CFA/VISHNO 2016

Acoustic simulation in open plan offices: How to comply with NF S31-199?

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Since open plan office users often complain of annoyance due to noise, it is critical to consider acoustic quality when designing such a workspace. Recently, the French standardization organization (AFNOR) released a new standard (NF S31-199) relative to the assessment of the acoustic quality of open plan offices. This standard defines four types of open plan offices based on the field of activity they accommodate : call centers, project spaces, administrative spaces and public reception spaces. For each type of workspace, target values for chosen acoustic indicators ensuring the acoustic comfort of the employees are provided. This paper presents four acoustic designs of a virtual open space, achieving the recommendations of the NF S31-199 standard for the four types of workspaces it defines. A hybrid simulation method combining beam and particle tracing algorithms is used to simulate acoustic impulse responses and derive pertinent acoustic indicators. It is applied to assess the performance of common acoustic solutions used in the design of open plan offices and optimize their layout in order to comply with the NF S31-199 standard.

1 Introduction

The acoustic environment of open plan offices 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]. The NF S31-199 standard [3] aims at providing to all parties involved in open plan office design, a method to ensure the acoustic comfort of the employees. It consists in basic conception rules to improve the acoustic performance of the workplace and specific recommendations in terms of acoustic indicators depending on the field of activity the workplace accommodates. Four types of open plan offices are defined : call centers, project spaces, administrative spaces and public reception spaces. For each of these, target values for pertinent acoustic indicators are recommended and general solutions to reach the required performances are detailed so as to guide open plan office designers in their task.

The aim of this paper is to illustrate the NF S31-199 standard by presenting a possible design solution for each of the four types of open plan offices. First, the framework of the NF S31-199 is presented to identify the key points of the acoustic design of an open office. Second, the hybrid impulse response simulation algorithm and the methods to derive the pertinent acoustic indicators [4] are detailed. This simulation framework is based on the ICARE simulation algorithm and its graphical user interface (AcouSPACE) is actually under development. Then, an office layout is proposed for each of the four types of offices introduced in the standard and compliance with the recommendations in terms of acoustic indicators is verified. Overall, it is shown that the standard recommendations can be verified with a prediction method based on impulse response simulations. Consequently, during the design process of an open office, different acoustic solutions can be tested and compared before engaging the fit-out works and the associated costs.

2 The NF S31-199 standard

Nowadays, open plan offices are used for a wide variety of work activities. These activities induce very different acoustic issues and therefore there is no universal acoustic solution for all open plan offices. In fact, when employees constantly speak over the phone in a call center, the sound attenuation between adjacent workstations should be much higher than in a collaborative workspace where teamwork is an important matter. To solve such issues and help open plan office designers in improving acoustic comfort, the NF S31-199 defines four types of open offices (call centers, project spaces, administrative spaces and public reception spaces) and provides for each case, target values for a pertinent selection of acoustic indicators. It introduces three interaction levels between an employee and its working environment that may induce noise annoyance : the workstation level, the team level and the office level. For each interaction level, acoustic indicators and recommended values are defined :

- Ambient noise ($L_{A,eq}$) at the workstation level.
- Attenuation between adjacent workstations (D_n) at the team level.
- Reverberation time (Tr), sound decay ($D_{2,S}$) and sound isolation indicators at the office level.

There are many aspects in the conception of an open space that affect acoustic indicators values. The design of an open office that fulfills all the requirements of the standard might be a demanding work. Therefore, the NF S31-199 also details basic conception rules that can help in reducing ambient noise, reverberation time or sound propagation in the office. For example, coffee areas as well as printer and meeting rooms should be physically separated so as the noise generated in these areas does not diffuse in the open plan office. This simple recommendation needs to be accounted for early in the office design process but it can remarkably reduce the ambient noise in the office. Also, the distance between the workstations and the average area per employee are crucial aspects. Although a higher average area per employee reduces the capacity of the office it also reduces the number of potential speech sources. Knowing that speech noise is the first cause of sound annoyance at the workplace [5], overcrowding an open office is clearly counterproductive. Concerning the acoustic treatment of the office, the NF S31-199 highlights the importance of applying ceiling treatment first and consider low height partition walls as a second step. In fact, their efficiency is highly dependent on the absorption coefficient of the ceiling.

These different aspects where considered in this work to design examples of a call center, a collaborative workspace, an administrative workspace and a public reception space that comply with the standard recommendations. The next section presents the simulation method used to verify the compliance with the standard of each proposed open office design.

3 Simulation method

3.1 Impulse response simulation

An effective way to predict the acoustic characteristics of a workspace is to simulate the acoustic impulse response between carefully chosen source and receiver positions. Other prediction methods based on empirical laws derived from large measurment campains exist [6]. Such methods can produce useful quick estimates for a given number of acoustic indicators but do not reach the precision of numerical simulation that use as input the 3D model of the considered space.

In this paper, the ICARE impulse response simulation method described in [4] is used. It is a hybrid simulation method that consists in using beam tracing up to a predefined transition order to obtain early reflections (including edge diffraction) and particle tracing to compute diffuse reflections and late reverberation. 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.

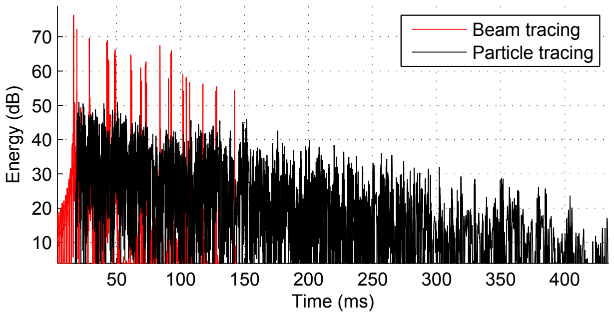

FIGURE 1 – Echograms of the two components of the hybrid simulation method with a transition order equal to 3.

Considered individually, both beam and particle tracing cannot simulate precisely and efficiently an impulse response, however the hybrid method benefits from the advantages of both algorithms without undergoing their known issues :

- 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 computationally even for complex geometries.
- Diffusion is rendered with particle tracing. It simulates both surface roughness effects and diffraction due to office cluttering.

3.2 Acoustic indicators calculation

Impulse response simulation reflects precisely acoustic propagation phenomena. Therefore, it can be used to derive any acoustic indicator provided that sufficient information on sources and receivers is given. This section presents the methods used to derive the indicators considered in the NF S31-199 standard : D_n, $L_{A,eq}$, D_2, S and Tr. Indicators assessing the isolation from exterior noise are not considered in this work even though standard calculation methods for such indicators exists [7].

3.2.1 Acoustic attenuation D_n

The acoustic attenuation D_n between a source and a receiver position is the difference in decibels between the sound pressure level of an omnidirectional pink noise source at a one meter distance in free field, noted $L_{p,Ls,1m}$, and the sound pressure level measured at the receiver position n, noted $L_{p,Ls,n}$.

$$D_n = L_{p,Ls,1m} - L_{p,Ls,n} \tag{1}$$

D_n has to be measured in the frequency range between 125Hz and 8kHz. To derive the attenuation D_n from a simulated impulse response between a source and a receiver position, the easiest method consists in convolving a pink noise with the impulse response and calculate the octave band levels of both the pink noise and the convolved pink noise. $L_{p,Ls,1m}$ and $L_{p,Ls,n}$ are then obtained as the logarithmic sums over the octave bands 125Hz to 8kHz of the octave band levels of the pink noise and the convolved pink noise respectively.

3.2.2 Ambient noise level $L_{A,eq}$

The ambient noise level $L_{A,eq}$ is the noise level in A-weighted decibels in the office averaged over at least half a working day. This indicator assesses the average noise exposure of an employee during a normal working day. In this paper, in order to simplify the calculations, it is assumed that the main contribution to ambient noise is speech. However, it is possible to consider other sources in this method as long as the sources directivities and emission levels are known.

To derive the ambient noise level at a receiver position, the mouth positions of all the employees at their working positions are considered as sources and their directivity is defined based on the values provided in [8, 9]. In an open office each employee is a potential source but does not speak hundred percent of the time. Therefore, average percentages of time during which employees speak are defined empirically based on the type of activity the open office accommodates. The values chosen in this study are given in Table 1.

TABLEAU 1 – Average percentage of time during which employees speak at their workstations during a normal working day.

Type of open office	Percentage of time speaking (P)
Call center	40%
Collaborative	15%
Administrative	5%
Public reception	40%

Note that during a normal discussion between two persons, each person actually speaks only 50 percent of the time, therefore a 50 percent value corresponds to the situation in which all employees have discussions during all their working day.

The sound pressure level at the receiver position n received from the speech source s in octave band i can be written :

$$L_{p,S,n,s,i} = D_{n,s,i} + L_{p,S,1m,i} \tag{2}$$

where $D_{n,s,i}$ is the sound attenuation between source s and receiver n in octave band i calculated from the impulse response between these two positions. $L_{p,S,1m,i}$ is sound pressure level of normal voice in octave band i of a directional speech source at 1m in free field (defined in Table 1 in ISO 3382-3 [8]).

Then, the contribution of each source s to the A-weighted ambient noise level at receiver position n can be written as :

$$L_{A,eq,n,s} = 10\log_{10}\left(\frac{\mathrm{P}}{100}\sum_{i=1}^{7}10^{\left(\frac{L_{p,S,n,s,i}+A_i}{10}\right)}\right) \qquad (3)$$

where p is the average percentage of time during which the source s is active during a normal working day (see Table 1). A_i is the A-weighting factor in octave band i.

Finally, the average ambient noise level at receiver position n can be derived as the logarithmic sum of the contributions of all sources in the office :

$$L_{A,eq,n} = 10\log_{10}\left(\sum_{s}10^{\left(\frac{L_{A,eq,n,s}}{10}\right)}\right) \qquad (4)$$

3.2.3 Spatial decay of A weighted speech sound pressure level per distance doubling $D_{2,S}$

The spatial decay of A-weighted speech sound pressure level per distance doubling $D_{2,S}$ is estimated by a setting a source position and a trajectory of receivers over workstations of the open office according to the ISO 3382-3 standard. The A-weighted levels of the speech source at each receiver position are calculated with impulse responses simulated with an omnidirectional source and the normal speech octave band levels defined in ISO 3382-3.

3.2.4 Reverberation time Tr

The NF S31-199 standard specifies two different indicators for the reverberation time, Tr_{125} which is the reverberation time in the octave band 125Hz and Tr which is average reverberation time over the octave band 500Hz, 1kHz and 2kHz as specified in the NF S31-080 standard [10]. In this work, one source position and four to six receiver positions were used to estimate these reverberation times in the different open office designs. The backward integrations of the squared octave band filtered impulse responses are used to the derive the decay curves and estimate the reverberation times.

4 Case study

In this section, an example of open plan office design complying with the recommendations of the NF S31-199 standard for each of the four office types is presented. The four designs differ only by the layout of the workstations and the use of low height partition walls between workstations : the dimensions of the office are identical and the absorption coefficients of the materials are the same in the four cases (see Figure 2). The office is 29 meters long, 14 meters wide and 2.5 meters high. It features a carpeted floor, standard plaster walls and a very efficient ceiling. The low partition elements are also absorptive and can be placed either in the alleys or in-between adjacent worskstations.

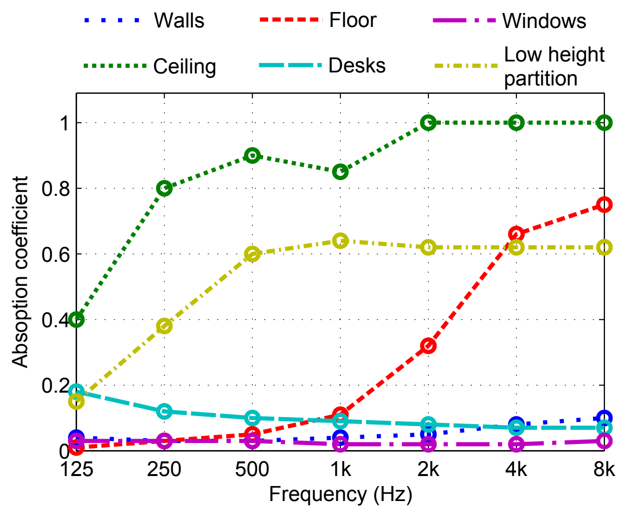

FIGURE 2 – Absorption coefficients for surface materials

4.1 Type 1 : call centers

In call centers, employees usually do not collaborate in their tasks. Each employee is likely to represent a source of noise for his colleagues. It is important to separate physically the workstations with low height partition walls. Figure 3 shows a 3D view of the proposed call center. It has 40 workstations. The average area per employee is approximately $10m^2$ which is minimum recommended area according to the NF X35-102 standard [11] relative to open office ergonomics. The partition walls are 1.6m high in order to provide high acoustic attenuation between workstations and are arranged in a way that they suppress most direct propagation paths between adjacent workstations.

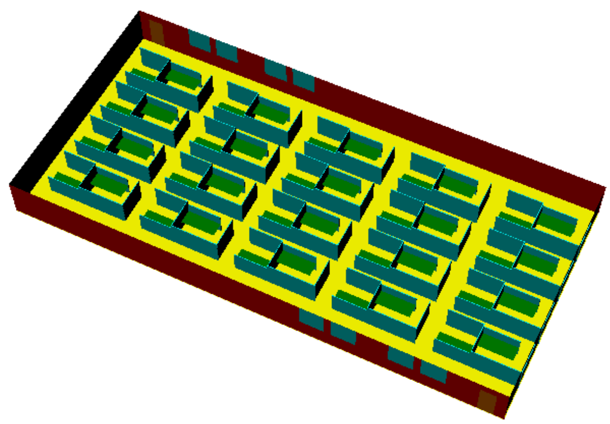

FIGURE 3 – 3D view of the proposed type 1 workspace.

Figure 4 is a plan view of the office showing the sources and receivers used for the estimation of acoustic indicators. Three receiver positions are considered for the estimation of the ambient noise level $L_{A,eq}$. As there are 40 workstations, 39 source positions are used as speech sources to estimate the ambient noise at each receiver position. These sources are active 40% of the time as this office is a call center where employees spend the most part of their time on the phone (see Table 1).

To make sure that the acoustic attenuation D_n between workstations is always greater than the target value for call centers (6 dB), the minimum acoustic attenuation between a receiver position and all adjacent source positions has been estimated for three different receiver positions. In this

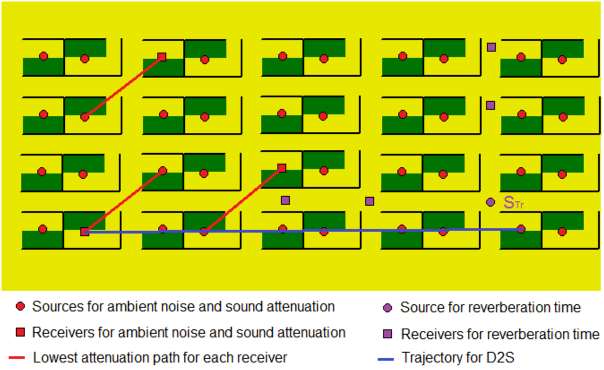

FIGURE 4 – Sources and receivers positions for acoustic indicators simulation in type 1 office.

office layout, the minimum attenuation for each receiver corresponds to the closest source that still has a direct propagation path to the receiver (see red lines in Figure 4). The trajectory for the sound decay per distance doubling $D_{2,S}$ consists in seven receiver positions placed over the workstations as required by the ISO 3382-3 standard. For reverberation time, the source and the receivers are placed in the alleys along the two main dimensions of the office. Table 2 presents the recommended indicator values and the simulation results for the proposed office layout.

TABLEAU 2 – NF S31-199 recommendations and simulation results for type 1 workspace

Indicator	Recommendation	Simulation
$L_{A,eq}$	$48 \leq . \leq 52$ dB(A)	46.6 dB(A)
		47.3 dB(A)
		47.4 dB(A)
D_n	≥ 6 dB	10.1 dB
		9.9 dB
		7.4 dB
$D_{2,S}$	≥ 7 dB	8.3 dB
Tr_{125}	≤ 0.8 s	0.56 s
Tr	≤ 0.6 s	0.68 s

The ambient noise levels are approximately 1 dB(A) lower than the minimum recommended values and 5 dB(A) lower that the maximum. As only speech sources have been accounted for in this simulation, the obtained ambient noise levels are acceptable. The minimum D_n values for the three considered receivers are 10.1 dB, 9.9 dB and 7.4 dB. All simulated D_n values are greater than 6 dB as required by the standard. The simulated $D_{2,S}$ is also acceptable as the obtained value (8.3 dB) is greater than the required 7 dB. The reverberation time is very close to the target values both for the 125Hz octave band and the mid frequencies. Overall, the partitioning walls efficiently increase sound attenuation between workstations thanks to the high absorption of the ceiling. These elements also reduce the ambient noise level and the reverberation time as they absorb an important part of acoustic energy. Overall, the proposed design appears to be relevant to accommodate a call center.

4.2 Type 2 : project spaces

In project spaces, employees work in small groups on common projects. Communication among groups is important but should not disturb other groups working on different subjects. In project spaces, low height partition walls can be installed to mark the limits between different groups. Figure 5 shows the proposed office layout and the considered source and receiver positions for acoustic indicators estimation. It has 36 workstations separated in groups of two or four desks by 1.8m high partition walls. The height of the partition walls is very high to increase the sound decay in the office.

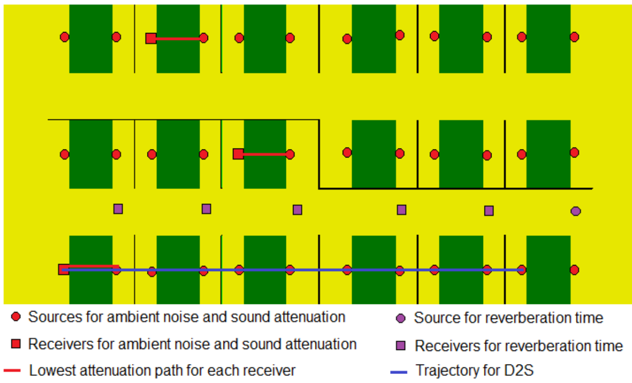

FIGURE 5 – Sources and receivers positions for acoustic indicators simulation in type 2 office.

Table 3 presents the recommended indicator values for type 2 offices and the simulation results. The ambient noise level is simulated in three receiver positions as in the previous case but speech sources are active 15% of the time to correspond to a project space configuration. All simulated indicators comply with the recommendations except the reverberation time which is slightly higher. This value is due to a flutter echo between the two parallel plaster walls and can be easily corrected by placing an absorbing or diffusive panel on one of them in the alignment of the alleys. Sound attenuation D_n in this case is lower than zero as there are multiple early reflections between adjacent workstations that increase the perceived sound level.

TABLEAU 3 – Recommendations and simulation results for type 2 workspace

Indicator	Recommendation	Simulation
$L_{A,eq}$	$45 \leq . \leq 50$ dB(A)	47.6 dB(A)
		44.5 dB(A)
		47.8 dB(A)
D_n	≤ 4 dB	−2.8 dB
		−0.2 dB
		−1.9 dB
$D_{2,S}$	≥ 9 dB	9.1 dB
Tr_{125}	≤ 0.8 s	0.81 s
Tr	≤ 0.6 s	0.83 s

4.3 Type 3 : administrative spaces

In administrative spaces, employees perform individual tasks that require concentration. Communication with colleagues is rare and the ambient noise level is generally low. The recommendations in terms of acoustic indicators are the same as for the call center except for the ambient noise which is required to be much lower for administrative spaces. The proposed layout is shown in Figure 6. It is similar to the project space but has additional partitioning screens of 1.3m in between facing workstations. The same sources and receivers positions as for the project space were used in these simulations. For ambient noise estimation, sources are active only 5% of the time.

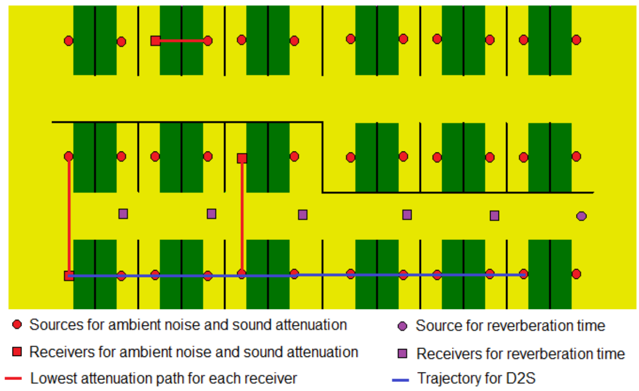

FIGURE 6 – Sources and receivers positions for acoustic indicators simulation in type 3 office.

Table 4 presents the recommended indicator values for type 3 offices and the simulated results. As in the previous case, all simulated indicators comply with the recommendations except reverberation time which is slightly higher due to the same flutter echo. For administrative spaces, speech sources may not be the only significant contributions to ambient noise. Therefore, ambient noise might be underestimated in this simulation. However, as the simulated values are significantly lower than the 45 dB(A) maximum level, the true ambient noise should remain in the required range. Once the flutter echo is suppressed, the proposed layout should be pertinent to host an administrative office.

TABLEAU 4 – Recommendations and simulation results for type 3 workspace

Indicator	Recommendation	Simulation
$L_{A,eq}$	$40 \leq . \leq 45$ dB(A)	42.4 dB(A)
		39.9 dB(A)
		41.6 dB(A)
D_n	≥ 6 dB	6.4 dB
		6.9 dB
		5.9 dB
$D_{2,S}$	≥ 7 dB	8.0 dB
Tr_{125}	≤ 0.8 s	0.74 s
Tr	≤ 0.6 s	0.71 s

4.4 Type 4 : public reception spaces

In public reception spaces, confidentiality is an important matter. The employees often discuss of private matters with their clients. Sound propagation between workstations needs to be limited with low height partitions. Public reception spaces often include waiting rooms or areas for customers. These rooms often represent important noise sources that significantly contribute to the ambient noise level in the office. Figure 7 shows the proposed office layout. It consists in sixteen reception desks and two waiting rooms. The partitioning walls are 1.8m high to ensure the confidentiality of conversations.

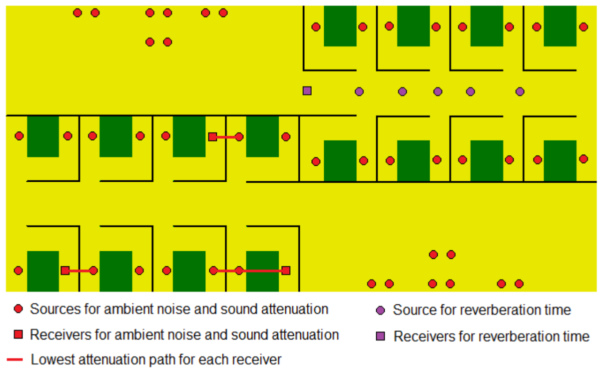

FIGURE 7 – Sources and receivers positions for acoustic indicators simulation in type 4 office.

Table 5 presents the recommended indicator values for type 4 offices and the simulated results. Note that for ambient noise simulation at a receiver position, all remaining positions are considered as active sources 40% of the time, except the client position facing the employee. In fact, the client needs to be considered as a useful source signal and not as a disturbing noise contributing to the ambient noise level. Similarly, the closest client position is not considered to estimate sound attenuation D_n (see red lines in Figure7).

The proposed design complies with the recommendations but the amount of partitioning elements could probably be reduced as the sound attenuation is 3 to 5 dB higher than the recommended D_n value. The ambient noise is much lower than the maximum recommended level. This margin is convenient to account for additional noise sources from the outside of the office as access doors could be often open during a normal working day. Estimated reverberation times are acceptable for this type of office.

TABLEAU 5 – Recommendations and simulation results for type 4 workspace

Indicator	Recommendation	Simulation
$L_{A,eq}$	≤ 55 dB(A)	46.1 dB(A)
		45.9 dB(A)
		46.3 dB(A)
D_n	≥ 6 dB	11.6 dB
		10.5 dB
		9.2 dB
Tr_{125}	≤ 1.0 s	0.75 s
Tr	≤ 0.8 s	0.75 s

5 Conclusion

In this paper, the new French standard NF S31-199 relative open office acoustics is presented. It details the acoustic requirements for the design of an open office. These requirements depend on the field of activity the office accommodates. The assessment method to verify the compliance of a given office design with the recommendations of the standard is also detailed. It is based on the ICARE impulse response simulation algorithm with carefully chosen sources and receivers positions. Four office designs are proposed : a call center, a project space, an administrative space and a public reception space. The effect of the different acoustic solutions used in these designs is analyzed and compliance with the standard requirements is verified for each case.

Generally speaking, it is shown that the recommended indicator values in the NF S31-199 can be easily achieved with common acoustic solutions used in modern open office designs. It is important to consider an absorptive ceiling together with partitioning elements to reduce sound propagation between workstations. Also, in open offices with parallel walls, diffusive or absorptive materials can be used to reduce flutter echos and hence obtain acceptable reverberation times.

General conception rules provided in the standard can be followed to design a first draft of an office and 3D simulations allow to adjust the design by varying the positions and heights of partitioning elements as well as the absorption coefficients for surface materials. Hence, 3D simulations permit the separate assessment of the effect of various acoustics solutions so as to design the optimal office for the required activity.

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