Spatial distribution of thermal comfort: A case study in Paris’ station

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Abstract
The present work deals with the determination of thermal comfort maps in large enclosures. Currently no specific approach is proposed to this end as building simulation relies on a nodal approach, where the computed scalar values (e.g. temperature, humidity, solar flux) are homogeneously distributed in zones whatever their size. We present here a method allowing for the calculation of a spatial distribution of thermal comfort, enhancing the classical approach by a precise determination of indoor solar fluxes and isothermal air velocities.

Introduction
In Building Energy Simulation (BES), the environmental variables for thermal comfort such as air velocity, radiant temperature, dry bulb temperature and relative humidity are nodal, meaning a single value is computed for each thermal zone, regardless of their size. This long-used approach is valid for most of the built environment, however it may prove to be inappropriate in specific cases, such as widely open and/or glazed buildings. Radiation and convection being major contributors to the heat balance of the human body (Pickup et al., 2000; Höppe, 1999), the existence of indoor solar fluxes and of significant variations in the air velocity field cannot be overlooked for a proper evaluation of thermal comfort.

In commercial BES softwares, for the calculation of comfort, air velocities are usually taken at a constant 0.13 [m/s], corresponding roughly to the natural convection around the body, or can be set by the user. Regarding the internal solar flux distribution, the most detailed options allow to compute the incident flux on each internal surface but, except for daylighting simulations, no refined spatial discretisation is proposed.

Furthermore, the classical comfort indexes (PMV, adaptive comfort model, etc.) are unsuited for the case of semi-open spaces subject to large spatial variations of the radiant or velocity fields (Pickup et al., 2000) and where the human metabolism rarely reaches its steady state (Höppe, 2002).

As commercial tools lack the spatial distribution of radiant temperature including both long- and short-wave contributions and air velocity fields as well as appropriate comfort indexes, the aim of the present work is to provide a method allowing to "enrich" the nodal approach with hourly solar distribution and air velocity fields and allow for the calculation of a detailed distribution of thermal comfort.

In the following, a proof of concept is proposed here under the form of a case study, using the state-of-the-art open-source softwares: EnergyPlus, coupled with Radiance and OpenFOAM. This method allows to determine at an hourly time step the four ambient parameters required for the computation of comfort: air temperature and relative humidity obtained here as nodal values, radiant temperatures including the solar contribution and air velocities as field values.

As a by-product, the analysis of the results allows to compare two comfort indexes, highlighting interesting discrepancies of thermal sensation for identical indoor conditions.

Brief description of the case study
Paris Gare de l’Est station is located in Paris 10th arrondissement, in a densely built environment (see Figure 1). The station was erected in the XIXth century and is mainly made of masonry walls and zinc roof cladding. It consists of three halls and one concourse giving access to the platforms.

The two lateral halls have glazed gable roofs and rose windows positioned on the the south-south-west facing facade, as well as connections to the forecourt (right of Figure 1). They are linked through a central hall with no opening to the outside (except for a connection to the forecourt). The three halls are then connected to a longitudinal concourse.

The area of interest in the presented work is the lateral hall, where the spatial occupancy planning is questioned, between waiting areas, stores, station signage, train station schedules area, etc.

Part I – Indoor Solar Radiation

The solar radiation models in the EnergyPlus routine and the functions used in Radiance both use Perez’ sky model with the direct normal and diffuse horizontal radiation from a weather file as input.

From the author’s experience with EnergyPlus’s rou-
time for the computation of indoor solar distribution, it is limited to non-convex geometries and occasionally tends to produce erroneous, scattered sun patches on discretised indoor ground surfaces.

The method described in Subramaniam (2017) is used in order to overcome these problems and obtain the indoor solar radiation, with Radiance’s gendaymtx executable. An example of result if presented on Figure 2 showing the indoor direct flux, where both the influence of the rose window and the glazed roof can be observed.

\[ T^*_r = \sqrt{T^4 + \frac{\alpha \varphi f_p}{\sigma \varepsilon}} \] (1)

where \( T^*_r \) is the radiant temperature computed with the longwave radiation contribution in the BES and \( f_p \) is a projection factor allowing to convert the flux received on the ground to the one on a cylinder, which is coherent with the chosen comfort indexes (see Part III). Variables \( \alpha, \varphi, \sigma, \varepsilon \) are respectively the solar absorptivity of the individual, solar radiation at normal incidence, Stefan Boltzmann constant and emissivity of the individual. Subsequently, the \( T^*_r \) field is used for the computation of the comfort index.

**Part II – Air Flow**

Classical BES tools lack the capability of providing accurate pressure coefficients for the determination of natural ventilation and cannot compute air velocities fields for the estimation of thermal comfort. Indeed, semi-open spaces are much influenced by natural ventilation and draught can be a non-negligible source of discomfort.

In commercial BES tools, pressure coefficients are determined using empirical relationships that are valid for rectangular, low-rise buildings, placed in regular built environment (Swami and Chandra, 1987). Reality is often more complex and the pressures on facades must hence be determined more accurately. Furthermore, the human body being very sensitive to air movement (Höppe, 1999), with indoor zones widely and/or permanently open to the outdoor, the computation of the indoor velocity field cannot be avoided.

In this section we present the methods and hypotheses made in order to obtain the pressure and velocity fields on facade and in the indoor. The widely used and validated OpenFOAM open-source CFD software is used throughout this study (Jasak et al., 2007), together with its meshing libraries: BlockMesh and SnappyHexMesh.

**Meshing with a Wind Tunnel Approach**

In the present work, a numerical wind tunnel experiment approach was used, allowing to study a given urban context under various incoming wind directions and intensities and reducing the meshing effort.

The general mesh set-up is configured to enforce all the general guidelines for environmental flow problems (Franke et al., 2004; Tominaga et al., 2008), mainly related to computational domain dimensions (see Figure 3) and relative grid parameters: grid sizes, expansion ratios, local densities, as well as convergence criteria and relaxation factors.

However, the computational effort demanded by each of those simulations is significant. In order to de-
crease the overall computational cost, a meshing methodology partly inspired by Toparlar et al. (2015), where a single hexaedral domain in meshed for six different inflow directions, led to a unique mesh, assembled from two components (Walther et al., 2020): a central cylindrical mesh with the urban area to investigate, as found also in Kastner and Dogan (2018), enclosed within a rectangular mesh. A coherent meshing of the outer discretizations at the domains allow for relative rotations of the subdomains, as shown on Figure 4, keeping a conformal mesh interface. Hence, for every desired wind incidence, the remeshing process is replaced by a simple rotation and stitching of the two submeshes.

Unlike in Kastner and Dogan (2018), the outer parallelepiped domain was kept, mainly in the purpose to set up boundary conditions directly from OpenFOAM libraries, without additional development.

The resulting mesh in the context of the case study has following features: the mesh size is about $30 \times 10^6$ cells, with cells as small as $\sim 0.4$ [m]. In the context of the presented case study, the mesh computation was run on 32 processors server, a rather robust version of desktop computers, and took about 2.5 hours to complete. However, as stated, the eleven other meshes will be done in minutes by a simple rotation and stitching of the sub-parts with an appropriate angle.

Simulation set-up

Following (Franke and Baklanov, 2007; Tominaga et al., 2008), the main numerical hypothesis for the air flow simulations are:

- The CFD approach chosen is the RANS framework (Reynolds Averaged Navier Stokes), with a SIMPLE steady-state solver.
- The turbulence is handled with a $k - \omega$ SST model, which is a good trade-off between precision in near wall areas (inner part of the boundary layer, where a $k - \omega$ formulation is used), and a stable and rather fast resolution in the main free-stream, with a $k - \varepsilon$ behaviour.
- The inlet velocity profile has to be able to reproduce the Atmospheric Boundary Layer, hence a logarithmic velocity profile is used (varying with the altitude $z$), together with corresponding profiles for turbulent variables.
- The ground gets assigned a representative roughness for urban areas, whereas the sides and top boundaries of the domain are defined with a "slip" boundary condition.
- The buildings surfaces are treated with appropriate rough wall functions.
- The median meteorological velocity is used as inlet reference velocity at $z = 10$ m for each wind direction.
- A mesh sensitivity analysis is carried out both for the "external" and the "overall" meshes.
- The convergence criteria are set up to $10^{-4}$ on the main residual quantities.

For a more detailed CFD set-up description, the reader is referred to urban scale wind comfort studies, e.g. (Blocken et al., 2016).

The site’s wind data is processed into 12 equal bins representing 30°, the first one being centred on North. Twelve wind directions are simulated, using the wind rose presented on Figure 5.

Outdoor: Pressure coefficients

The method presented in Walther et al. (2019, 2020) is chosen for the computation of natural ventilation, using CFD to obtain the detailed pressure boundary conditions that will serve as an input for BES.

An example of averaged pressure coefficients $C_p$ obtained for the East Hall is presented Figure 6, for a facade opening facing the South-West, as well as for

![Figure 3: Mesh dimensions according to the highest building height $H$.](image)

![Figure 4: Mesh rotations for wind incidences from North to East, every 30°.](image)

![Figure 5: Paris-Montsouris windrose (10m).](image)
Comparing Figures 5 and 6, one can observe that the highest $C_p$ are not necessarily along the main wind directions, as the local urban context significantly influences the pressure field. The obtained pressure coefficients are then fed into EnergyPlus’s air flow network model (Walton and Dols, 2003), for a better natural ventilation estimation. The comparison between the standard, empirical pressure coefficients and the CFD-based may exhibit up to 160% relative difference in air change rate for such buildings in dense urban contexts (Walther et al., 2020), hence the determination of accurate pressure boundary conditions appears as utterly necessary.

Indoor: Air velocities

Having set up a model to compute the pressure on facades, it appears that obtaining the indoor air velocities is not out reach. As a by-product, the first simulation yields a numerical set-up allowing to compute indoor velocity fields within the open building with a moderate additional effort. After adding a simplified geometrical model of the interior zones matching the BES’ ones, the twelve CFD simulations can be run again using most of the previous numerical setup. A new mesh of the cylindrical zone including the indoor geometry must of course be generated. Concretely:

- The authors estimate the additional set-up time to 20-25% of the time spent for the outdoor simulation set-up. What may seem as a low time increase is mainly due to the fact that the indoors are already modeled for the BES software. The geometries ”only” need to be simplified and stitched. The existing set-up is then used throughout the complete set of CFD simulations.
- Following the same procedure as for for the ”external” mesh, the resulting meshes are bigger by less than 6%, with approximately $31.7 \times 10^6$ cells, and took approximately 4 hours to compute on a 32 nodes server, compared to the 2.5 hours for the external set-up. This time increase owes to the level of detail of the indoors and subsequent mesh refinement.
- As for the actual CFD wind simulations, the observed simulation time for the second set of CFD simulations if 1.3 times higher than the closed-building ones, with 1.55 hours on the same server.

An example of indoor air velocities for the whole train station is given in Figure 7 for an East wind (one of the 12 directional simulations).

The hourly indoor velocities maps are reconstructed by field interpolation: for a given wind incidence angle, the closest angle of the 12 computed fields is selected. The amplitude is determined by scaling the CFD simulation (performed with the median velocity for this incidence angle) with the meteorological wind velocity at this hour of the year (Delpech et al., 2005), a commonly used technique in urban scale wind simulations. The indoor velocity field at a given hour is illustrated on Figure 8 for the area of interest.

Part III – Comfort index

Rapid fluctuations of ambient conditions and short exposure times of occupants to the ambiance imply using an appropriate comfort index. Amongst the many existing comfort indexes, transient models are adapted to such contexts. The transient ”two-nodes model”, used to derive the Standard Effective
Temperature (SET\(^*\)) as in Pickup et al. (2000) and the Physiological Equivalent Temperature (PET) initially by Höppe (1999) are appropriate representations of the human physiology for the outdoor and semi-outdoor environments. In those models, the human body is represented as two cylinders standing for the core and skin, encircled by a clothing layer (see Figure 9). Metabolic activity, vasomotricity, breathing, heat and vapour diffusion as well as temperature control are taken into account by mathematical relations. For a given activity level and clothing, the model provides the physiological response of the body exposed to a given environment, composed of an air temperature, radiant temperature, relative humidity and air velocity. The values obtained are the core temperature, skin temperatures and the skin wettedness. In simple terms, the comfort index, be it the PET or SET\(^*\), is then computed as the operative temperature of a “typical indoor” (id est low air velocity, 50% relative humidity and appropriate clothing for the metabolic activity level) that provokes the same physiological response as the actual environment. The open-source version of the PET that can be found in Walther and Goestchel (2018) serves for the computations.

It is not clear in the literature which of the PET or SET\(^*\) comfort index shall be preferably used. In absence of a consensus view, both will be compared in this study. Both the PET and SET\(^*\) levels correspond to categories of thermal sensation respectively as per Höppe (1999); Nishi and Gagge (1977), summarised in Table 1.

Clothing varies over the year on a daily basis. In the simulation, it is hence adapted after the correlation from Schiavon and Lee (2013), providing the clothing level depending on the temperature at 6 AM. Noticeably, the dependence to air velocity of heat and vapour transfer properties of clothing is also taken into account as per the model found in Havenith et al. (1999).

The diagram on Figure 10 represents the different methods and tools used to compute the comfort level from the hourly solar fluxes and air velocity fields.

### Results

In this section, the results obtained with the methods presented above are analysed. The SET\(^*\) and PET comfort indexes are compared in terms of thermal sensation categories obtained.

### Comfort maps

An example of result is presented on Figure 11. One can observe the influence of the sun patch and of the air velocities near the openings. Owing to solar radiation, the increase of the mean radiant temperature can be as high as ~ 30 [K] (Spagnolo and De Dear, 2003), which translates to an elevated PET index value in the sun patch.

The practical use of such data can however be improved by performing a statistical analysis, e.g. the average PET during the opening hours of the hottest week in the year, shown on Figure 12. The same type of figure can be obtained for the SET\(^*\), exhibiting the same patterns.

In order to preserve both temporal and spatial variation of comfort, the Outdoor Thermal Comfort Autonomy (OTCA) introduced by (Nazarian et al., 2019) was used for the qualification of space. For each point in space, the OTCA is defined as the fraction of time in the comfort zone:

\[
OTCA = \frac{1}{n} \sum_{h=1}^{n} T
\]
Figure 10: Determination of spatial comfort: Diagram of the workflow and simulation coupling.

Figure 11: PET map at 1 PM in mid-July.

Figure 12: Average PET during the hottest week.

Figure 13: Indoor OTCA: percentage of time in the "comfortable" PET range during the station’s opening hours.

Comparison of comfort indexes

The results obtained allow for the comparison of comfort indexes in the same ambient conditions. Interestingly, the computation of the OTCA for the PET and SET* comfort indexes yields different results. When comparing the yearly OTCA maps for the "Slightly warm" sensation presented on Figure 14, the following can be observed:

- For the PET, the whole surface is "Slightly Warm" at least 88% of time, whereas for the SET*, no area is "Slightly Warm" more than 15% of time (in this case, most of the SET* OTCA lies in the "Comfortable" and "Slightly Cool" perception ranges).

- The patterns are similar, as the "color inversion" between both Figures is related to the fact that the two comfort indexes scale differently with the thermal sensation. The inversion occurs as the

where \( T = 1 \) if the chosen comfort index \( T \) is within the comfortable temperature range, \( T = 0 \) else. Computing the OTCA for other thermal sensations may also be instructive: Instead of using the bounds of the comfort range in Equation (2), those of the chosen thermal sensation presented in Table 1 are used.

An example of result for the yearly OTCA computed with the PET is presented on Figure 13, where one can observe that this zone is comfortable between 1.5% and 20% of time depending on the location.
zones involved are predominantly in the upper or lower thermal sensation category.

This results shows that, for similar ambient conditions, the comfort indexes are not equivalent and the PET happens to qualify the ambience as warmer by one category of thermal sensation.

Looking at the percentage of the surface in the different thermal sensation categories for each comfort index, on Figure 15 for PET and Figure 16 for SET*, one can observe the existence of an offset. Indeed, the PET "feels" warmer by about one thermal sensation category for the same indoor conditions.

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<table>
<thead>
<tr>
<th>% of surface area in thermal sensation category</th>
<th># Weeks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Cold</td>
<td>0</td>
</tr>
<tr>
<td>Cold</td>
<td>20</td>
</tr>
<tr>
<td>Cool</td>
<td>40</td>
</tr>
<tr>
<td>Slightly Cool</td>
<td>60</td>
</tr>
<tr>
<td>Comfortable</td>
<td>80</td>
</tr>
<tr>
<td>Slightly Warm</td>
<td>20</td>
</tr>
<tr>
<td>Warm</td>
<td>40</td>
</tr>
<tr>
<td>Hot</td>
<td>60</td>
</tr>
<tr>
<td>Very Hot</td>
<td>80</td>
</tr>
</tbody>
</table>
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Figure 14: Comparison of the "Slightly Warm" OTCA for the PET (left) and SET* (right), during the hottest month (July), from 5AM to 11PM.

In the present case study, it also appears that the PET comfort index exhibits more nuances in the thermal sensations over the year:

- During the summer period, for the PET, the summer days are mostly "Slightly Warm" and "Warm", whereas for the SET* they are mostly "Comfortable" and "Slightly Warm". An offset by about one category of thermal sensation is visible.
- During the winter season, the SET* index for most of the area of interest is assessed to be "Slightly Cool", whereas the PET shows more nuances between "Cool" and "Comfortable".

Conclusion & Perspectives

In this paper, a method using open-source softwares and allowing for the determination of a spatial distribution of indoor comfort was described. As a proof of concept, it was applied to Paris Gare de l’Est train station.

The results about the method can be summarized as follows:

- The approach presented in this work allows for the computation of a spatial distribution of comfort indexes in indoor spaces. It provides a better estimation of local indoor comfort and of the understanding of the causes of local thermal discomfort, as the contributions of solar radiation and air velocities are calculated with appropriate methods.
- The study of the comfort patterns obtained is interesting for architects as it becomes possible to differentiate "sub-zones" of occupation within a given volume and provides information at a higher level of detail than previously available to space designers.
- The computational expense is not negligible but remains affordable on a robust desktop computer.

About the results obtained, interestingly they differ depending on the comfort index considered:

- Although the dynamics and patterns of the comfort indexes obtained are similar, the thermal sensation categories are different. A sensitivity analysis to the ambient parameters of their respective mathematical models may provide a better insight of the origins of this behaviour.
- The question remains open as to the most suitable comfort index to be used.

As a perspective, one could argue that zonal models are a cheaper alternative to computational fluid dynamics. The numerically challenging coupling of such models with EnergyPlus is currently investigated.

Longwave heat transfer between individuals and their surrounding surfaces is not treated in this work, although it may significantly impact thermal comfort. The detailed radiation computation with view factors on idealised individuals is explored and will be the topic of a future communication.
References


