A hybrid method for open plan offices acoustics prediction using beam and particle tracing

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Summary
Since open plan office users often complain of annoyance due to noise, it is critical to consider acoustic quality when designing such a workspace. This can be achieved with acoustic simulation methods, however, it is often difficult to obtain precise results in reasonable computation times. This paper presents a hybrid simulation method combining beam and particle tracing algorithms. It is intended to overcome known issues of these simulation methods and take advantage of their benefits while maintaining low computation times. First, the hybrid method is assessed on the estimation of acoustic indicators as speech intelligibility, reverberation time and spatial decay measured in eleven existing work environments. It is shown that simulation results are in good accordance with measurements and that the hybrid method performs better than a standard beam tracing algorithm, particularly for reverberation time estimations. An example of acoustic design of an open plan office is then considered in order to analyze the effects of commonly used acoustic elements. This work is part of the MEPAS project, a common 2-year project between INRS and CSTB funded by ANSES, which aims to develop an efficient calculation method for the prediction of open plan office acoustics.

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1. Introduction

The acoustic environment of an open plan office has an obvious impact on the comfort of the workers. A poor acoustic design can induce a loss of concentration and hence of productivity [1]. It may also affect a worker's health through chronic fatigue or negative stress at the workplace [2]. It is therefore important to develop effective prediction methods in order to be able, in the design stage, to adapt the acoustic features of a workspace to the field of activity it will accommodate.

Acoustic prediction can be done empirically or through numerical simulation. Keränen and Hongisto have statistically defined empirical laws based on a large measurement campaign on a representative open plan office panel [3]. Their method is effective but it is bounded to cases with similar characteristics to those used to define the empirical laws. For more specific cases, numerical simulations are the only solution to achieve accurate acoustic prediction.

An exhaustive description of existing acoustic simulation methods is presented by Svensson in [4]. Svensson highlights the benefits and the drawbacks of different simulation methods, pointing out the difficulty to model specular reflections, diffuse reflection and edge diffraction in an efficient way that overcomes the exploding computational time. In this paper, a hybrid method implemented in the ICARE software and based on beam tracing for early reflections and particle tracing for the diffuse field and late reflections is described. It has been developed to solve the issues encountered with standard simulation methods while maintaining a reasonable computational time. The principles of the method have already been described in a previous paper [5] including also time dependent radiosity to handle more precisely purely diffuse paths. In the context of open plan office acoustics, time dependent radiosity is not considered as is has no significant effect on acoustic indicators calculation. To some extent, the hybrid method presented here is similar to the method introduced by Naylor [6]. However, beam tracing is used here instead of the image-source method for early reflections and particle tracing is used instead of a diffuse ray tracing algorithm for the late part of the impulse response.

First, this paper discusses the characteristics of beam and particle tracing algorithms to justify their complementarity for impulse response prediction in enclosed spaces. Necessary information on 3D modeling of studied spaces is also provided to settle the framework of this work. In a second part, the performance of the hybrid simulation method is compared to the beam tracing algorithm though comparison between measured and simulated acoustic indicators. Finally, a case study of a virtual open plan office is presented to show how this simulation method can be used for open plan office design.

This study is part of the MEPAS project which aims at developing a quick acoustic prediction method to assess the impact of different open plan office design parameters on the workers acoustic comfort.

2. Impulse response simulation

ICARE is an acoustic simulation software that calculates the impulse response between a source and a receiver position. It features different simulation algorithms including beam tracing and particle tracing. In this section, the advantages and drawbacks of these two algorithms are presented in order to show that their combination results in an efficient acoustic simulation tool. Detailed information on these simulation methods can be found in [5].

2.1. Beam tracing

Beam tracing aims at finding a finite number of acoustic paths between a source and a receiver position. The impulse response calculation is performed in two stages. First, the acoustic paths are computed up to given reflection and diffraction orders. Then, the attenuation of each path is computed using the absorption coefficients defined for each encountered surface and diffraction coefficients for each encountered edge. The impulse response is obtained by summing the contributions of all paths. As this technique includes edge diffraction, it is suitable for open plan office acoustics prediction. In fact, workstations are often separated with partition walls and therefore, edge diffracted paths often carry a significant part of acoustic energy [7]. Note also that beam tracing accounts for phase information as it performs narrow band calculations in the frequency domain. Nevertheless, it has two major drawbacks that impede its use for open plan office acoustics prediction:

- A trade-off often arises between algorithm convergence and computational time. In closed environments, the algorithm complexity is exponentially dependent on the maximum reflection and diffraction orders (and so is the total number of paths). Therefore, it is often difficult to achieve convergence in reasonable computation times.
- Diffusion is not handled in beam tracing algorithms. Hence, surface roughness and office cluttering cannot be modeled in beam tracing by this means.

2.2. Particle tracing

ICARE also features a particle tracing algorithm. It consists in emitting a large number of particles from the source in randomly chosen directions. At each contact with a surface, a particle looses energy due to absorption and is either specularly reflected or scattered based on Lambert's diffusion law. A sphere is used as particle collector at the receiver position. The time of arrival and the remaining energy of each collected particle are used to build the echogram of the impulse response. This process is performed energetically (no phase information) for each octave band before combining the contributions to obtain the full bandwith echogram. Particle tracing presents two major drawbacks for open plan office acoustics prediction:

- It is difficult to render precisely early reflections due to time discretization. An early reflection may get split into separate contributions if the chosen time step is too short. On the contrary, distinct early reflections may get merged if the time step is too long.
- Edge diffraction is not handled in particle tracing algorithms.

2.3. Hybrid method

The hybrid method consists in using beam tracing up to a pre-defined transition order to obtain early reflections (including edge diffraction) and particle tracing to compute the remaining part of the impulse response. This remaining part is composed of all the contributions containing at least one diffuse reflection and all purely specular contributions with a reflection order greater than the transition order. Care is taken that no overlap occurs between beam and particle tracing contributions. Figure 1 shows an example of echograms of the two components of the hybrid simulation method. Note that the particle tracing part starts early in the time response due to low order diffuse contributions.

This approach solves the issues of beam and particle tracing considered individually:

- Early specular reflections and edge diffraction are precisely simulated with beam tracing.
- As beam tracing is used only for low order paths (typically less than 5), it remains very efficient even for complex geometries.
- Diffusion is rendered with particle tracing. It simulates both surface roughness effects and diffraction due to office cluttering.

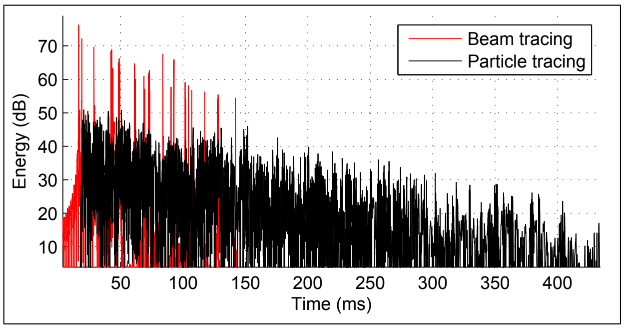

Figure 1. Echograms of the two components of the hybrid simulation method with a transition order equal to 3.

2.4. Model design

The model design stage includes the creation of the 3D model and the assignment of all coefficients (scattering and absorption) for the surface materials. This section discusses briefly important matters that need to be accounted for during this stage.

Algorithms as beam tracing are not suitable to handle geometries with small-sized elements. It is therefore appropriate to neglect small-sized elements during the design of the 3D model to avoid abnormal results. Their effect in terms of acoustics can be approximated by increasing the scattering coefficient of all large surfaces. In practice, the hybrid simulation method renders surface roughness with scattering in the mid to high frequency range and it renders small surface diffraction with scattering in the low to mid frequency range. To simplify the assignment of scattering coefficients to the surfaces of a 3D model, we propose to set a unique (frequency independent) scattering coefficient to all surfaces. Parametric studies showed that a scattering coefficient of 0.3 is appropriate to simulate enclosed spaces like open plan offices. In the following, all considered 3D models contain only the floor, the ceiling, walls, workstations and partition walls if applicable. The cluttering is not modeled as its effect is approximated with large surface scattering.

3. Application to open plan offices

During the MEPAS project, measurement campaigns were carried out in eleven different offices by INRS. Standard acoustic indicators as speech intelligibility (STI), rate of spatial decay (DL_2), reverberation time (RT) and octave band background noise were measured. The 3D models of these eleven offices have been created and the hybrid simulation method has been applied to estimate acoustic indicators from simulated impulse responses. In the following, comparisons between measured and simulated acoustic indicators are presented. To highlight the benefits of the hybrid method, the results are also confronted to the acoustic indicators estimated with a simple beam tracing method.

3.1. Considered acoustic indicators

The standard ISO 3382-3:2013 lists the acoustic indicators relevant for open plan office acoustics assessment. The two main indicators are speech intelligibility STI and the rate of spatial decay of sound pressure level per distance doubling DL_2. Other indicators, such as the distraction distance r_D, the privacy distance r_P and the A-weighted sound pressure level of speech at a distance of 4 m $L_{p,A,S,4m}$ can be easily derived from these two main indicators. The reverberation time is also considered here as it is widely used in the field of room acoustics. The background noise level has not been simulated in this work due to insufficient knowledge of contributing noise sources. Still, the measured octave band background noise levels are used as input to the estimation of the STI from simulated impulse responses. STI calculations are performed according to standard CEI 60268:16:2011.

3.2. Considered open plan offices

The DL_2, STI, RT and background noise of eleven existing open plan offices have been measured by INRS. Examples of created 3D models are shown in Figure 2. The considered offices include call centers, administrative or collaborative work places and also public places with reception desks. Their surfaces range from 90 to $850m^2$. Depending on the field of activity, these places present a variety of different acoustic protection elements such as absorbing panels, desk screens between adjacent workstations or partition screens. Hence, this panel is considered as representative of the variety of open plan offices in France.

3.3. Results

To show the benefit of the hybrid method over a simple beam tracing algorithm, the results of both simulation methods are compared to measurements. For the beam tracing algorithm only, the maximum reflection order is set to 14 to ensure convergence and no edge diffraction is considered at such calculation depth as it would induce excessive calculation times. On the other hand, the hybrid method is configured with a transition order of 3, second order edge diffraction, $K = 10^5$ particles and a scattering coefficient of 0.3 for all surfaces.

Figure 3 shows the comparison between the 49 measured and simulated STI values. One can see that both beam tracing and the hybrid method perform well in this task. However, there is a significant difference between beam tracing and the hybrid method for measurements 13 and 14. Beam tracing underestimates the STI because of missing edge diffracted paths. In fact, these two measurements correspond to situations where source and receiver positions are placed at adjacent workstations separated with a desk screen. Table I presents the mean absolute differences between measured and simulated indicator values. Overall, both methods have similar performance

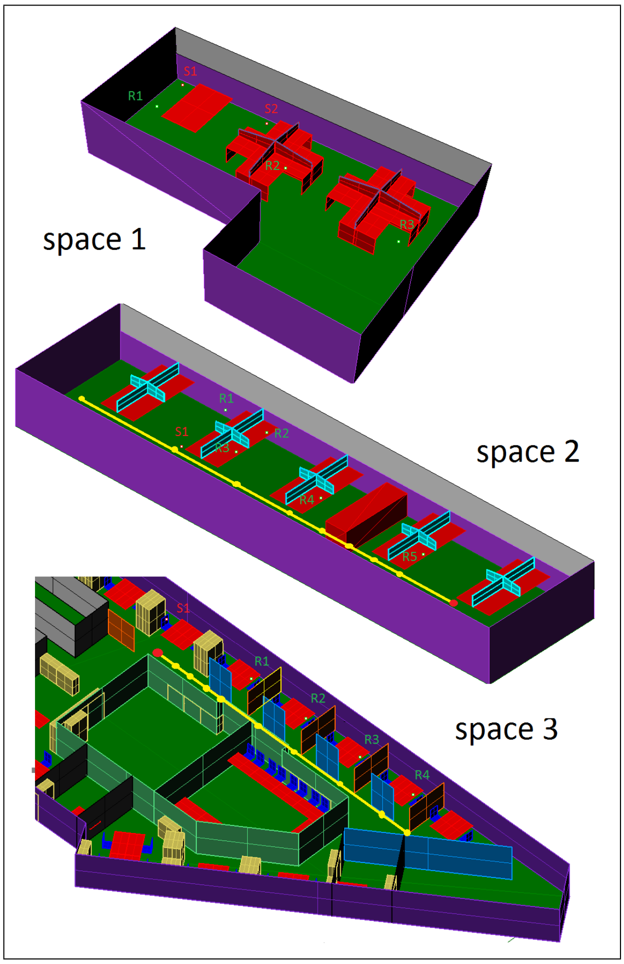

Figure 2. 3D models of three studied spaces. Examples of source (S1, S2, ...) and receiver (R1, R2, ...) positions are shown. Source positions are in red, receiver positions in green for the STI measurements and in yellow for measurement along the spatial decay line.

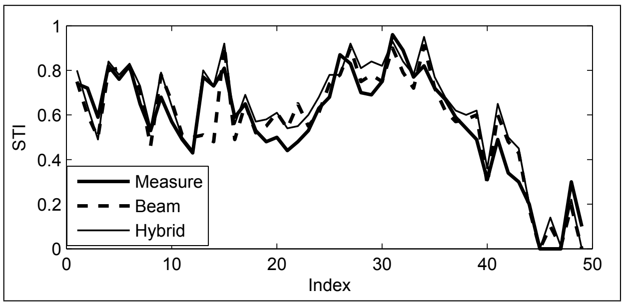

Figure 3. Comparison between the 49 measured and simulated speech intelligibility values.

for STI estimation as mean difference between measurements and simulations is 0.07 for both methods.

Figure 4 presents the comparison between the 27 measured and simulated reverberation time values. The beam tracing algorithm often overestimates the true reverberation time. This overestimation is a known result for purely specular algorithms [4] and it is due to high order specular acoustic paths between parallel rigid surfaces. The hybrid method cancels such abnormal behavior with diffusion and hence, the results are much closer to the measurements. The mean difference between measurements and simulation is 0.11 s for the hybrid method while it is 0.32 s for the beam racing algorithm (see Table I).

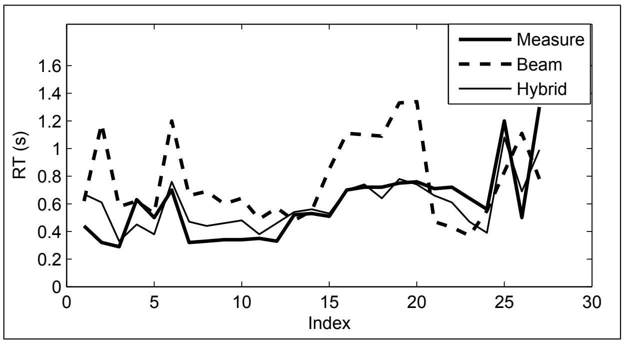

Figure 4. Comparison between the 27 measured and simulated reverberation time values.

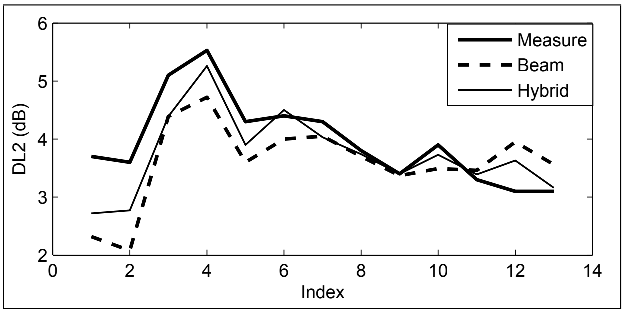

Figure 5. Comparison between the 13 measured and simulated spatial decay values.

Table I. Number of comparisons between measurements and simulations for each acoustic indicator and mean difference between measured indicators and simulated indicators with both simulation algorithms.

	Nb	$\lvert$Measure − Beam$\rvert$	$\lvert$Measure − Hybrid$\rvert$
STI	49	0.07	0.07
TR	27	0.32 s	0.11 s
DL_2	13	0.60 dB	0.34 dB

Then, Figure 5 presents the comparison between the 13 measured and simulated spatial decay rates per distance doubling. Both methods tend to slightly underestimate this indicator in some cases. However, the hybrid method performs better on average as the mean difference between measurements and simulations is 0.34 dB for the hybrid method while it reaches 0.60 dB for the beam tracing algorithm.

The hybrid method appears conclusively more precise than beam tracing. As expected, the greatest improvement brought by the hybrid method concerns reverberation time estimations. The negative correlation between reverberation time and spatial decay explains the underestimation of this indicator by the beam tracing method. Finally, the performances for

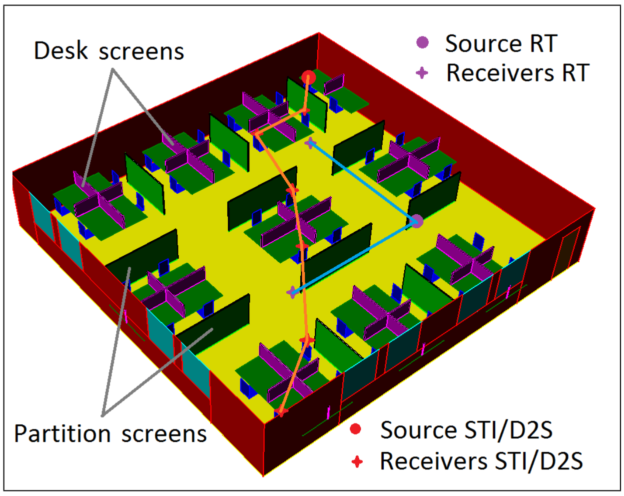

Figure 6. 3D model of the considered virtual office. All acoustic solutions are depicted including desk and partition screens. Source and receiver positions for indicator estimation are also shown.

STI calculations are equivalent except for cases where edge diffraction is critical. Note that these results were obtained with roughly estimated absorption coefficients for most surfaces and 3D models approximately created out of 2D-drawings. Hence, there are many potential causes for the residual errors observed between measurements and simulations.

4. Open plan office design

In the last part of this paper, an example of acoustic design of a virtual open plan office is presented. The purpose is to show how common acoustic solutions affect the indicators characterizing the acoustic performance of a work environment.

4.1. Studied cases

The virtual office considered here is shown in Figure 6. Its surface area is 200 m^2 and it has a high occupation density as it contains 38 workstations. Three acoustic indicators are computed: the reverberation time, speech intelligibility and the rate of spatial decay of speech (D_2S). The D_2S indicator is similar to the spatial decay rate per distance doubling (DL_2) except that the measurement trajectory is chosen over workstations (see Figure 6) instead of a straight trajectory along an alley. Also, the source emission spectrum is set to correspond to normal speech instead of pink noise (see standard NF EN ISO 14257:2002). To enable speech intelligibility estimation the background noise level in the office is set to the NR35 octave band levels (defined in the standard NF S30-010).

Four configurations corresponding to different stages of acoustic optimization are presented. These configurations are summarized in Table II. *Configuration 0* corresponds to the virtual office with a low absorption ceiling and no desk screens neither partition screens. Subsequent configurations correspond to increasing acoustic performance, starting with a high absorption ceiling and then to the addition of absorbent screens: low height screens on desks and then 1.5 meters high partition screens in the alleys.

Table II. Characteristics of the four office configurations corresponding to increasing acoustic performance.

	Ceiling	Desk screens	Partition screens
cfg 0	low abs.	✗	✗
cfg 1	high abs.	✗	✗
cfg 2	high abs.	✓	✗
cfg 3	high abs.	✓	✓

4.2. Results

Figure 7 presents the effect of the acoustic optimization stages on the three considered indicators. Reverberation time estimations can be interpreted with regard to the French standard on acoustic performance levels of working environments NF S31-080. This standard defines three performance levels for open plan offices (standard, efficient and highly efficient) depending on various acoustic indicators. The replacement of the ceiling brings the most significant improvement as it induces a drop in the RT from approximately 0.85 s to 0.6 s. This improvement results in a classification change from "standard level" to "highly efficient level" regarding reverberation time. The addition of screens further decreases the reverberation time but the improvement is limited as the additional absorbent surface is not significant compared to the ceiling and the floor surfaces (absorbent carpet covering on floor). Conversely, speech intelligibility is mostly affected by the addition of separative screens. Indeed, as long as the direct path between the source and the receiver exists, increasing ceiling absorption has no significant effect. However, once the ceiling provides high absorption, the cancellation of the direct path between a source and a receiver drops the STI of about 0.3. Finally, the most significant effect on the spatial decay of speech is observed when adding desk screens to adjacent work stations (*configuration 2*). Overall, an increase of 2 dB can be achieved for this indicator, raising it from 2.7 dB in *configuration 0* to 4.7 dB in *configuration 3*. The NF S31-080 standard does not consider the D_2S but the DL_2. For this indicator an increase from 2.7 dB to 4.7 dB corresponds to a classification change from "standard level" to "highly efficient level".

The hybrid simulation method applied to the prediction of acoustic indicators for open plan office allows estimating the relative effects of various acoustic elements commonly used for the design of these work environments. However, it is important to point out that what is considered as improvements of the acoustic quality, meaning, decrease of the reverber-

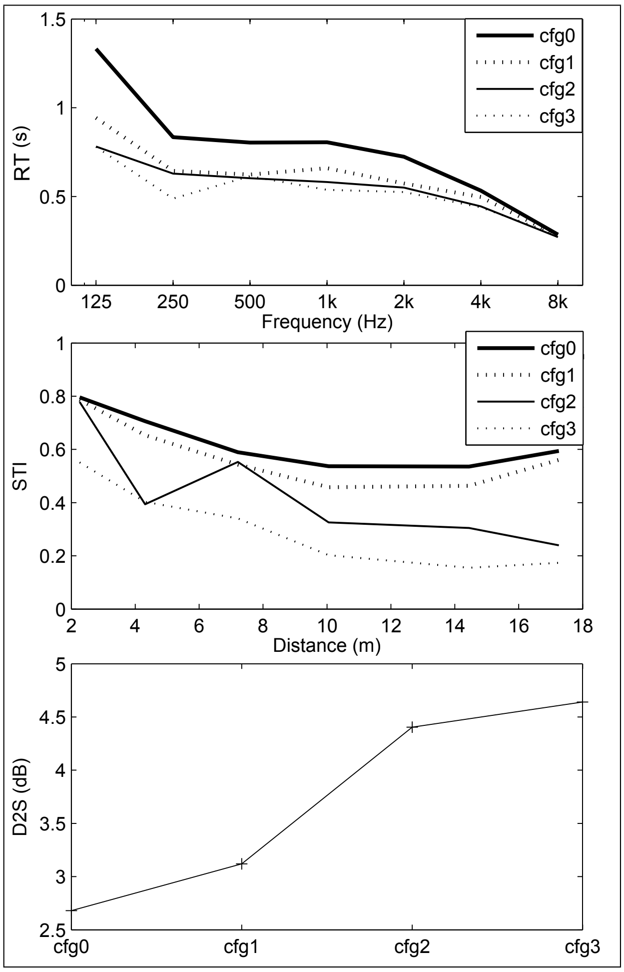

Figure 7. Effect of different optimization elements on acoustic indicators in a virtual office (up: RT, middle: STI and bottom: D_2S).

ation time and of the speech intelligibility and increase of the spatial decay, not always goes along with a better comfort for the employees. Optimal values for acoustic indicators depend on the type of activity carried out in the office. For example, a low STI value between adjacent workstations is required in call centers to preserve the employees concentration. This can be achieved by placing desk screens and partition walls between workstations. However, when collaborative work is a priority a high STI is preferred between adjacent workstations and therefore, no desk screens should be installed. To account for such considerations and guide open plan office designers, effective acoustic prediction tools are of great importance.

5. Conclusions

A hybrid simulation method based on the combination of beam and particle tracing has been applied to the prediction of acoustic indicators in open plan offices. The precision of the calculations was analyzed through comparisons with measurements in eleven existing open plan offices. It has been shown that the hybrid method performs better than a standard beam tracing algorithm in the estimation of acoustic indicators as speech intelligibility, reverberation time and spatial decay. The achieved precision level is sufficient for an accurate prediction of the acoustic performance of a workspace. Residual errors between measurements and simulations are due to multiple causes such as uncertainty on absorption coefficients, accuracy of the 3D models, positioning of sources and receivers and also measurements accuracy.

An example of application of this prediction method to the design of a virtual office has been presented. Different acoustic optimization elements were analyzed in regard to their effect on acoustic indicators. It was shown that reverberation time can be reduced by 30 percent, speech intelligibility by 0.3 and spatial decay can be increased by 2 dB with simple acoustic solutions as an absorptive ceiling and acoustic screens. However, the use of such acoustic elements needs to be examined on a case-by-case basis so as to optimize the comfort of the employees with respect to their professional activity.

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