USE OF THE VEPZO MODEL TO OPTIMIZE A HYBRID VENTILATION SYSTEM

Victor Norrefeldt[1], Gunnar Grün[1], Christoph van Treeck[1,2]
1: Fraunhofer-Institut für Bauphysik, Valley, Deutschland
2: RWTH Aachen, Lehrstuhl für Energieeffizientes Bauen, Aachen, Germany

ABSTRACT

The method presented in this paper extends previous work on a velocity propagating zonal model (VEPZO) which has been presented at the previous BauSIM 2010 conference [Norrefeldt et al. 2010]. The model subdivides a single air volume space into several zones where adjacent elements exchange air through connected flow paths. The model functionality has been extended to represent the local room air temperature distribution. The VEPZO model is further coupled to a genetic algorithm, an optimization procedure derived from Darwin's law of "survival of the fittest". This coupling elaborates to solve for optimized positions and intensities of air inlets and outlets or heat sources in a room. An application example is shown in this paper in terms of optimizing window usage in a hybrid classroom ventilation system.

INTRODUCTION

Accurate modeling of buildings and vehicles requires knowledge about the internal air distribution both in terms of velocity and temperature. A single-zone model considers the air in a building to be perfectly mixed "from cellar to roof". A multizone model typically refines this to a room level. Air exchanges occur between rooms or with the environment. On the other hand, Computational Fluid Dynamics (CFD) solves the Navier-Stokes equations numerically on a very fine grid. This provides a high level of detail of airflows in a room but requires large computational resources. The zonal model is an alternative. Zonal models decompose a room into a number of zones, typically 10 to 100 [Boukhris et al. 2009]. The flow model between zones is based on the Bernoulli-equation resulting in a square root function of the pressure difference:

$$\dot{m} = C_d \cdot A \cdot \sqrt{2 \cdot \rho \cdot \Delta p} \qquad (1)$$

With C_d: discharge coefficient, A: common area of connected zones, ρ: density of air, Δp: pressure difference between zones. Mass balances within spaces accordingly lead to an equation set which is to be solved for the unknown pressure values.

At zero pressure difference, the square root is numerically unstable due to its infinite gradient. Furthermore, the Bernoulli equation takes the distance between two zones only implicitly into account through the discharge coefficient. Therefore, the number of zones directly impacts the total pressure drop along a room [Axley 2001]. Once air enters a zone, its velocity is supposed to dissipate. Therefore, the zonal formulation is not valid in areas with driving flows due to jets or plumes [Wurtz et al. 1999]. Here, [Inard et al. 1996] suggest using special jet-, plume- or thermal boundary layer correlations to compute the amount of air entrained from the surrounding "normal" zones.

The authors consider the local resolution and computational speed of zonal models beneficial for optimization, bearing at the same time in mind restrictions due to resolution accuracy. However, the selection of a suitable correlation for driving flows is unpractial for optimization applications. Already slight changes in the model may have an impact e.g. when switching from an isothermal to buoyancy influenced jet. Therefore, the VElocity Propagating ZOnal model (VEPZO) has been implemented. The velocity of air is a property of the zones and can therefore be propagated into space. The flow model computes the airflow acceleration from the forces acting on the portion of air contained in the flow path instead of using the Bernoulli equation. . This allows to skip special correlations for driving flows. At steady-state the sum of forces and thus the acceleration become equal to zero and the achieved velocity is maintained.

When using a zonal model for optimization applications, one must consider that discrete and continous parameters may coexist. Discrete parameters are for example the location of a heat source or ventilation device in a specific zone. Continous parameters are their intensities. Furthermore, the structure of the problem is not priorly known and several optimal solutions may exist. The Genetic Algorithm (Figure 1) can deal with these constraints. It translates Darwin's law "of survival of the fittest" to technical optimization applications. Better performing solutions have a higher probability to reach the next generation.

Before the algorithm starts, a set of parameters is binary encoded by a suite of bits admitting the values 0 or 1. For discrete parameters the number of bits is determined by the number of admissible values. E.g. for four possible values two bits are needed. Continuous parameters need to be discretized for binary coding. The required resolution between a fixed minimal and maximal value of the continuous parameter determines the number of bits (cf. [Anderson et al. 1996]). The population size is a tradeoff between the time needed to evaluate all individuals and the necessity to have a sufficient level of heterogeneity between the solutions to avoid the optimization on only a subset of the whole parameter space. [Alander 1992] finds that the number of individuals should be between one or two times the number of bits needed to encode an individual.

A fitness evaluation is obtained from the simulation result of a specific set of parameters. Elitism guarantees that the fittest individuals are always transferred to the next generation and do not get coincidently lost. Selection randomly picks a series of pairs and the best individual of each pair passes to the next generation. The crossover operator exchanges genetic information between two individuals [De Jong 1975]. The goal is that two relatively well performing individuals can mix their genetic information forming an even better individual. Mutation randomly alters the genetic information by inverting a bit [De Jong 1975].

The loop of selection, elitism, mutation and crossover stops when a stop criterion is fulfilled. Typical criterions are that the best individual has not improved in the last iterations, that a maximum number of iterations has been reached, that the uniformity of the population is above a certain level or that the fitness is above a certain threshold [Madadi and Balaji 2008].

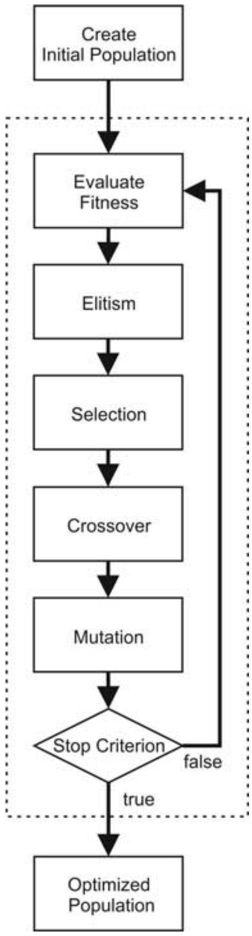

Figure 1: Genetic Algorithm

METHOD

The two main components of the VEPZO model are a zone model and a flow model (Figure 2). A flow model connects two adjacent zones. Each zone can have up to six neighbors, one in each Cartesian direction. Air properties are computed from models contained in the Modelica.Media [Modelica Association 2012] package thus allowing taking into account non-isothermal cases. Depending on the application, the air model can be changed from dry to moist air. Even pollutant could be taken into account. The advantage of implementing the zonal model into Modelica is that it can be coupled to other existing models.This section gives a description of the VEPZO model and the implemented Genetic Algorihtm. A more detailed description of the VEPZO model can be found in [Norrefeldt et al. 2012].

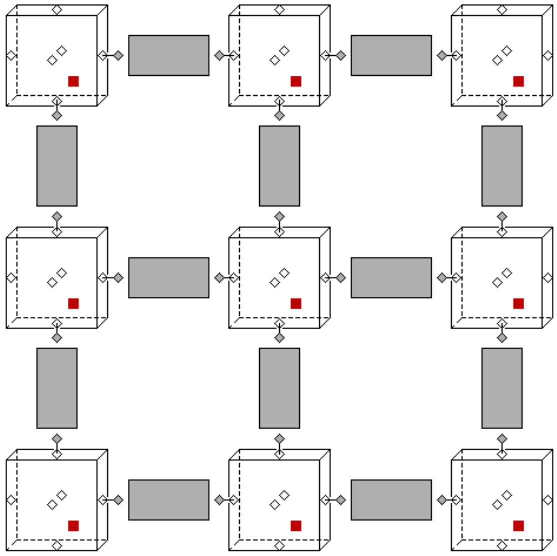

Figure 2: Zonal model in x-z direction (y not shown); cubes: zones; grey rectangles: flows; rhombs: airflow ports; red solid squares: heat ports.

Zone model

Air contained in a zone i of size Δx_i, Δy_i, Δz_i and volume V_i with density ρ_i and specific enthalpy h_i is assumed to be perfectly mixed. In the zones, the dynamic conservation of mass (equation (2)) and enthalpy (equation (3)) are enforced. The mass conservation takes into account the amount of air $m_{i,j}$ exchanged with adjacent zones and airflows provided by various sources or sinks $m_{source,i}$ (ventilation, openings, etc.) in zone i. When steady state is reached, the net sum of all exchanged airflows in a zone becomes zero. Heat flows Q due to convection from and to walls or heat sources contained in the zone are added to the thermal energy balance.

$$\frac{\partial \rho_i}{\partial t} = \frac{\sum_j \dot{m}_{i,j} + \sum_{sources} \dot{m}_{source,i}}{V_i} \qquad (2)$$

$$V_i \cdot \rho_i \cdot \frac{\partial h_i}{\partial t} = \sum_j \dot{m}_{i,j} \cdot h_{i/j} + \sum_{sources} \dot{m}_{source} \cdot h_{i/source} + \sum_{heat\,flows} \dot{Q} \qquad (3)$$

A new feature of the VEPZO model is that a characteristic velocity vector (u,v,w) is assigned to the zones. Knowing the mass flow and its direction across each of the zone's surfaces, the flow velocity across these surfaces is determined: u_{left}, u_{right}, v_{front}, v_{back}, w_{bottom}, w_{top} for the left, right, front, back, bottom and top surfaces (shown for x-direction in Figure 3 and Table 1).

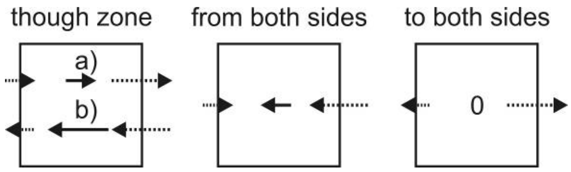

Figure 3: Assignment of characteristic velocity to a zone, dotted arrows: airflow across zone boundaries, solid arrow: characteristic velocity of zone. Left: flow through the zone, case a) left to right, case b) right to left, Middle: Air enters zone from both sides, Right: Air leaves zone on both sides

Table 1: Assignment of characteristic velocity components of a zone (for x-direction)

Flow through zone	Characteristic velocity
left → right	u_{left}
right → left	u_{right}
left and right → zone	$u_{left} - u_{right}$
zone → left and right	0

The zone shares the information about its characteristic velocity with the flow models surrounding it. This enables the VEPZO model to propagate the airflow velocity throughout the room without needing special correlations like jets or plumes.

Viscous loss flow model

Two adjacent zones are connected by a flow model in x, y or z direction.

The flow model computes the airflow acceleration or deceleration from the forces acting on it. These are pressure difference F_P, momentum difference F_M (shown for x-direction), in the z-direction gravitation F_G and the viscous force F_V (equations (4) to (9)).

$$F_P = -A \cdot (p_j - p_i) \qquad (4)$$

$$F_{M,x} = -\rho \cdot A \cdot (u_j^2 - u_i^2) \qquad (5)$$

$$F_G = -\rho \cdot g \cdot A \cdot \Delta z_{ij} \qquad (6)$$

The viscous forces act parallel to the flow direction. In the selected approach of the VEPZO model, flows are connected and exchange information with zones only. However, to calculate the shear stress, an information exchange between parallel flow models would be necessary. To avoid connections between the flow models, viscous losses are calculated in the zone models but used in the flow models.

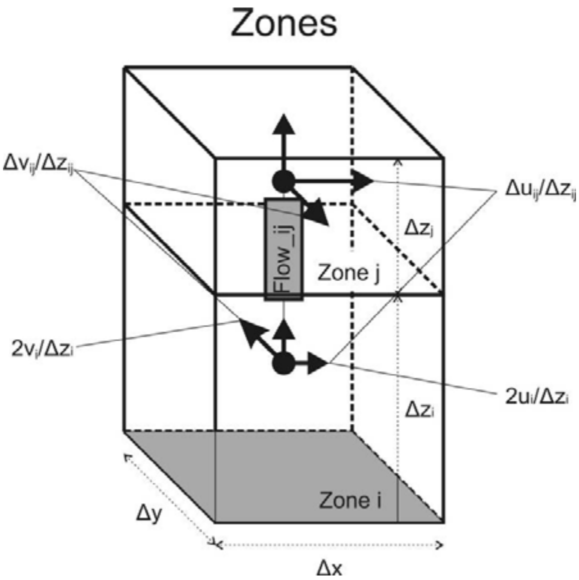

Figure 4: Computation of velocity gradient if lower boundary of zone i is a wall.

The characteristic velocity vector provided by zones enables the flow model to calculate the gradient of the two velocity components perpendicular to the flow model direction (Figure 4). If a wall is adjacent to the zone, the velocity at the wall is assumed to be zero. Equation (7) provides an overview of gradient calculations in x-direction.

Gradient in flow model		Gradients at walls		
$\frac{\Delta v_{ij}}{\Delta x_{ij}}$	$\frac{\Delta w_{ij}}{\Delta x_{ij}}$	$\frac{2 \cdot v_i}{\Delta x_i}$	$\frac{2 \cdot w_i}{\Delta x_i}$	(7)

The gradient information is transmitted from the flow model to the zone model. In the zone model this gradient causes shear stresses on its boundaries. Summing these shear stresses along the boundaries yields the viscous forces $F_{V,x}$ ($F_{V,y}$, and $F_{V,z}$ accordingly) in the zones (μ: dynamic viscosity of air):

$$F_{Vx,Zone} = \mu \cdot \left\{ \begin{array}{l} \left[\left(\frac{\Delta u}{\Delta y} \right)_{back} - \left(\frac{\Delta u}{\Delta y} \right)_{front} \right] \cdot \Delta x \cdot \Delta z + \\ \left[\left(\frac{\Delta u}{\Delta z} \right)_{up} - \left(\frac{\Delta u}{\Delta z} \right)_{down} \right] \cdot \Delta x \cdot \Delta y \end{array} \right\} \quad (8)$$

Because the flow model covers half of the length of each adjacent zone the resulting viscous force in the flow model is the sum of half of the viscous forces in the zones.

$$F_{Vx,Flow} = \frac{1}{2} \cdot \left(F_{Vx,Zone,i} + F_{Vx,Zone,j} \right) \quad (9)$$

The sum of the forces acting on a flow path yields the acceleration of the portion of contained air.

$$A \cdot \Delta x_{ij} \cdot \rho \cdot \frac{du}{dt} = F_P + F_{M,x} + F_{Vx,Flow} \quad (10)$$

The mass flow is obtained straightforward from the velocity in a flow path. This mass flow information is transmitted to the zone model.

$$\dot{m}_x = \rho \cdot A \cdot u \quad (11)$$

Singular loss model and buoyant singular loss model

For singular elements such as doors or windows, flow models other than the viscous loss model may be more suitable. Two models are available for these elements, a singular loss model and a buoyant singular loss model. The singular loss model allows airflow in one direction only whereas the buoyant singular loss model is able to compute a two-way airflow due to a temperature difference in the adjacent zones.
The flow model implemented for the singular loss model is similar to the viscous loss model. The only change is that viscous forces F_V are not taken into account. Instead, a singular loss model yielding the force F_{loss} is used in Equation (10). This force increases with the square of the velocity. A loss factor f_{loss} is introduced to scale losses. This factor has to be estimated.

$$F_{loss,x} = -f_{loss} \cdot A \cdot \Delta x_{ij} \cdot \rho \cdot \mathrm{sign}(u) \cdot u^2 \quad (12)$$

In the buoyant singular loss model cooler air flows into the lower part of the opening whereas the warmer air flows into the upper part. When two zones are connected by a buoyant singular loss model, the linearized pressure profiles are superimposed to result in a static pressure difference and a buoyant pressure difference. Depending on whether the pressure difference changes sign along the height of the opening, a one or two way flow occurs. The implemented buoyant flow path is decomposed into horizontal slices. For each slice of area A_k at the height z_k the pressure difference is calculated according to Equation (13) yielding a force $F_{P,k}$.

$$F_{P,k} = A_k \cdot \left[(p_j - p_i) - (\rho_j - \rho_i) \cdot g \cdot (z_k - z_0) \right] \quad (13)$$

The momentum forces are not implemented in the buoyant model as velocities vary along the height of the opening and thus no characteristic velocity can be deduced. Losses are modelled as in the singular loss model yielding a force $F_{loss,k}$ per slice k. For each slice Equation (14) is used to compute the airflow velocity.

$$A_k \cdot \Delta x_{ij} \cdot \rho \cdot \frac{du_k}{dt} = F_{P,k} + F_{loss,k,x} \quad (14)$$

The summation of the computed velocities yields the mass flow exchanged through a buoyant singular loss model.

Coefficient estimation

In the viscous loss model, the viscosity is used as a parameter to tune the model. Similar to the idea of using a turbulent viscosity to take into account losses, an apparent viscosity is used instead of the dynamic viscosity. During implementation of the VEPZO model, $\mu = 0.001$ Pa·s produced results that are in good accordance with case studies presented in previous publications [Norrefeldt et al. 2010; Norrefeldt et al. 2012; Norrefeldt and Grün 2011]. For singular losses by doors or windows f_{loss} was found to be 1.2.

Genetic Algorithm implementation

The Genetic Algorithm is implemented as an Excel macro. The population size is chosen 1.5 times the number of bits needed to encode the gene, one elite is used and probability for crossover and mutation are 70% and 10% respectively. The algorithm stops if the best fitness has not improved for the last five generations.

The macro communicates with the Modelica Model by the DDE interface (direct data exchange). An initialization file with the individual's parameter set is created and read by the VEPZO model. The simulation is launched. The result is translated to a fitness value read by the Genetic Algorithm. In the end of the optimization, a list of all evaluated parameter sets and their corresponding fitnesses is exported.

COMPARISON OF COUPLING OF VEPZO AND GENETIC ALGORITHM WITH LITERATURE

[Madadi and Balaji 2008] present a study in which the location of three heat sources in a cavity of size 0.4 x 0.4 m (Figure 5) is optimized to guarantee the best cooling. Air enters in the lower left opening with an inlet velocity of 4 m/s, 300 K and leaves on the upper right side. Walls are considered adiabatic.

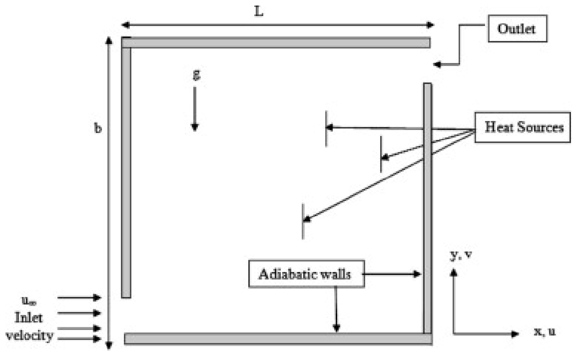

Figure 5: Geometrical setup [Madadi and Balaji 2008].

With the VEPZO-model the cavity is represented by 4 x 4 equally sized zones (Figure 6) with unity depth. Based on information in [Madadi and Balaji 2008], it was concluded that each heat source emits 40 W. A fixed heat source model from the Modelica.Standard library is plugged to the VEPZO model. The inlet is modelled by a velocity source, the outlet by a pressure sink.

The parameters for the Genetic Algorithm are the coordinates of the heat sources (Table 2). These values can be encoded by two bits, thus resulting in a total chromosome size of 12 bits.

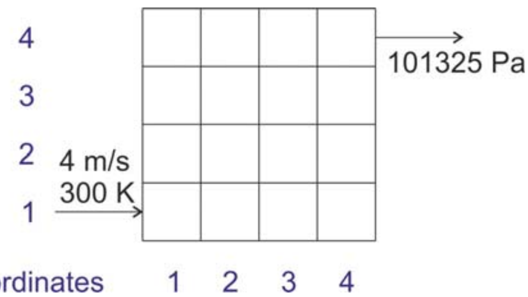

Figure 6: Zoning of cavity and attribution of coordinates in the VEPZO-model .

Table 2: Location parameters of heat sources

Coordinates	Values			
x_1	1	2	3	4
z_1	1	2	3	4
x_2	1	2	3	4
z_2	1	2	3	4
x_3	1	2	3	4
z_3	1	2	3	4

Figure 7 shows the optimal placement found by [Madadi and Balaji 2008]. The heat sources are placed in the upper right area. The surface temperature of the heat sources was used in the fitness function. This temperature depends on the temperature of the surrounding air and the local heat transfer coefficient. The latter one cannot be obtained with the VEPZO model due to the rough discretization. Therefore, the selected fitness function in this example uses the maximal air temperature of the zones with the goal to minimize this temperature.

The optimization with the VEPZO model is launched five times. The number of simulations was between 34 and 55 in each run. The time to reach convergence of one run was around one minute on an Intel® Core™ i5 CPU M 540 @ 2.35 GHz, 3 GB RAM portable computer. Each run resulted in several best solutions with the fitness -0.254 corresponding to a maximal temperature of 300.254 K (27.1 °C). A result similar to the investigated case is found and 20 other results with equal fitness (Figure 8).

Even though a high number of equally performing solutions is found, some global conclusions can be drawn. All results have in common that at least one source is placed in zone (4, 4). Furthermore, the heat sources are placed along the expected main airflow path. No heat sources are placed in zones (1, 2) to (3, 4).

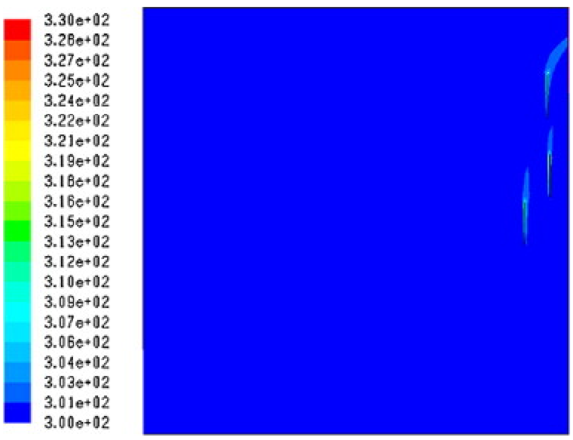

Figure 7: Optimal placement of heat sources [Madadi and Balaji 2008].

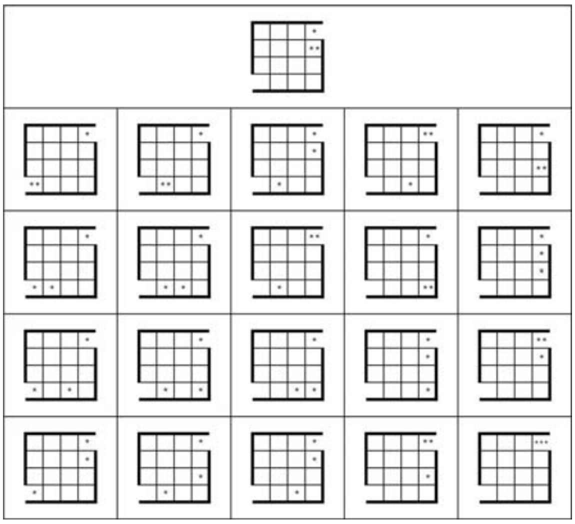

Figure 8: Optimal configurations of heat source locations (maximal temperature: 300.254 K) found with a Genetic Algorithm and the VEPZO model.

APPLICATION EXAMPLE

In this application example, a hybrid ventilation system of a classroom and the possible placement of heat sources like computers is investigated. The term hybrid ventilation refers to mechanical ventilation assisted by natural ventilation, for example through windows [IEA Annex 35 2006].

Many classrooms have operable windows; however, their use is limited when outside air temperatures are low. The presented application example aims at finding an optimal solution for the airflow provided by a ventilation system and the use of windows. Indoor air quality shall be sufficient without violating constraints of thermal comfort.

The application example simulates the period of 90 minutes after pupils have entered the classroom. The underlying assumption is that a certain configuration is selected in the beginning; but changes are not made during this time (as it is common practise).

The dimension of the classroom is admitted to be 9 x 6 x 4 m (L x W x H). It is subdivided into 6 x 4 x 4 = 96 zones of equal size (Figure 9).

At the upper left wall, an air inlet for mechanical ventilation is located, at the lower right wall an air outlet (Figure 10). The inlet is modelled by a mass flow source, the outlet by a fixed pressure of 101325 Pa. Heat recovery between exhaust and supply air is considered with an overall efficiency of 80 %.

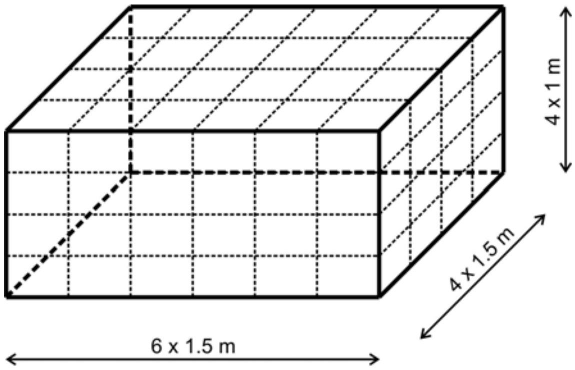

Figure 9: Zoning of classroom.

On the front surface six windows that can be closed, tilted or widely opened are located. The size of the windows is 1 x 1 m (H x B). For a tilted window an analytical formula describing the two-way airflow due to the temperature difference ΔT and mean temperature T_m of inside and outside air is used [Norrefeldt 2008] (equation (15)). The tilt width s is the distance between the upper part of a tilted window and the frame. This width is assumed to be 10 cm. The neutral height h_n can be determined from the condition that the incoming and leaving amount of air must be equal. The widely opened window is modelled by the buoyant singular loss model ($f_{loss} = 1.2$).

$$\dot{m}_{entering} = \rho \cdot \frac{8}{15} \cdot \frac{s}{H} \cdot \sqrt{\frac{2 \cdot g \cdot \Delta T}{T_m}} \cdot h_n^{5/2}$$

$$\dot{m}_{leaving} = \rho \cdot \sqrt{\frac{2 \cdot g \cdot \Delta T}{T_m}} \cdot \left[\begin{array}{l} \frac{4}{3} \cdot \frac{s}{H} \cdot \left(H \cdot (H - h_n)^{3/2} - \frac{2}{5} \cdot (H - h_n)^{5/2} \right) \\ + \sqrt{H - h_n} \cdot s \cdot B \end{array} \right] \qquad (15)$$

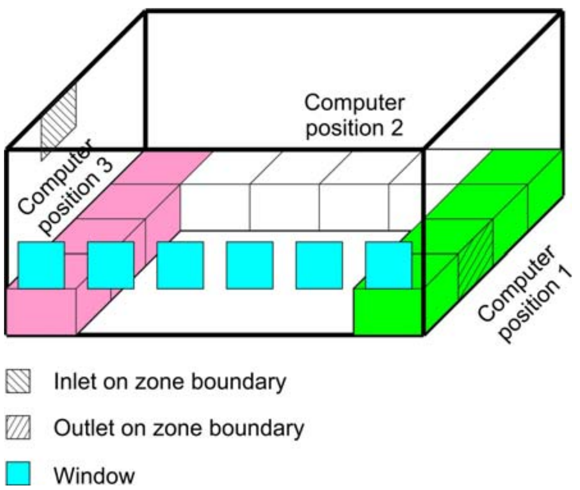

Figure 10: Variation possibilities in the classroom example

Heat and carbon dioxide sources are supposed to represent 30 pupils and one teacher. Each of them emit 37.5 W by convection and 37.5 W by radiation as well as 22.4 l/h of carbon dioxide. Four computers release convective heat of 450 W each and could be placed along three different walls (Figure 10).

Walls are supposed to be isothermal during the simulation time of 90 minutes. By this assumption, simulation speed is largely increased as the relatively slow system of a building wall does not need to be solved together with the relatively fast system of air movement. Initial air temperature and carbon dioxide concentration is 20 °C and 300 ppm. Outside air temperature and carbon dioxide concentration is admitted to be 1 °C and 300 ppm.

The Genetic Algorithm varies the opening state of the six windows (closed=0, tilted=1, widely open=2), the supply airflow rate of the mechanical ventilation (0.001, 0.05, 0.1, 0.2, 0.4, 0.6 kg/s) and the placement of computers (positions 1, 2, 3). An individual is coded by 17 bits yielding a population size of 26 individuals. The total number of possible combinations is $6 \cdot 3^6 \cdot 3 = 13122$.

The target of the optimization is to keep carbon dioxide concentration below 1500 ppm, air temperature within 20 to 22 °C and heating demand of the mechanical system as low as possible. The optimal result would have a fitness of 0, corresponding to a ventilation system that needs no additional heating and respects the defined temperature and carbon dioxide concentration limits.

The optimization procedure was launched five times to avoid drawing conclusions from only one randomly obtained result. For one run the number of model evaluations was between 51 and 90 and time until convergence of the optimization procedure was 28 to 44 min on an Intel® Core™ i5 CPU @ 2.35 GHz 3 GB Ram computer. In total 15 distinct solutions were found with the fitness of zero (Table 3). The solutions can be roughly categorized. The lowest needed mechanical ventilation supply rate is 0.1 kg/s. Then two windows need to be tilted. At 0.2 kg/s up to one window can be tilted. At 0.4 kg/s all windows should remain closed. It should be noted that the people located in the room are an important heat load. Therefore, the ventilation system does not need to recover the entire heat from the exhaust air. Due to this, it is energetically not harmful to exchange part of the ventilation air by open windows.

To assess whether the computer location has an impact, the first solution was altered by placing the computer on position 3 insead of position 1. This led to a less effective ventilation and a carbon dioxide level above 1500 ppm, which resulted in a fitness of -0.68 in the end of 90 minutes.

Variations of the window position showed to have no impact. Therefore, the authors suppose that the number of windows opened is more important than the accurate position. It should be noted that this case investigates single sided ventliation. For cross ventilation the position of opened windows is believed to have a bigger impact.

Table 3: Found results with optimal fitness of 0 (window state 1: tilted, empty: closed)

Position computer	Window 1	Window 2	Window 3	Window 4	Window 5	Window 6	Mechnical Ventilation in kg/s
1	1					1	0.1
1		1		1			0.1
1				1	1		0.1
1							0.2
2							0.2
1				1			0.2
1					1		0.2
1	1						0.2
1						1	0.2
1		1					0.2
2		1					0.2
2	1						0.2
3	1						0.2
3		1					0.2
1							0.4

DISCUSSION

The results (Table 3) can be categorized in three basic solutions: 0.1 kg/s of mechanical supply and two windows tilted, 0.2 kg/s and up to one window tilted and 0.4 kg/s with all windows closed. The combination of the VEPZO model with a Genetic Algorithm found this by only evaluating 3% of the total number of possibilites.

The resolution of results is limited to the size of the zones. Very local effects like cold falling air under a window or the actual jet formation of the mechanical ventilation supply cannot be taken into account. Blockage of airflow by furniture is neglected. As long as ventilation devices are not obstructed, it is considered that this assumption is not harmful.

CONCLUSION

In this paper, the coupling of the zonal model VEPZO and a genetic algorithm is shown. Due to the relatively quick computation and the local resolution, the zonal model can be used to optimize the location of ventilation devices' and heat sources' location and intensity. This method is compared to an example from literature. The reported result and several further possibilities for an optimal solution are found. An application example considers a simplified classroom where the following settings can be varied: opening of six distinct windows (closed, tilted, widely open), location of heat sources (computers) and amount of mechanical ventilation. The goal of the optimization is to reduce the required amount of heating for mechanical ventilation under cold conditions while providing adequate indoor air quality and thermal comfort. At an admitted outdoor air temperature of 1 °C several optimal solutions were found that can be roughly categorized: ventilation supply of 0.1 kg/s and two windows tilted, 0.2 kg/s and up to 1 window tilted or 0.4 kg/s and windows closed.

The benefit of he coupling of the VEPZO model with the genetic algorithm is that a set of promising solutions is quickly identified. On this reduced search space, further and more refined methods may be used when designing a ventilation system.

OUTVIEW

A possibility for further development of the procedure is to use Modelica's Functional Mockup Interface export option for the VEPZO model. This allows easy coupling to other software environments without the DDE-interface. Probably code for other optimization algorithms already exists in other programming languages that could thus be used. Even the cosimulation of the VEPZO model with other simulation approaches could be achieved by this export.

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