DEVELOPMENT OF NEW FACADES BY COMBINED MODELING OF THERMAL SOUND AND VENTILATION ASPECTS AT EARLY DESIGN PHASES

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ABSTRACT

Facades must meet with continuously increasing requirements concerning design quality and technical performance.

It will be shown that neither extremely simplifying nor highly detailed simulation tools with complete geometrical representation really help to develop new facade types during the early stages of design. Due to simplified physical modelling, conceptual variations may not be adequately represented and this means that different properties cannot be seen. Detailed simulation programs provide proof - but in most cases only with regard to a single aspect of facade qualities – of whether a well defined set of parameters is already given and if an adequate representation is already integrated. This often prevents the perception of interdependencies and hinders the development of ideas.

Based on the author's experience concerning simulation techniques and the process of facade consultancy services, a method with an adapted degree of abstraction was developed.

Combined modelling of thermal, sound insulation and ventilation aspects during early design stages is described and a new multilayered facade is presented.

KEYWORDS

optimization, thermal, sound-insulation, ventilation, double facade

INTRODUCTION

The demand for continuously increasing building comfort was met for a long time solely at the expense of energy and resource input. Thermal simulation programs were used in order to develop targeted calculatory forecasts of optimization potentials.

This not only changed design and construction techniques, but also affected planning methodology. The criterion of energy optimization became the central evaluation criterion for the building shell.

It was attempted to transfer the successful energy optimization approach from residential buildings to all types of buildings. As the enormous resource demand of many new office buildings and the very similar outer appearance of buildings world-wide despite completely different climatic conditions show, success here is quite moderate.

Besides the large number of people involved in the planning and design process of larger office buildings, the crucial difference is, in particular, the fact that success is measured against a significantly more complex catalog of criteria.

Handling a variety of projects the author got the impression that exactly this complexity prevents optimization methods only taking one single aspect into account from beeing integrated into early design process. Based on the author's experience simulation merely serves as a tool to proof compliance with statutory requirements if there is no integration achieved before. Increasingly user-friendly interfaces seemingly eliminate the need to know the basic physical relationships. During the planning process, the engineers expect the architect as the decision-maker to supply all necessary input parameters in order to subsequently generate the simulation result.

The general attempt to fundamentally change the planning process appears to be plausible from the researcher's perspective. But from the author's point of view there is a lack of tools which let the planner actively offer advice during early project phases or let him perform a benchmarking of variants without producing banal statements due to a small number of parameters or extremely simplifying models.

Especially with a view to planning responsibility and liability risks, adapting the planning tools seems to be a more promising approach to the author.

This paper shows how this might be achieved taking the combination of building physics and climatic requirements into account.

REQUIREMENTS PROFILE

The complex nature of the requirements for the building shell is a function of the number of different stakeholders – architect, investor, operator, user, public authorities – and of the large number of component groups of which the shell surface comprises.

The left hand side of Fig. 1 shows in a tree structure those properties of the building which determine its energy quality in relation to the environment (energy balance) as well as those properties which have a direct influence on the user's performance (utilization quality and indoor ambience). Other criteria which are important for the overall system, such as maintenance requirements, life or safety/security equipment, were neglected with a view to the subject matter of this paper.

The right hand side is a simplified presentation of the constituent parts of the building shell (transparent parts, openings, opaque parts and shading/ antidazzle) with the pertinent specific properties.

The numbering illustrates one example of the far-reaching interdependencies from acoustical quality (1) over (2 - 4) to construction of openings (5.1) and thermal comfort (5.2) which branches out to "x" different aspects (5.2.x). The section on '*Airing versus acoustics'* gives a more detailed explanation as to why these correlations should also be integrated into a design tool.

When developing the concept, the planner responsible for the building shell must establish the link between the quality criteria and the facade element and identify and quantify mutual dependencies.

On the basis of this understanding, the planner is able to respond to the design intentions and, from his technical perspective, propose alternatives of a higher quality or develop new solutions.

PRECISION VERSUS COMPLEXITY

The discussion on calculation approaches which can used to predict facade properties and will give appropriate representation of the desired components refers, on the one hand, to the requirement that the totality of qualities (Fig. 1, left column) be evaluated during the concept development phase using a set of parameters which should be as simple as possible. But is also based on the fact that the architect and other parties involved in the planning and design process mostly develop their concepts according to component categories (Fig. 1, right column).

The energy, climate, acoustic and ventilation criteria were hence analyzed in order to identify the simplest model approach which describes the influence of possible component modifications. It was an empirical fact from working with detailed programs for overall simulation that the number of input parameters otherwise increases to a level where these

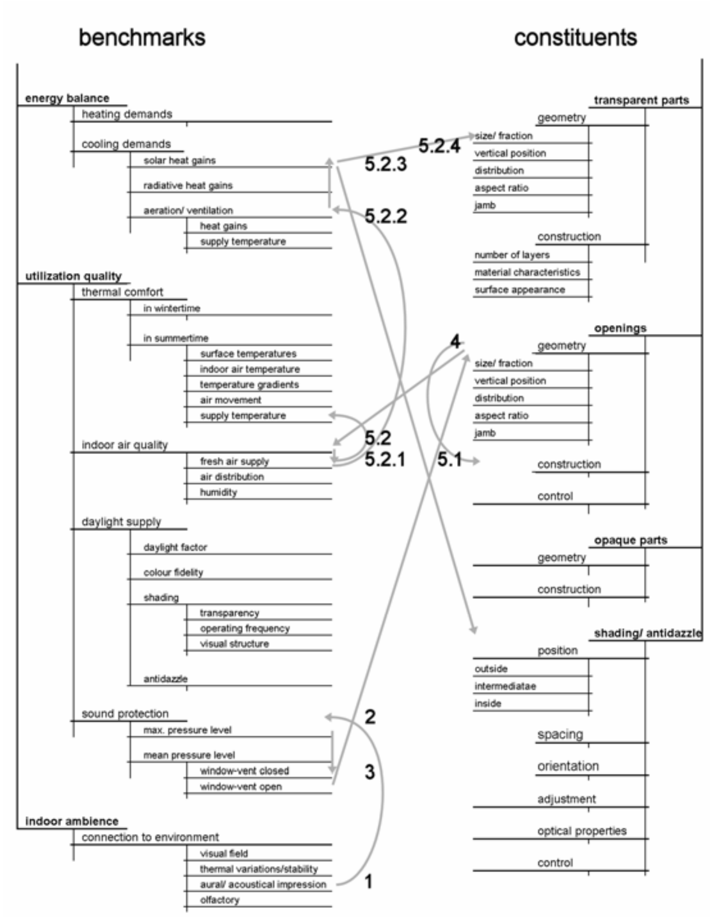


Fig. 1 - functional requirements

parameters can no longer be handled during the concept phase.

If the qualities shown in Fig. 1 are to be evaluated, the following physical properties of a facade must be implemented within the model:

- thermal properties
- optical properties
- acoustic properties
- airing/ ventilation of facade spacing
- coupling to room conditions

It was found that a generalized model approach can be implemented by developing modules which correspond to the functional levels of the facade structure. An overview of the algorithms is found in (Dijk et al., Manuals BSIM, COMIS,TAS, TRNSYS)

Thermal properties and airing of facade spacing

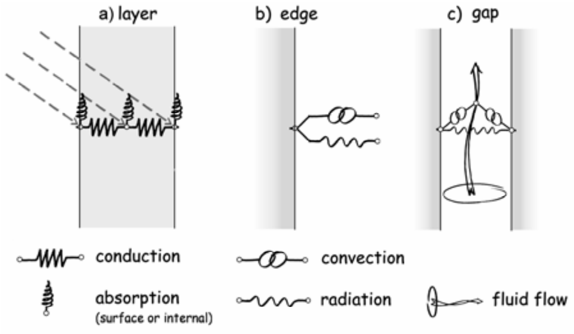


Fig. 2 - thermal and fluid flows

The simplest representataion of a single layer is a heat flow network which consists of three temperature nodes (Fig. 2a). The temperature nodes are coupled by the thermal conductivity of the layer. The balance node in the center is necessary in order to break down the total absorption of transparent layers into surface and volume shares. The same model can then be used to consider absorption of coatings or printing on the front and back and in the central area in the case of laminated glazing. No storage effects were initially implemented because the largest share of the heat loads of office buildings in most cases penetrates through the transparent parts and because the outer shell of office buildings mostly consists of materials with a lower thermal mass.

When implementing the thermal connection of the facade terminations (Fig. 2b) to interior or exterior conditions, convection and long-wave radiation exchanges must be considered separately. Temperatures where long-wave radiation exchange reaches relevant magnitudes occur with both interior sun protection and exterior glazing with higher absorption capabilities. Furthermore, this value is necessary for comfort calculations.

The individual facade levels are separated by air or gas filled gaps (Fig. 2c). These gaps can be isolated against the environment, they can permit free air flow or they can be fitted with mechanically assisted ventilation. Isolated and gas filled cavities exist in the case of thermoglazing solutions. Freely ventilated gaps exist in the case of simple facades and consist of a combination of glazing level and sun protection level. However, freely ventilated gaps must also be considered in the case of non-transparent, ventilated facades and, in particular, in the case of double-glazed windows or double facades (Grabe von et al.). Depending on whether the connection is made to the exterior or to the interior space, the ventilation heat flow must be linked to the interior or exterior air temperature in the energy balance. If a reciprocal contact exists, the balance must be drawn up depending on the resultant, uplift-induced flow (Feustel E et al.).

Optical properties of layered systems

The combined optical properties of the transparent layers (glass layers) in conjunction with the sun protection and glare protection level directly determine the cooling requirements as a function of their total energy transmission, the thermal comfort as a function of their emissivities, and daylight quality as a function of their light transmission capability.

The transmission (τ), reflection (r) and absorption (α) coefficients of glass layers are dependent on both wavelength and angle of incidence (EN 13363). Except for dichroitic glass or holographic foil, this angular dependence is always isotropic.

Fig. 3a. shows the radiation components for the single layer.

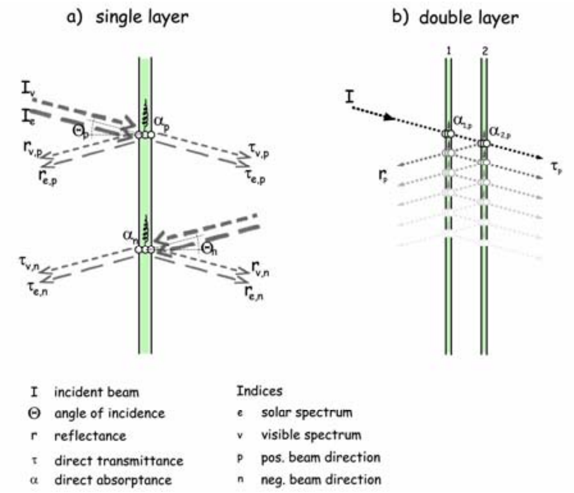


Fig. 3 - optical properties of single and double layer

In order to be able to evaluate both energy and daylight requirements, a two-band model is required as a minimum with regard to the optical properties (visible: $380\ nm \leq \lambda \leq 780\ nm$, solar: $280\ nm \leq \lambda \leq 2500\ nm$) (Rubin et al.). Solar radiation only has relevant energy fraction up to 2500 nm and transmission of float glass is nearly zero above 4700 nm (Wavenumber $n < 2100\ cm^{-2}$). This range corresponds to radiative temperatures above 340°C (Wien's displacement law) which in general would not occur. By this modeling on the basis of Planck's law of black body radiation (Fig. 2b+c) is sufficient for the long-wave band ($\lambda > 2500$ nm).

Although the spectrum-resolved calculation methodology applied in the relevant standard (EN 13363-2) is more precise, profiting from this advantage would require the complete set of optical data – transmission, reflection, absorption - in frequency and also angle dependent represention for both directions of propagation and, furthermore, climatic data with spectrum-resolved irradiation values. A parameter set of this size might be handled to provide proof but not to develop imaginative concepts during a design phase.

Even a simple facade that consists of insulating glass and sun protection already has three optically relevant levels. The overall properties of the layered structure can be determined by gradually combining the characteristics of two levels (Fig. 3 - optical properties of single and double layer) to form one level until only a single layer remains (Fig. 4 - recursive reduction).

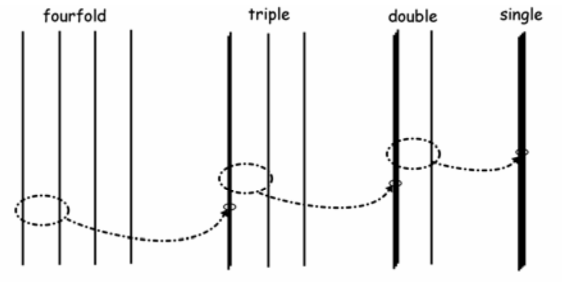


Fig. 4 - recursive reduction

Whereas light scattering foils or screen curtains feature only a minor or isotropic dependence of their optical properties with regard to the angle of incidence Θ, the properties of sun protection systems are often anisotropic (Fig. 5).

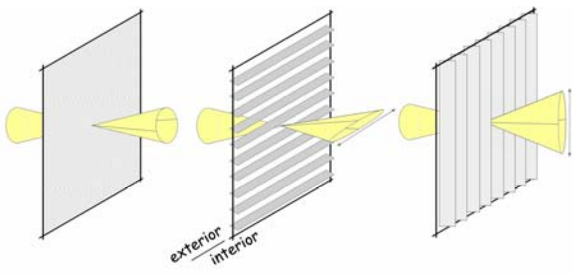


Fig. 5 - isotropic, horizontal and vertical geometry

If a particular type of sun protection is specified in the interest of maximum free vision and achievable sun protection or for design reasons, an analysis of anisotropic optical properties is inevitable. Since most facade structures are implemented with precisely horizontally or vertically oriented symmetry directions, a one-dimensional list suffices and no two-dimensional parameter array is required if the respective reference angle is used in the calculations.

Fig. 6 shows the elevation (el') in relation to the normal plane for a horizontally oriented sun protection system. The el' value of vertical facades results from the real position of the sun (elevation el, azimuth az) according to the following equation (Eq. 1):

$$el' = \arctan\left(\frac{\tan(el)}{\cos(az')}\right) \quad (1)$$

The comparison between the sun elevation el and the elevation el' projected to normal plane as well as el to the angle of incidence Θ on the facade surface shows that these are completely different.

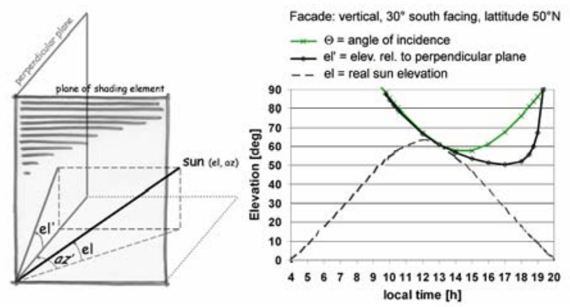


Fig. 6- real and projected elevation

It is hence definitely not enough to determine angle-dependent properties of a sun protection system with anisotropic action solely on the basis of the angular parameters of the glass calculations.

Fig. 7 gives a slight impression about the representation of the heat transfer and optics part in the solver-tool (EES) which was used to implement the set of equations.

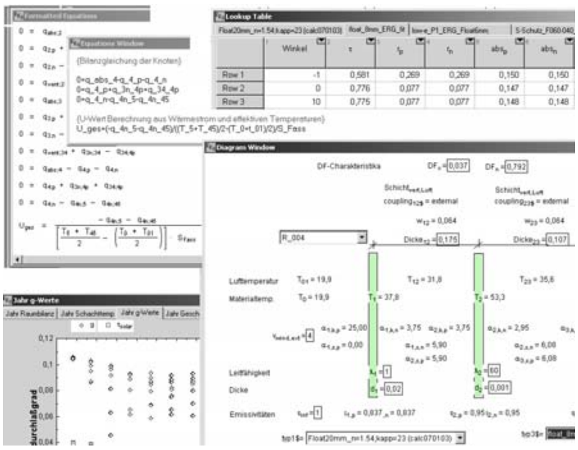


Fig. 7 - heat& optics-part, implemented in EES visible windows: equation, formatted equation, plot table, lookup table, diagram window (main)

Airing versus acoustics

The wish to erect office buildings with a high glazing share is not merely due to the impressive effect created but also illustrates that the fact that the building shell is expected not to isolate users from the outside world. Especially in temperate climates, the possibility to vary the contact between a building and the outside world not just in terms of visual appearance, but also in terms of thermal, olfactory and acoustic factors, is hence a particular quality criterion.

Complete mechanically assisted conditioning with ventilation, heating in winter and cooling in summer is not absolutely necessary for office buildings in temperate zones. Thermal comfort can often be achieved simply by heating in winter and passive cooling measures in summer, such as ventilation by night. Doing without mechanical assistance is often considered by users to be a positive element, not just with a view to operating costs, but also as a particularly healthy and environment-friendly solution.

This is, however, only valid if the free exchange of air through the facade ensures the minimum quality of room air and if noise emissions during ventilation phases are kept within reasonable limits. Whereas binding standards typically exist in the individual countries with regard to minimum sound insulation levels of facades in a closed condition, the mutual dependence between achievable ventilation rate and noise exposure through the open facade is often neglected in facade design.

In order to illustrate the far-reaching correlations, Fig. 1 graphically shows the interaction with other target qualities and direct influences on facade parts on the basis of the target quality related to exterior contact - *aural & acoustic impression (No.1 and following)*. We can see that the other criteria, such as *thermal comfort* and *cooling demands*, are just a few "hops" apart. Demands for specific qualities are proliferating within the hierarchy.

Especially office buildings in central urban locations are often exposed to very high noise emission levels. Just like in the case of the closed facade, the maximum level L_{pAFmax} and the average level $L_{pA,eq,T}$ can be used as en evaluation criterion also under ventilation conditions. One will, however, have to assume that a more intensive contact with the outside world is desired and that there is a lesser demand for silence. Acceptable levels are hence of a magnitude where office communication is still considered to be largely undisturbed, for example, during telephone calls. The range within which focused working is possible in office environments is specified at $L_{pA,eq,T}$ = 30-55 dB(A) (VDI 2058). The upper limit is hence plausible when it comes to designing ventilation conditions.

The indoor sound pressure level $L_{p,i}$ with window ventilation can be considered, precisely as in the case of the closed facade, by drawing up a sound level balance that takes room absorption into consideration (Eq. 2). The airborne noise insulation $R_{w,res}$ of the opened facade can be approximated – neglecting effects of orifice reflection and attenuation due to changes in sectional area – by the surface-weighted logarithmic addition of the closed parts of the building and the insulation factor for the opening surface ($R_{w,\,opening}$ = 0 dB) (Cremer L.).

$$L_{p,i} = L_{p,e} - R_{w,res} + 10 \cdot \log\left(\frac{S}{A}\right) \qquad (2)$$

$$R_{w,res} = -10 \cdot \log\left(\frac{1}{S_{res}} \cdot \left(\sum_{closed} S_j \cdot 10^{-R_j/10} + S_{opening} \cdot 10^{0}\right)\right)$$

$L_{p,i}$ external soundpressure level [dB]
S facade area [m²]
S_j closed subsurfaces, $S_{opening}$ window aperture [m²]
A equivalent absoption area [m²]

The basic equation (Eq. 2) shows that small aperture cross-sections already reduce the achievable airborne noise insulation to a significant extent. The frequency-dependent level calculation for a typical office space with an all-glass facade $R_{w,closed}$ = 40 dB with traffic noise conditions of $L_{p,e}$ = 70 dB(A) already gives an indoor noise level of $L_{p,i}$ = 55 dB(A) with a 3% aperture share and as much as 58 dB(A) with 6% and 60 dB(A) with 10%.

The antagonistic dependencies – the larger the opening, the better the ventilation, but the less favorable the indoor sound level and vice versa – together with the non-linear behavior illustrates the optimization problem.

Multi-layered, ventilated facades are one option to enable window ventilation despite elevated outdoor sound levels. Transparent levels serving as noise shields are fitted in front of the opening. The aim is to reduce noise immissions without unreasonably restricting the ventilation rate.

Fig. 8 shows that a clear optimum exists for the aperture width – 0.16 m² in this case – with a combined evaluation of noise and room air quality. This information can be used at the planning stage in order to identify a suitable geometry of the opening wings (point 1).

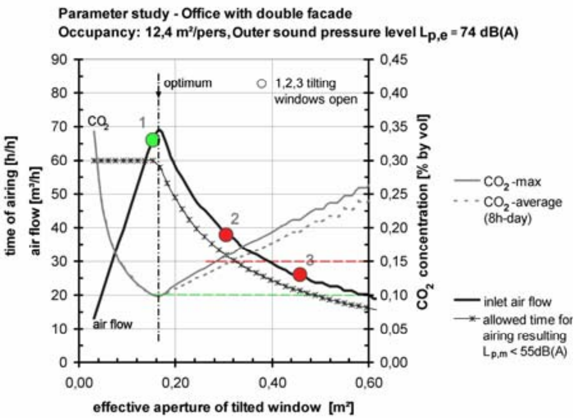


Fig. 8 – indoor air quality versus effective aperture in case of limited indoor sound pressure level

Coupling to room conditions

In contrast to conventional thermal simulation approaches, the facade was analyzed separately from the interior building parts and HVAC components in order to minimize the set of parameters. The boundary conditions for the indoor situation (temperature, gradient, lighting, etc.) are hence set within the bandwidth of what is permissible for room climate, taking the (time-resolved) outdoor conditions into consideration. This approach is precise enough for the concept phase because the bandwidth of acceptable indoor conditions is very narrow compared to the variations of outdoor conditions.

THE APPLICATION EXAMPLE OF THE RV OFFICE

Design requirements (architect)

- Transparent glass skin in neutral color

Functional requirements (customer)

- The facade is to provide a good relationship for users.
- Despite a high outdoor noise level, free window ventilation is to be possible all year round.
- Good room climate conditions even without mechanically assisted cooling or ventilation.
- Use of a sun protection system despite strong outdoor wind exposure at the location.

Analyzing the boundary planning conditions

Given the climatic conditions at the location, room-high glazing would require strong sun protection glazing in a non-neutral color or additional cooling which would not comply with the planning requirements.

In order to minimize the high solar loads, the sun shades would have to be let down over long periods in the case of room-high glazing. Visual contact with the outside would hence be restricted despite the large share of glazed surfaces.

Valuable contact with the outside world requires adequate insulation against outdoor noise in the case of window ventilation. A high outdoor noise level of L_m= 73 dB(A) prevails at the location during the day. The indoor sound level of 62 dB(A) which would result in the case of window ventilation with minimum opening surfaces would not be reasonable.

The concept approach

- Ventilated glass shield as a facing level in order to reduce outdoor noise exposure
- Reducing effective glass fraction in spite of a full-glass outer shell by use of partially opaque inner facade

The disadvantages of conventional double facades are in most cases due to high heat loads which result from unwanted heating up of fresh air in summer and limited ventilation of the facade space.

Idea and planning hypothesis

"*Geometric offset between floor separation and facade box"* (Fig. 9)
In the absence of wind, the ventilation of a facade shaft is solely caused by thermal lift. A temperature difference between shaft and exterior space is hence absolutely necessary even if this is undesirable from a room climate perspective.

However, the pre-heating rate of the fresh air is extremely reduced if the window opening and the upper part the facade shaft - where a hot-air cushion usually builds - are not on the same level.

The higher the acceptable heating up of areas not relevant for ventilation may be, the higher the fresh-air flow that can be achieved through the facade shaft and the better the achievable room air quality.

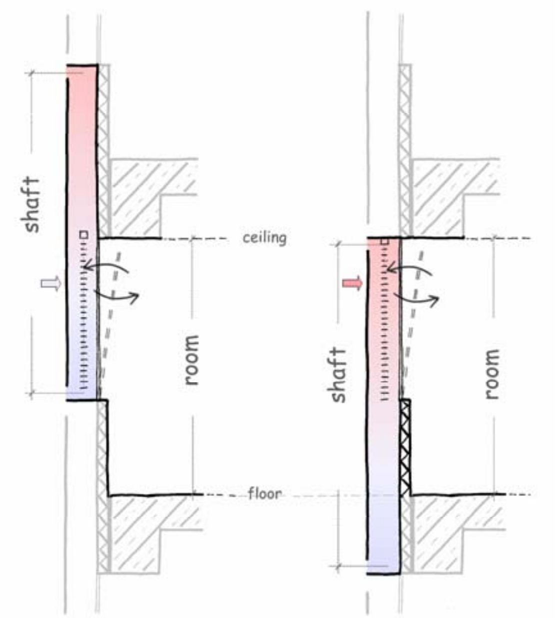


Fig. 9 - Room & shaft - staggered / matching levels

Approach for the model calculations

The overall model for the thermal and ventilation properties accordingly (Fig. 10) results from the individual modules (material, shaft, side and room connection) and from the connection of the window and panel area.

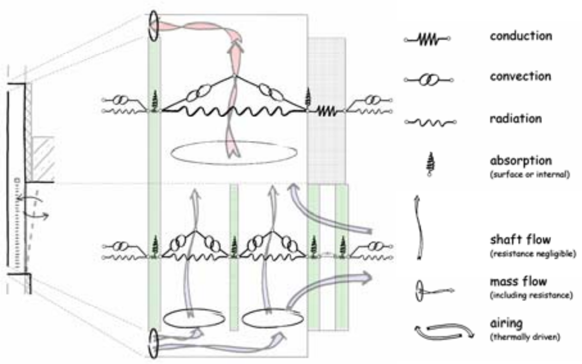


Fig. 10. - simplified facade modeling

With the above-described calculation approaches, the ventilation rate vs. time curve as plotted in Fig. 11 is obtained under the climatic conditions prevailing in summer, for example. By means of adaptation of structural parts and geometry, sufficient ventilation rates were achieved in order to discharge the heat from the facade space and to ensure the free ventilation of the offices (concerning the ventilation of a 3-bay office, refer to Fig. 11 and Fig. 12).

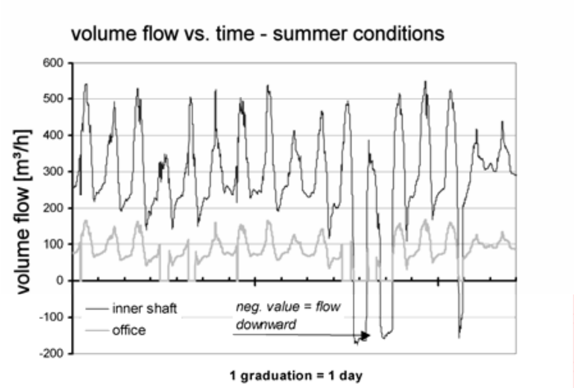


Fig. 11 - time series (2 occupants, 3 bays)

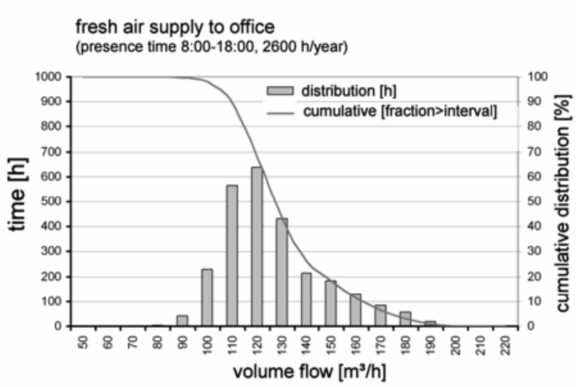


Fig. 12 - frequency distribution (2 occupants, 3 bays)

The resultant sound level in the indoor space is crucially determined by the opening widths of the facade shaft and inner tilt window. The permissible ventilation time is a function of the permissible maximum and mean sound levels. The combination of the two properties also gives the effective ventilation rate that can be achieved.

In this project, optimization resulted in a mean level of 55 dB(A) with a permissible ventilation time of 38 min/h. Taking the achievable ventilation rates into consideration, maximum CO_2 concentrations of better than 0.11% by volume were obtained during 90% of the occupancy time and values below 0.14 % by volume during 99% of the occupancy time (Fig. 13).

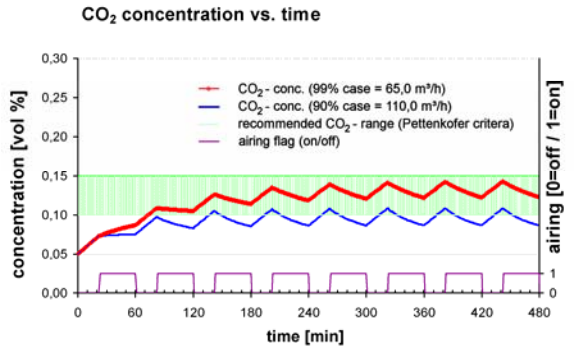


Fig. 13 – calculated CO_2 range during occupancy

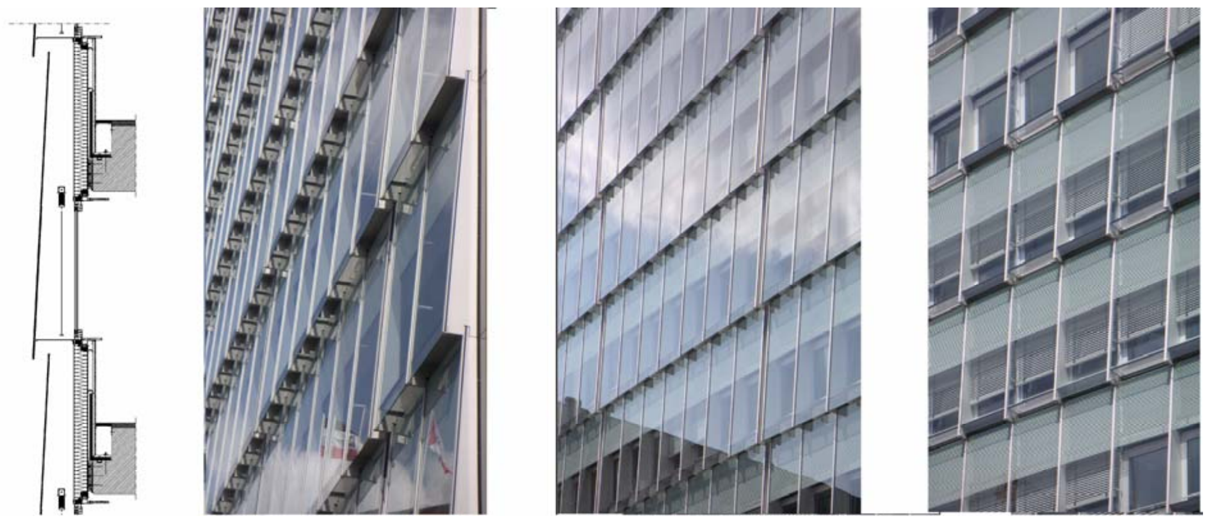
Result

The calculation model includes the combination of acoustic, ventilation and thermal quality. The abstraction level of the model system is adapted to the issues relevant during the concept phase and enables not only an assessment of the quality of the reciprocal dependencies, but also the quantification of variations of geometry or materials. Only this enables an active solution-finding process during a phase that still permits a wide variation bandwidth.

The 'staggered shaft facade' idea was implemented in compliance with functional and design boundary conditions with air supply and exhaust air openings in a staggered arrangement from bay to bay as well as partially printed front glazing in the panel area (Fig. 14).

Additional, mechanically assisted ventilation was not necessary. Only certain areas subject to increased requirements (conference area, executive floor) were fitted with additional cooling.

Fig. 14 – 'staggered shaft façade', implemented 2002



Compared to the building variant with room-high glazing first desired from a design and renting perspective, the resource demand is significantly smaller.

The decision in favor of implementing the concept idea and the as-built planning were based on the above-described model calculations. It was not until at a later stage that calculations using 3D - CFD (Fig. 15) were carried out in order to verify the calculations and analyze the selected model approaches. The illustration shows the favorable air temperatures in the area of the opening wings.

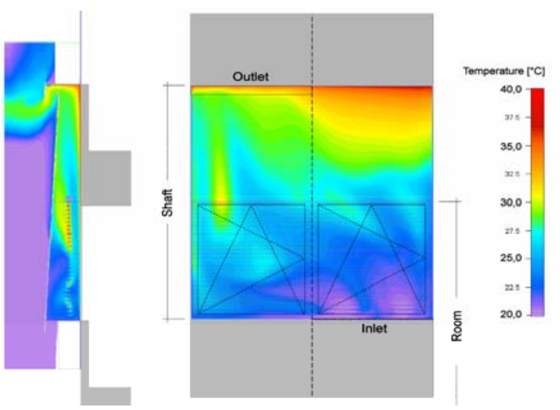


Fig. 15 3D-CFD of 'staggered shaft facade' at 500 W/m² insolation, shading closed

CONCLUSION

A design tool which is to support the early concept phases must be capable of covering several sub-areas parallel because especially during the concept phase the planner's degree of freedom is still so large that completely different building qualities must be compared and quantified.

Physically abstract models must be used in order to be able to keep the set of parameters within reasonable limits. Limited accuracy of the model is acceptable during this phase because it is relative accuracies – i.e. the comparison of variants – rather than absolute accuracies which matter at this stage. However, to an extent much greater than in the case of verification calculations it must be possible to check whether the chosen model simplification in fact represents a varied component property.

A program environment is hence required which gives access to each and every part of the model, where individual modules can be executed alone, and where the model equations are separated from the I/O codes in the most distinct manner possible.

The EES-engineering-equation-solver used enabled very rapid prototype development because it is possible to enter equations in a natural form and because resolving to the variables and iteration is carried out automatically. However, system-related restrictions become apparent with regard to the other aims.

Besides considerations concerning abstracting model approaches, the aim is to develop the simulation principle shown here in such a manner that individual modules are automatically refined in their complexity if a set of more precise data is available.

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