.640	0.702
3	Y2_average	Volume Velocity Lt 1	0.601	0.675
4	Y2_maximum	Volume Velocity Lt 1	0.602	0.693
5	Y3_average	Volume Velocity Lt 2	0.640	0.699
6	Y3_maximum	Volume Velocity Lt 2	0.561	0.744
7	Y4_average	Vertical Velocity at Inlet-Outlet	0.643	0.744
8	Y4_maximum	Vertical Velocity at Inlet-Outlet	0.601	0.685
9	Y5_average	Vertical Velocity at Tangential	0.603	0.645
10	Y5_maximum	Vertical Velocity at Tangential	0.610	0.688
11	Y6_average	Horizontal Velocity 60cm Lt 2	0.738	0.817
12	Y6_maximum	Horizontal Velocity 60cm Lt 2	0.710	0.888
13	Y7_average	Horizontal Velocity 150cm Lt 1	0.663	0.855
14	Y7_maximum	Horizontal Velocity 150cm Lt 1	0.719	0.896
15	Y8_average	Horizontal Velocity 150cm Lt 2	0.602	0.609
16	Y8_maximum	Horizontal Velocity 150cm Lt 2	0.602	0.618

Y	Dependent Variable	Number of Independent Variables	
		Selected	Largest
Y1_average	Volume Velocity Lt 1 and Lt 2	8	13
Y1_maximum	Volume Velocity Lt 1 and Lt 2	3	9
Y2_average	Volume Velocity Lt 1	7	10
Y2_maximum	Volume Velocity Lt 1	4	10
Y3_average	Volume Velocity Lt 2	4	11
Y3_maximum	Volume Velocity Lt 2	3	9
Y4_average	Vertical Velocity at Inlet-Outlet	3	10
Y4_maximum	Vertical Velocity at Inlet-Outlet	3	11
Y5_average	Vertical Velocity at Tangential	3	12
Y5_maximum	Vertical Velocity at Tangential	3	13
Y6_average	Horizontal Velocity 60cm Lt 2	4	9
Y6_maximum	Horizontal Velocity 60cm Lt 2	3	13
Y7_average	Horizontal Velocity 150cm Lt 1	3	12
Y7_maximum	Horizontal Velocity 150cm Lt 1	4	14
Y8_average	Horizontal Velocity 150cm Lt 2	3	10
Y8_maximum	Horizontal Velocity 150cm Lt 2	3	10
Y9_average	Horizontal Velocity 150cm Lt 1	11	12

The Y1–Y9 measurement zone with $R^2 < 0.6$ was excluded because it did not meet the requirements for generating architectural knowledge.

In determining the initial predictive formula for natural ventilation, the highest R^2 value with the smallest number of variables was selected. The findings indicate that the largest R^2 value (●) and the main variable (●) are used to determine the formula, together with the highest relevant number of independent variables.

Based on table 3, measurements among Y1 – Y9 that produced R^2 values ≤ 0.60 were excluded from consideration in developing the prediction

equation. Models with R^2 values ≥ 0.60 and their corresponding numbers of determining variables are presented graphically in figure 6.

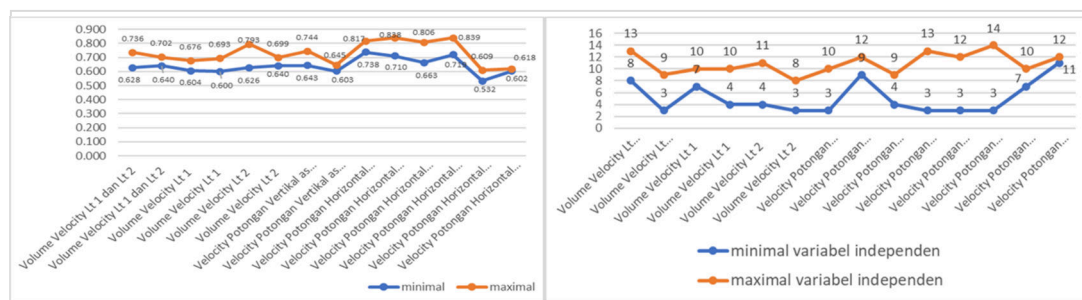


Figure 6. SPSS linear regression analysis results: Min-Max R^2 values in 9 measurement zones in the row house

The results presented in table 3 and figure 6 indicate the possibility of establishing two prediction tools: a simple prediction tool and a complex prediction tool. The equation developed for the simple prediction tool is: $Y = 4.046 - 0.738 \times \{\text{Building Width (X1)}\} + 0.282 \times \{\text{Number of Doors on the 2nd Floor (X10)}\} +$

$0.204 \times \{\text{Width of Window Inlet on the Front Façade of the 2nd Floor (X16)}\} + 0.381 \times \{\text{Area of Vertical Stair Void (X6)}\}$. This equation is applicable only to row houses with widths within the 4–6.5 m range. The limitations associated with the linear equation are illustrated in the corresponding linear-equation graph.

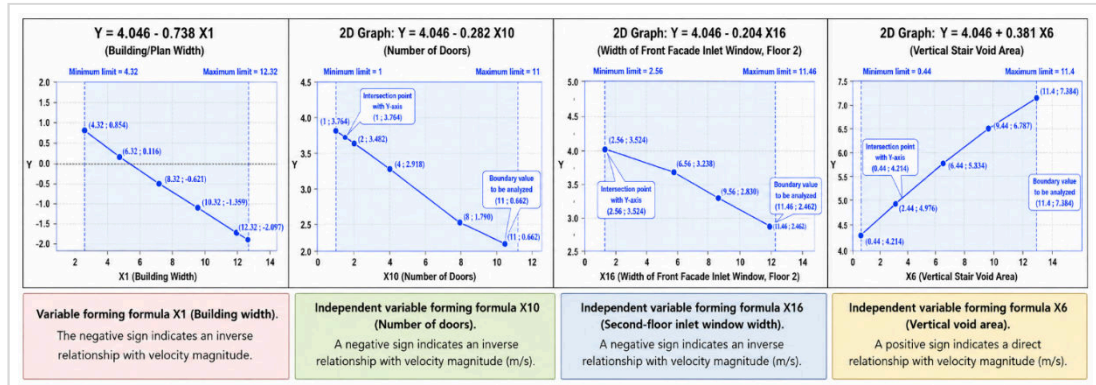


Figure 7. Graph of the linear equation formula constraints for the row house prediction tool

A more complex prediction model generated an R^2 value of 0.867, indicating a higher level of accuracy for predicting airflow velocity in row houses. This model incorporates 16 independent variables. The resulting equation is: $Y = -6.593 + 2.479 \times \{\text{Area of Vertical Stair Void Hole (X6)}\} - 2.522 \times \{\text{Building Width (X1)}\} + 1.889 \times \{\text{Width of Inlet Window on Front Façade, 2nd Floor (X16)}\} - 0.293 \times \{\text{Area of Courtyard Void with Open Roof (X8)}\} - 0.254 \times \{\text{Area of Indoor Vertical Void (X7)}\} + 5.872 \times \{\text{Height of Bouvenly Window (X14)}\} + 0.399 \times \{\text{Width/Length of Massive Wall Perpendicular to Wind Direction (X3)}\} + 0.705 \times \{\text{Number of Doors on 1st Floor (X9)}\} + 1.269 \times \{\text{Width of Main Door (X11)}\} + 0.594 \times \{\text{Width of Outlet Window on 1st Floor (X17)}\} - 0.746 \times \{\text{Number of Doors on 2nd Floor (X10)}\} + 5.314 \times \{\text{Position of Window from Floor Elevation, Public Space (X19)}\} - 0.500 \times \{\text{Width of Outlet Window on 2nd Floor (X18)}\} - 0.097 \times \{\text{Wall Perpendicular to Wind Direction, Solid/Hollow (X4)}\}.$

Conclusions

The findings demonstrate that an R^2 value of 0.738 is determined by four principal variables that function as predictors of velocity in RD: building width, despite its negative coefficient; the number of doors on the second floor; the width of the inlet window on the front facade of the second floor; and the area of the stair void. Variables with negative coefficients indicate an inverse relationship with airflow velocity; in other words, when the corresponding geometric dimension increases, the predicted velocity value decreases. In particular, an increase in building width is associated with a reduction in airflow

velocity. The initial design strategy, which integrates architectural and interior geometric considerations, is capable of producing improved airflow velocity conditions in row houses located in tropical urban environments. The CFD simulations conducted across 212 row house cases demonstrate that the combination of horizontal and vertical ventilation through the stack effect generated by the stair void can produce a more stable and evenly distributed airflow pattern, particularly on the second floor.

This research also successfully developed an airflow-velocity prediction tool in the form of a linear equation that is straightforward to apply, rapid, practical, and sufficiently accurate for supporting natural ventilation prediction during the early design phase. The model is effective for early-stage application because it requires only a limited number of geometric variables while retaining a satisfactory level of predictive accuracy.

In addition, the research generated a complex prediction model with an R^2 value of 0.867, consisting of 16 significant geometric variables and consequently providing a higher level of predictive precision for the advanced design development stage. The principal novelty of this research lies in the development of a prediction tool based on the integration of building design geometry, encompassing both architectural and interior characteristics, that can translate complex CFD simulation results through linear regression analysis. The stepwise model converts these complex relationships into a practical linear equation, thereby providing a useful instrument for making natural ventilation design decisions more rapidly and efficiently without compromising architectural design creativity.

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Khotijah Lahji contributed to the research concepts preparation, methodologies, investigations, data analysis, visualization, articles drafting and revisions.

Agus Budi Purnomo contribute to the research concepts preparation and literature reviews, data analysis, of article drafts preparation and validation.

Inavonna contribute to methodology, supervision, and validation.

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