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Acoustic design of open-plan offices

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Title: Acoustic design of open-plan offices

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Abstract: The acoustic conditions in open-plan offices were investigated in a Nordic cooperation project. Measurements were carried out in five open-plan offices along with a questionnaire to gather the staff’s subjective judgments. A programme for the acoustic measurements was drawn up, specifying how to perform the measurements and which type of parameters to measure. The acoustic parameters included are Reverberation time T20, Early decay time (EDT), Clarity (C50), Speech transmission index (STI), Speech intelligibility index (SII), Privacy index (PI), Rate of spatial decay of sound pressure levels per distance doubling (DL2), Excess of sound pressure level with respect to a reference curve (DLf), and background noise levels in occupied and unoccupied offices. A refurbishment programme was carried out in two of the offices. Measurements were performed after refurbishment and a questionnaire was completed. It is concluded that parameters relating to sound propagation, such as DL2 and DLf, are appropriate for the acoustic evaluation of open-plan spaces. A refurbishment programme was carried out in two open-plan offices. It has been shown that DL2 and DLf are sensitive to the acoustic treatment carried out and that they also reflect an improvement in the subjective judgment as regards the acoustic environment in general. Moreover, these parameters can be converted into a (comfort) radius indicating the distance for achievement of a certain reduction of the sound level from a sound source. This application could serve as a practical tool for the acoustic planning of open-plan offices.
Executive summary

Main objectives:
- To develop room acoustics descriptors that objectively quantify the sound environment in open-plan offices.
- The descriptors must reflect the subjective perception of the acoustic conditions.
- The descriptors should be useful in the acoustic design of open-plan offices and give guidance and recommendations for the planning and acoustic treatment of open-plan offices.

Method:
- Room acoustic measurements were performed in five open-plan offices. The offices were located in Denmark, Norway, Finland and Sweden. Two were in Sweden. Several room acoustic parameters were measured relating to speech clarity, reverberance, sound strength and sound distribution. A questionnaire was directed at the staff in all offices. A refurbishment programme was performed in two of the offices. After the refurbishment programme the measurements and the questionnaire was implemented again.

Results and conclusions:
- There is a need for complementary parameters for the acoustic evaluation of open-plan offices. Ordinary room acoustic parameters such as reverberation time are not sufficient for a relevant characterization of the acoustic environment in open-plan areas. The influence of interior design on sound propagation over distance is a crucial factor for the overall impression of the acoustic environment and its suitability as an effective workplace. Parameters relating to sound propagation, such as DL$_2$ and DL$_f$ are therefore appropriate for open-plan areas. It was shown that DL$_2$ and DL$_f$ are sensitive to the acoustic treatment carried out and that they also reflect the improvement in the subjective judgment regarding the acoustic environment in general. Moreover, these parameters can be converted into a (comfort) radius indicating the distance needed to achieve a certain reduction of the sound level from a sound source. This application could serve as a practical tool for the acoustic planning of open-plan offices.

Recommendations:
- The project group expects the findings in this report to be useful in the acoustic design of open-plan offices and that the room acoustic parameters suggested will create a basis for guidelines, recommendations and standards as regards open-plan offices, thus contributing to an improved work environment.
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Preface

This project has been financed partly by Nordic Innovation Centre within the Nordtest project no. 05090 (Innovativt byggande) and partly by Saint-Gobain Ecophon. Saint-Gobain Ecophon supplied material for the intervention study in the open-plan offices in Denmark and Sweden. The financial and material support is hereby gratefully acknowledged. The measurements have been performed at open-plan offices in Sweden, Denmark, Norway and Finland.
1. Introduction

The extensive use of open-plan solutions for offices has highlighted the problems of acoustic conditions in these environments. The differences in architectural design, the planning of working areas and the activities taking place have also been challenging in respect of acoustic evaluations. In North America, the extensive experience (Bradley 2003, 2007, Moreland 1989) and use of open-plan offices (OPOs) has also resulted in several standard procedures (ASTM E 1111, 1130, 1110) for securing speech privacy at work stations, especially in the commonly used open-plan offices with a cellular structure often referred to as cubicles. To ensure speech privacy at work stations in such structures, sound propagation needs to be considered at a detailed level, taking different effects into account such as the sound absorbing treatment, screens, size of work station and background noise (Wang and Bradley 2002). In Europe, the purpose of using an open-plan structure is often to create flexible solutions that support communication between employees and working teams, but such a structure also permits concentrated work. In these environments, the creation of a high level of speech privacy is normally not a realistic goal or even an intention. Instead, the organisation of work stations should support communication between members of the same team but depress speech sound from neighbouring groups working on other projects. This implies that the prevention of sound propagation over long distances is important. Nevertheless, extraneous speech is the major source of disturbance in OPOs and it is well recognized that it has a detrimental effect on cognitive performance (Schlittmeier et al. 2007, Hongisto 2007, BAR FOKA 2008, Venetjoki et al. 2005). However, many investigations are performed under laboratory conditions using sound stimuli not typical for offices, so it is thus not obvious how the results apply to open-plan conditions and the corresponding sound activity. In a modern flexible OPO, the creation of a functional work station is a complex process in which acoustic planning is only one part of a series of considerations that has to be addressed. The open-plan office should support both communication and concentrated work. Thus, for an OPO to be an efficient and comfortable place of work, there are several requirements other than acoustic treatment that have to be fulfilled, such as:

- sufficient number of sound-insulated rooms for concentrated work and meetings,
- flexible solutions for computers and mobile telephony with wireless connection,
- staff awareness of purpose of OPOs and information on how to behave to reduce annoyance,
- planning of work stations to simplify communication between team members and minimize disturbance between different groups,
- acoustic planning for the activities in question.

A method for approaching room acoustic design is presented in (Nilsson and Svensson 2008, Nilsson and Hellström 2009). The main principle in this approach is the taking into account of the multidimensional character of people’s perception of sound, the character of the room (shape, volume, distribution of absorption) and the activity that is planned for the room. These three factors interact and have to be considered in the acoustic design in order to secure an appropriate acoustic environment. A consequence of the human perception of sound is that several room acoustic descriptors normally have to be used to achieve a relevant evaluation of the room acoustics. Using reverberation time only will often be insufficient and sometimes even misleading (Nilsson 2007). Taking into consideration the shape, size and
distribution of sound-absorbing material, it is appropriate to distinguish between different room types. With the exception of large industrial spaces and premises for performances such as concert halls and theatres, and restricting the analysis to ordinary rooms, there are at least three groups of rooms that have to be analysed in different ways. The reverberant rooms where the diffuse field assumption is valid are room types where the late reverberation time (T20 or T30 according to ISO 3382-1) works as a global parameter and characterizes the acoustic conditions sufficiently well. However, this room type is uncommon in practice. A more common room type is the one with an absorbent ceiling. In this type of room, the diffuse field assumption is not normally fulfilled and the reverberation time alone is not enough to characterize the acoustic conditions. Room acoustic descriptors related to different sensations such as steady-state sound levels, speech clarity and reverberance have to be evaluated separately. Another room type is that with an extended form such as open-plan spaces and corridors. Typically, this room type has room acoustic parameters that vary over distance from source and are thus not useful as global descriptors of the interior environment. As regards these spaces, measures relating to sound propagation seem to be more appropriate for room acoustic characterization (Keränen et al. 2007 2008, Virjonen et al. 2009, Hongisto et al, 2004, Petersen 2008, Pop and Rindel 2005).

The aim of this work is to suggest appropriate, objective parameters for a simple, practical evaluation of open-plan offices. The purpose of the parameters is to ensure that the overall basic acoustic conditions in an open-plan office are sufficient for the activities to be performed there. The intention is that the measures shall reflect the interior fittings of the office and reflect critical parameters with regard to the design and planning. These critical parameters can apply to the choice of materials and outer layer for the room’s surfaces and furnishings, to general room layout and/or the use of the work stations. A measurement methodology for evaluating room acoustics in large office spaces in a meaningful way can also lead to sound solutions relating to the work environment. This will benefit both employers and workers and lead to improved efficiency, less absenteeism and increased job satisfaction. It can also help to increase accessibility for individuals suffering from hearing loss. A good acoustic environment minimizes the risk of office workers having to leave work early because of significant pressure arising from an unsuitable working environment.

2. Method

Five OPOs have been investigated. Two offices were located in Stockholm (Sweden) and one each in Copenhagen (Denmark), Helsinki (Finland) and Stavanger (Norway). The two offices in Stockholm were in the same building but belonged to different departments.

For two of the offices an intervention programme was decided. The office in Stockholm with the helpdesk function and the office in Copenhagen were selected for an acoustic refurbishment programme. The reason for this selection was that the staff in these offices were those, according to the initial inquiry, whom the acoustic conditions disturbed most.

The examination of the five offices included room acoustic measurements accompanied by a questionnaire addressed at the staff. The measurements and questionnaire were repeated after the refurbishment of the two offices selected in the intervention programme.
2.1 Acoustic parameters

Room acoustic parameters relating to the quality aspects of reverberance, speech clarity, sound strength and sound propagation were measured. The room acoustic parameters measured are listed in Table 2. Measurement positions were chosen along lines in the offices as illustrated in Figure 1. Preferably, positions were chosen at work stations. The speech intelligibility parameters STI and SII were measured using both a directional and an omnidirectional loudspeaker. The directional loudspeaker Aculab fulfils the requirements in ASTM E 1179-87. Other parameters were measured using the omnidirectional loudspeaker. The loudspeakers used are presented in Table 1.

<table>
<thead>
<tr>
<th>Loudspeaker type</th>
<th>Manufacture</th>
<th>Model</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omnidirectional (referred to as omni)</td>
<td>Different manufacturers</td>
<td></td>
<td>EDT, T&lt;sub&gt;20&lt;/sub&gt;, STI, SII, PI, D&lt;sub&gt;50&lt;/sub&gt;,</td>
</tr>
<tr>
<td>Directional (referred to as dir)</td>
<td>Genelec</td>
<td>1029A</td>
<td>STI</td>
</tr>
<tr>
<td>Directional (referred to as aculab)</td>
<td>Aculab</td>
<td></td>
<td>According to ASTM E 1179 SII, PI</td>
</tr>
</tbody>
</table>

The background noise levels were, if possible, measured in relation to
1. normal activity
2. activity without staff but with ventilation noise on
3. activity without staff and with ventilation noise off

The frequency region, where appropriate, was 50 to 5000 Hz in the third octave band. The parameters were measured according to relevant standards. For the sound propagation measures DL<sub>2</sub> and DL<sub>f</sub> according to ISO 14257, an omnidirectional loudspeaker was used as a sound source. The loudspeaker emitted a pink noise signal at a constant sound power level. The sound propagation values DL<sub>2</sub> and DL<sub>f</sub> were evaluated for the octave band 125 to 4000 Hz and for the dB(A) values.
### Table 2. Room acoustic parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Designation</th>
<th>Unit</th>
<th>Explanation</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early decay time</td>
<td>EDT</td>
<td>s</td>
<td>Speed at which sound disappears</td>
<td>ISO 3382-1/2</td>
</tr>
<tr>
<td>Reverberation time</td>
<td>T20</td>
<td>s</td>
<td>see above</td>
<td>see above</td>
</tr>
<tr>
<td>Clarity of speech (&quot;Definition&quot;, &quot;Deutlichkeit&quot;)</td>
<td>D$_{50}$*</td>
<td>%</td>
<td>Measures the balance between early- and late- arriving energy</td>
<td>see above</td>
</tr>
<tr>
<td>Speech transmission index</td>
<td>STI</td>
<td>-</td>
<td>Quality of speech transfer from speaker to listener</td>
<td>IEC 60268-16</td>
</tr>
<tr>
<td>Speech intelligibility index</td>
<td>SII</td>
<td>-</td>
<td>see above</td>
<td>ANSI S3.5-1997</td>
</tr>
<tr>
<td>Privacy index</td>
<td>PI</td>
<td></td>
<td>PI = (1 - SII) · 100%</td>
<td>ASTM E 1130-02</td>
</tr>
<tr>
<td>Rate of spatial decay of sound level per distance doubling</td>
<td>DL$_2$</td>
<td>dB</td>
<td>Measure sound decrease using distance from sound source</td>
<td>ISO 14257</td>
</tr>
<tr>
<td>Excess of sound level rel. free field</td>
<td>DL$_{f}$</td>
<td>dB</td>
<td>Measure of room’s contribution to sound level at different distances</td>
<td>see above</td>
</tr>
</tbody>
</table>

*Speech clarity $C_{50}$ is defined in ISO 3382-1. The relation between $C_{50}$ and $D_{50}$ is

$$C_{50} = 10 \times \log\left(\frac{D_{50}}{1 - D_{50}}\right) \text{ dB}$$  \hspace{1cm} (1)
Sound distribution parameters

The spatial sound distribution curves are characterized by the parameters $DL_2$ and $DL_f$ according to ISO 14257. An omnidirectional loudspeaker producing pink noise was used as a sound source. Measurements were carried out along the two paths shown in Figure 1. The loudspeaker and microphone were placed at a height of 1.2 metres above the floor.

The rate of spatial decay of sound pressure level per distance doubling, $DL_2$, was calculated using the least square method and given by the following equation:

$$DL_2 = -\log(2) \cdot \frac{\sum_{i=n}^{m} D_i \cdot \log\left(\frac{r_i}{r_0}\right)}{\sum_{i=n}^{m} \log\left(\frac{r_i}{r_0}\right)} \text{ dB}$$

where

$z=m-n+1$, $m$ and $n$ are the index numbers of the measurement positions with $m$ being the most distant position

$r_i$ is the distance to the measurement position $i$

$r_0$ is the reference distance 1 metre

$D_i = L_{p,i} - L_{W}$, $L_{p,i}$ is the sound pressure level (octave band or A-weighted) at the measurement position $i$, $L_w$ is the sound power level (octave band or A-weighted) of the omnidirectional loudspeaker

$DL_f$ is the average difference, over a given distance range, between the spatial sound distribution curve measured in the room and the spatial sound distribution curve for free field. The average value of $DL_f$ over the distance range limited by the microphone positions at distances $r_n$ and $r_m$ is given by:

$$DL_f = \frac{\sum_{i=n+1}^{m} \left[(DL_{f,i} + DL_{f,i-1}) \cdot \log\left(\frac{r_i}{r_{i-1}}\right)\right]}{2 \log\left(\frac{r_m}{r_n}\right)} \text{ dB}$$

where

$m$ and $n$ are the index numbers of the measurement positions with $m$ being the most distant position

$DL_{f,i} = D_i - D_{ref}$ where $D_i = L_{p,i} - L_{W}$, $L_{p,i}$ is the sound pressure level (octave band or A-weighted equivalent sound pressure level) at the measurement position $i$, $L_W$ is the sound power level (octave band or A-weighted equivalent sound power level) of the
omnidirectional loudspeaker. $D_{ref} = 10 \log \left( \frac{r_0^2}{4 \pi r^2} \right)$ is the spatial sound distribution curve in free field where $r$ is the distance between the sound source and the measurement position considered and $r_0$ is the reference distance = 1 metre

$r_i$ is the distance to the measurement position $i$

$r_n$ and $r_m$ are the distances defining the range for calculation of the average value $DL_f$

In this report we prefer to analyse sound distribution curves based on measurements of A-weighted equivalent sound pressure levels.

\[DL_f\]

Figure 1. Example of plan drawings for two of the open-plan offices investigated, showing measurement positions and direction.

The measurements were performed in furnished rooms without staff. The loudspeaker and microphone were located at working level, a height of 1.2 metres (simulating a person seated). The distance between the loudspeaker or microphone and any screen or wall was not less than 1 metre.

Besides room acoustic parameters, acoustic qualities in terms of communication, orientation, comfort and privacy were integrated into the project. For that reason, we developed two types of methodologies in order to measure and specify these qualities: site analysis and questionnaire.
2.2 Site analysis

Site analysis consists of a design methodology for acoustic design, applied to open-plan offices. The concept “acoustic design” has emerged recently from the architectural discipline (Hellström, 2003). Hitherto, architectural research has largely ignored sound design criteria. Research advocating acoustic design adds the dimension of sound as an important building block for architectural practice. Importantly, acoustic design integrates the acoustic climate with architectural issues (see Amphoux and Augoyard, 1993, 1995). In this project, the following criteria are integrated into site analysis:

- Architectural design – furnishing, materials and spatial structure
- Functional design – internal infrastructure in terms of movement, spatial integration, entrances, passages and meeting points.

However, these criteria are not directly considered in this project as it was not possible to reorganise the individual work stations of the open-plan offices investigated. Instead, a general discussion regarding the analysis of the design criteria is presented in sections 6 and 7.

2.3 Questionnaire

Beside the site analysis methodology, a major methodological tool relates to the development of a questionnaire. This was used as a complement to acoustic measurements, and thus functioned as a tool for design measures relating to large open-plan offices. The purpose of a questionnaire is to aid acousticians as well as architects in identifying critical criteria with regard to psychoacoustics (e.g., perception of the sound environment, psychosocial measures) as well as architectural design (e.g., internal infrastructure, furnishings). These subjective qualitative criteria were scrutinized and suitable parameters for the evaluation and design of open-plan spaces will be suggested. Moreover, the questionnaire methodology pinpoints the importance of obtaining information regarding site-specific criteria from the staff’s subjective point of view.

2.4 Design of questionnaire

The design of the questionnaire started with a collection of other established questionnaires that had a similar approach to the knowledge field (see references: list of questionnaires). Even though the relevance of these questionnaires differed, all of them included a few questions, or more, that were applicable to the research project. The selected questions were arranged with regard to the following criteria:

- Spatial comprehension
  - e.g. the comprehension of the open-plan office in terms of open/closed, public/private; location of sound sources; visual and acoustic screening; location of work station.
- Sound masking
  - e.g. surrounding sounds as a tool for privacy and/or disturbance; sounds from fans, lighting, computers, street, murmur, etc.
- Perceptual criteria
  - e.g. disturbing sounds with regard to concentration; speech privacy, etc.

1 Mats Nilsson, docent in psychoacoustics at Stockholm University and expert in design of questionnaires, was involved in this phase in order to guarantee the quality of the questionnaire.
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Psychosocial criteria
e.g. sensitivity to sound; comfort; interaction with colleagues.
Accomplishment / Design
e.g. personal redesign of the acoustic environment such as use of radio/Mp3, bookshelves, screens etc; working at home.

Most of the questions were divided into five multiple-choice answers. Before implementation, the questionnaire was tested on acoustics experts, as well as on a number of people who work in open-plan offices. The whole questionnaire comprises sixty questions, and takes thirty minutes at most to answer. Regarding ethical aspects, the answers were treated confidentially. Finally, before implementation of the questionnaire in the project, it was tested in situ, in a “real” open-plan office, where problems of sound disturbance were reported. The testbed was an office with fifteen employees.

3 Results

3.1 Results – Selection of offices and site analysis

Vattenfall – Stockholm
Two open-plan offices at Vattenfall in Stockholm were selected. Vattenfall’s core business is to produce and provide electricity and heat. The architectural design of the two offices (volume, plan, furnishings etc) was almost identical. In one of the offices the staff works with finance and the other office has a helpdesk function.

After initial implementation and analysis of the questionnaires, the helpdesk office was selected as a major case for the research project. The analysis of the questionnaires proved that the staff in the helpdesk office were disturbed by the acoustic environment to a much greater extent than the staff in the finance office. It can be added that there were more people in the helpdesk office (20) than in the finance office (16 ). See 5. Conclusion of Questionnaire and Measurements.

As mentioned above, around twenty people work in the helpdesk office. The office measures 18 x 11 metres. A schematic plan of the office prior to acoustic design can be found in Figure 22. The height of the sound-absorbing screens between the desks, prior to acoustic treatment, was 1.16 metres. The flooring was plastic, and the passage dividing the office into two parts had a needle-felt carpet. The ceiling was clad with suspended, sound-absorbing ceiling tiles, with the exception of the ceiling in the passage, which had no sound-absorbing material. The furnishings in the helpdesk office can be seen in Figure b1. Most of the staff in the office are divided into units of four people per working group.

Reference: internal project at ÅF Ingemansson, project no. 30-04191-06090100-A
Dicentia – Copenhagen

The digital media distribution company Dicentia in Copenhagen was selected as the other major case for the project. Around thirty people work in the office, which measures 25 x 9 metres. A schematic plan can be found in Figure 8.

The height of the bookshelves and screens is 1.4 metres. The floor has wall-to-wall carpeting. The ceiling, prior to acoustic treatment, was of semi-hard mineral wool tiles. The furnishings can be seen in Figure b2. Most of the staff in the office are divided into units of four people per working group.
Statoil – Stavanger
The project also includes an open-plan office connected to Statoil and located in Stavanger. Around thirty-five people work in the office, which measures approximately 21 x 20 metres. A schematic plan can be found in Figure 45.

The floor is covered with a textile carpet. The ceiling consists of sound-absorbing ceiling tiles (Ecophon Focus 20 mm), suspended approximately 1 metre, covering about 80% of the total area. Some areas of the walls are covered with perforated panels. The open-plan office is divided by perforated wooden screens, and each desk is equipped with perforated screens.

The evaluation of the questionnaire indicated that the acoustic climate in the open-plan offices was better than that at Vattenfall and Dicentia. Due to the fact that the office was brand new, no further measures were taken after the initial acoustic measurements and questionnaire.

Association of Finnish Civil Engineers, RIL ry – Helsinki
The project also embraces an open-plan office in Helsinki – that of the Association of Finnish Civil Engineers. Approximately 12 people work in the office. The ceiling is covered with two types of sound-absorbing materials: fibreboard (absorbing coefficient about 0.5) and mineral wool (absorbing coefficient about 0.9). The height of the bookshelves is 1.3 metres. A schematic plan can be found in Figure 61.

The evaluation of the questionnaire indicated that the acoustic design of the office had not been performed well. However, since the office was reorganised after the initial acoustic
measurements and questionnaire, and since the number of staff was quite limited, no further measures were taken.

**Acoustic design at Vattenfall and Dicentia after the refurbishment programme**

The offices in Stockholm (Vattenfall, Helpdesk) and Copenhagen (Dicentia) were selected for the refurbishment programme.

The acoustic design of the open-plan office at Vattenfall is as follows:

- New ceiling tiles mounted directly onto the ceiling in the corridor (Ecophon Master B 40 mm).

- Suspended ceiling sections (Ecophon Master Solo S) over all work stations, 2.1 metres above floor level. One ceiling (unit) covers four work stations. In addition to the acoustic effect, the purpose of the units is to divide the open-plan office into smaller sections, thus creating an enhanced spatial structure.

- Screen walls between the work stations (S-line – with absorbent material on both sides). Glass above the screens.

- One absorption segment mounted onto the wall (Ecophon Wall Panel Texona C 40 mm).

The design of the open-plan office was supervised by Ecophon AB, and can be seen in Figures b3 and b4.
Figure b3. Vattenfall Helpdesk, office in Sweden. Absorbent screen topped with glass and free-hanging units Ecophon Master Solo S over work stations.

Figure b4. Vattenfall Helpdesk, office in Sweden. Ecophon Wall Panel Texona C on wall in rest room.
The acoustic refurbishment of the open-plan office at Dicentia is as follows:

- New ceiling tiles in the whole room, suspended 200 millimetres (Ecophon Focus E 20mm).

- Suspended ceiling sections (Ecophon Master Solo S) over all work stations and also over the reception area, 2.1 metres above floor level. One ceiling (unit) covers four work stations. In addition to the acoustic effect, the purpose of the units is to divide the open-plan office into smaller sections, thus creating an enhanced spatial structure.

- One absorption segment mounted onto the wall opposite the window façade (Ecophon Wall Panel C Texona 40 mm).

The refurbishment of the open plan office was supervised by Ecophon, and can be seen in Figures 5b and 6b.
3.2 Results - Questionnaire before and after refurbishment

The questionnaire includes sixty questions. However, for the sake of clarity, the answers to 5 questions that are close connected to acoustic parameters and measures are presented below. (Due to the limited character of this report, it is not feasible to present the answers to all the questions.)

The selected questions related to acoustic conditions are:

1. How do you consider the acoustic environment from a general point of view?
2. How well is your work station screened off regarding telephone talk?
3. To what extent will colleagues' telephone talk negatively impact the possibility of accomplishing your task?
4. How well is your work station screened off regarding conversation?
5. To what extent will noise from colleagues, working apart, negatively impact the possibility of accomplishing your task?
Vattenfall – Helpdesk

The questionnaire was carried out at the helpdesk-office, and the staff had to answer the questions before and after the acoustic treatment. The evaluation of the questionnaire indicates that the acoustic treatment had a positive effect. The number of respondents to the questionnaire before and after the acoustic treatment was 14 and 10 respectively. The results are presented in Figure 2 and in Summary.
3. To what extent will colleagues' conversation over telephone have a negative impact on the possibility of accomplishing your task?

- Very great
- Great
- To some degree
- Small
- Not at all

Sweden Vattenfall - Helpdesk, before treatment  Sweden Vattenfall - Helpdesk, after treatment

4. How well is your workplace screened off regarding conversation?

- Very badly
- Badly
- Neither well nor badly
- Well
- Very well

Sweden Vattenfall - Helpdesk, before treatment  Sweden Vattenfall - Helpdesk, after treatment
5. To what extent will noise from colleagues’, working apart, have a negative impact on the possibility of accomplishing your task?

![Bar chart showing the results of the questionnaire before and after treatment at Vattenfall – helpdesk.](chart)

**Figure 2. Result of questionnaire before and after treatment at Vattenfall – helpdesk**

**Summary: Vattenfall – Helpdesk (the numbers in brackets refer to the questionnaire)**

**Question [no 26]**
Before acoustic treatment: 60% considered the acoustic environment, from a general point of view, as “bad” (40%) or “very bad” (20%).

After acoustic treatment: the percentage was reduced to 10% (“bad” 10%, “very bad” 0%).

**Question [no 47]**
Before acoustic treatment: 73% stated that their work station was “badly” (33%), or “very badly” (40%) screened off regarding telephone talk.

After acoustic design: the percentage was reduced to 20% (“badly” 20%, “very badly” 0%).

**Question [no 37.5]**
Before acoustic treatment: 66% stated that their colleagues’ telephone talk had a negative impact “to some degree” (13%), “great” (33%) and “very great” (20%), on the possibility of accomplishing their task.

After acoustic treatment: the percentage was reduced to 30% (“to some degree” 20%, “great” 10% and “very great” 0%).

**Question [no 48]**
Before acoustic treatment: 79% stated that their workstation was “badly” (36%) or “very badly” (43%) screened off regarding conversation.

After acoustic treatment: the percentage was reduced to 30% (“badly” 30%, “very badly” 0%).

Question [no 37.6]
Before acoustic treatment: 40% stated that noise from their colleagues, working apart, had a negative impact “to some degree” (13%), “great” (20%) or “very great” (7%) on the possibility of accomplishing their task.

After acoustic treatment: the percentage was reduced to 20% (“to some degree” 20%, “great” 0% and “very great” 0%).

Vattenfall – Finance department

The evaluation of the questionnaire at the finance office indicates that the acoustic climate works better there than at the helpdesk office above (see question no. 26). No further measures were taken after this initial questionnaire. The numbers of respondents was 5.
2. How well is your workplace screened off regarding conversation over telephone?

- very badly
- badly
- neither well nor badly
- well
- very well

Sweden Vattenfall - Economic department

3. To what extent will colleagues' conversation over telephone have a negative impact on the possibility of accomplish your task?

- very great
- great
- to some degree
- small
- not at all

Sweden Vattenfall - Economic department
4. How well is your workplace screened off regarding conversation?

5. To what extent will noise from colleagues’, working apart, have a negative impact on the possibility of accomplish your task?

Figure 4. Result of questionnaire at Vattenfall – Finance department
Summary: Vattenfall – Finance department (the numbers in brackets refer to the questionnaire).

Question [no 26]
Before acoustic treatment: 20% considered the acoustic environment, from a general point of view, as “bad” (20%) or “very bad” (0%).

Question [no 47]
Before acoustic treatment: 100% stated that their workstation was “badly” (0%) or “very badly” (100%) screened off regarding telephone talk.

Question [no 37.5]
Before acoustic treatment: 60% stated that their colleagues’ telephone talk had a negative impact “to some degree” (60%), “great” (0%) or “very great” (0%) on the possibility of accomplishing their task.

Question [no 48]
Before acoustic treatment: 100% stated that their workstation was “badly” (20%) or “very badly” (80%) screened off regarding conversation.

Question [no 37.6]
Before acoustic treatment: 0% stated that noise from their colleagues, working apart, had a negative impact on the possibility of accomplishing their task.

Dicentia

In the same way as at the helpdesk office at Vattenfall, the staff had to answer the questionnaire before and after the acoustic treatment. The evaluation of the questionnaire indicates that the acoustic design had a positive effect. However, the results have to be evaluated with some caution since the number of respondents was 16 before the acoustic treatment, and 7 thereafter. The reason for the reduced number of respondents after treatment was due to the fact that staff participating in the first inquiry has quit their jobs.
1. How do you consider the acoustic environment from a general point of view?

[Bar chart showing survey results]

- Very bad
- Bad
- Neither good nor bad
- Good
- Very good

Denmark, Dicentia, before treatment
Denmark, Dicentia, after treatment

2. How well is your workplace screened off regarding conversation over telephone?

[Bar chart showing survey results]

- Very badly
- Badly
- Neither well nor badly
- Well
- Very well

Denmark, Dicentia, before treatment
Denmark, Dicentia, after treatment
3. To what extent will colleagues' conversation over telephone have a negative impact on the possibility of accomplish your task?

4. How well is your workplace screened off regarding conversation?
5. To what extent will noise from colleagues’, working apart, have a negative impact on the possibility of accomplish your task?

![Bar chart showing the impact of noise from colleagues on the possibility of accomplishing tasks before and after acoustic treatment at Dicentia.](chart)

**Figure 5. Result of questionnaire before and after treatment at Dicentia**

**Summary: Dicentia (the numbers in brackets refer to the questionnaire)**

**Question [no 26]**
Before acoustic treatment: 69% considered the acoustic environment, from a general point of view, as “bad” (31%) or “very bad” (38%).

After acoustic treatment: the percentage was reduced to 29% (“bad” 29%, or “very bad” 0%).

**Question [no 47]**
Before acoustic treatment: 88% stated that their work station is “badly” (13%) or “very badly” (75%) screened off regarding telephone talk.

After acoustic treatment: the percentage was reduced to 71% (“badly” 14% or “very badly” 57%).

**Question [no 37.5]**
Before acoustic treatment: 88% stated that their colleagues’ telephone talk had a negative impact “to some degree” (56%), “great” (19%) or “very great” (13%) on the possibility of accomplishing their task.

After acoustic treatment: the percentage was reduced to 57% (“to some degree” 14%, “great” 43% or “very great” 0%).
Question [no 48]
Before acoustic treatment: 94% stated that their workstation was “badly” (19%) or “very badly” (75%) screened off regarding conversation.

After acoustic treatment: the percentage was reduced to 66% (“badly” 33% or “very badly” 33%).

Question [no 37.6]
Before acoustic treatment: 57% stated that noise from their colleagues, working apart, had a negative impact “to some degree” (38%), “great” (6%) or “very great” (13%) on the possibility of accomplishing their task.

After acoustic treatment: the percentage was the same as before, 57% (“to some degree” 43%, “great” 14% or “very great” 0%).

Statoil

The evaluation of the questionnaire indicated that the acoustic climate is better at Statoil than at the above open-plan offices: only 21% of the staff considered the acoustic environment, from a general point of view, as “bad” or “very bad”; the result is almost identical to that from the finance office at Vattenfall (20%). No further measures were taken after this initial questionnaire. The number of respondents was 19.
2. How well is your workplace screened off regarding conversation over telephone?

- Very badly
- Badly
- Neither well nor badly
- Well
- Very well

3. To what extent will colleagues' conversation over telephone have a negative impact on the possibility of accomplish your task?

- Very great
- Great
- To some degree
- Small
- Not at all
4. How well is your workplace screened off regarding conversation?

5. To what extent will noise from colleagues’, working apart, have a negative impact on the possibility of accomplish your task?

Figure 6. Result of questionnaire at Statoil.
Summary: Statoil (the numbers in brackets refer to the questionnaire).

Question [no 26]
Before acoustic treatment: 21% considered the acoustic environment, from a general point of view, as “bad” (16%) or “very bad” (5%).

Question [no 47]
Before acoustic treatment: 74% stated that their work station was “badly” (21%) or “very badly” (53%) screened off regarding telephone talk.

Question [no 37.5]
Before acoustic treatment: 45% stated that their colleagues’ telephone talk had a negative impact “to some degree” (28%), “great” (11%) or “very great” (6%) on the possibility of accomplishing their task.

Question [no 48]
Before acoustic treatment: 73% stated that their work station was “badly” (26%) or “very badly” (47%) screened off regarding conversation.

Question [no 37.6]
Before acoustic treatment: 18% stated that noise from their colleagues, working apart, had a negative impact “to some degree” (0%), “great” (18%) or “very great” (0%) on the possibility of accomplishing their task.

Association of Finnish Civil Engineers, RIL ry, Helsinki

The evaluation of the questionnaire indicated that the acoustic climate is not well perceived. No further measures were taken after this initial questionnaire. The number of respondents was 5.
1. How do you consider the acoustic environment from a general point of view?

- Very bad
- Bad
- Neither good nor bad
- Good
- Very good

Finland, RIL

2. How well is your workplace screened off regarding conversation over telephone?

- Very badly
- Badly
- Neither well nor bad
- Well
- Very well

Finland, RIL
3. To what extent will colleagues’ conversation over telephone have a negative impact on the possibility of accomplish your task

- very great
- great
- to some degree
- small
- not at all

4. How well is your workplace screened off regarding conversation?

- very badly
- badly
- neither well nor badly
- well
- very well
Summary:  RIL, Helsinki  (the numbers in brackets refer to the questionnaire).

**Question [no 26]**
Before acoustic treatment: 60% considered the acoustic environment, from a general point of view, as “bad” (60%) or “very bad” (0%).

**Question [no 47]**
Before acoustic treatment: 100% stated that their work station was “badly” (20%) or “very badly” (80%) screened off regarding telephone talk.

**Question [no 37.5]**
Before acoustic treatment: 80% stated that their colleagues’ telephone talk had a negative impact “to some degree” (40%), “great” (40%) or “very great” (0%) on their possibility to accomplish their task.

**Question [no 48]**
Before acoustic treatment: 100% stated that their work station was “badly” (20%) or “very badly” (80%) screened off regarding conversation.

**Question [no 37.6]**
Before acoustic treatment: 100% stated that noise from their colleagues, working apart, had a negative impact “to some degree” (80%), “great” (20%) or “very great” (0%) on the possibility of accomplishing their task.
3.3 Results – Room acoustic measurements

The measurement results will be presented for each of the open-plan offices. The measurements were performed by different acoustic consultant companies following a measurement plan decided in advance. However, for practical reasons, it was not possible in all cases to follow this plan strictly. Thus, minor differences in the presentations of the results for the offices will occur. At the end of this paragraph a summary and a comparison of the measurement results will be presented.

Dicentia – Denmark

Measurement results before and after refurbishment will be shown. Figure 8 on the left shows the source and measurement positions for the room acoustic parameters EDT, T\textsubscript{20}, D\textsubscript{50}, STI and SII and figure 8 on the right the measuring path for the sound distribution curves. The same positions were used both before and after refurbishment.

Figure 8. The open-plan office with measuring positions (left) and measuring paths for the sound distribution curves (right). Office: Dicentia - Denmark
Reverberation time and speech parameters

All the parameters were measured with the ventilation on. It was not possible to turn off the
ventilation as it was part of the entire building supply. The STI measurements were performed at
a calibrated output level of 62 dB(A) at a distance of 1 metre with the male-speech shaping filter
applied. However, the background noise was very low and was therefore presumed to have no
significant influence on speech intelligibility. Measurements of the speech parameters were made
according to IEC 60268-16:2003, ANSI 3.5-1997 and ASTM E 1130-02.
The SII parameter was calculated for 1/3-octave speech spectrum levels using the SII calculation
software downloaded from the website: www.sii.to. The source sound was pink noise and
corrections into ANSI S3.5-1997 standard speech spectrum levels were calculated for normal
vocal effort. The background noise levels for each measuring position were based on
measurements in the empty office. The same approach was used for the STI measurements.
The privacy index PI was calculated according to ASTM E 1130-02 as

\[
PI = (1 − SII) \cdot 100\% \quad (2)
\]

The results before and after refurbishment are presented in tables 3 and 4 respectively. The
values for the parameters EDT, T\textsubscript{20} and D correspond to an average for the octave band 250 to
2000 Hz.

Table 3. Reverberation time and speech parameters measured at Dicentia before refurbishment.
EDT, T\textsubscript{20} and D are given as an average for 250 to 2000 Hz.

<table>
<thead>
<tr>
<th>Measurement position (Figure 8)</th>
<th>Distance from source (m)</th>
<th>EDT (s)</th>
<th>T\textsubscript{20} (s)</th>
<th>D (%)</th>
<th>STI omni</th>
<th>STI dir</th>
<th>SII omni</th>
<th>SII aculab</th>
<th>PI omni (%)</th>
<th>PI aculab (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>0.36</td>
<td>0.45</td>
<td>0.87</td>
<td>-</td>
<td>-</td>
<td>0.95</td>
<td>0.96</td>
<td>4.8</td>
<td>4.1</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>0.59</td>
<td>0.52</td>
<td>0.72</td>
<td>0.69</td>
<td>0.77</td>
<td>0.92</td>
<td>0.91</td>
<td>7.8</td>
<td>8.9</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>0.51</td>
<td>0.60</td>
<td>0.72</td>
<td>-</td>
<td>-</td>
<td>0.84</td>
<td>0.83</td>
<td>16.2</td>
<td>17.0</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>0.54</td>
<td>0.54</td>
<td>0.68</td>
<td>0.66</td>
<td>0.74</td>
<td>0.89</td>
<td>0.88</td>
<td>11.0</td>
<td>11.8</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.76</td>
<td>0.80</td>
<td>0.96</td>
<td>0.96</td>
<td>4.2</td>
<td>3.7</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.72</td>
<td>0.76</td>
<td>0.97</td>
<td>0.97</td>
<td>3.3</td>
<td>2.6</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.71</td>
<td>0.76</td>
<td>0.96</td>
<td>0.96</td>
<td>4.1</td>
<td>3.8</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.50</td>
<td>0.60</td>
<td>0.69</td>
<td>0.69</td>
<td>31.2</td>
<td>30.6</td>
</tr>
</tbody>
</table>
Table 4. Reverberation time and speech parameters measured at Dicentia after refurbishment. EDT, T20 and D are given as an average for 250 to 2000 Hz.

<table>
<thead>
<tr>
<th>Measurement position (Figure 8)</th>
<th>Distance from source (m)</th>
<th>EDT (s)</th>
<th>T20 (s)</th>
<th>D (%)</th>
<th>STI omni</th>
<th>STI dir</th>
<th>SII omni</th>
<th>SII aculab</th>
<th>PI omni (%)</th>
<th>PI aculab</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4</td>
<td>0.20</td>
<td>0.37</td>
<td>0.95</td>
<td>-</td>
<td>-</td>
<td>0.96</td>
<td>-</td>
<td>3.6</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>11</td>
<td>0.37</td>
<td>0.40</td>
<td>0.87</td>
<td>0.83</td>
<td>0.82</td>
<td>0.94</td>
<td>-</td>
<td>6.3</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>16</td>
<td>0.45</td>
<td>0.44</td>
<td>0.85</td>
<td>-</td>
<td>-</td>
<td>0.81</td>
<td>-</td>
<td>18.7</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>11</td>
<td>0.36</td>
<td>0.40</td>
<td>0.83</td>
<td>0.76</td>
<td>0.72</td>
<td>0.85</td>
<td>-</td>
<td>15.2</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.83</td>
<td>0.88</td>
<td>0.96</td>
<td>-</td>
<td>3.9</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.79</td>
<td>0.78</td>
<td>0.93</td>
<td>-</td>
<td>7.4</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.75</td>
<td>0.76</td>
<td>0.91</td>
<td>-</td>
<td>9.5</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>16</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.66</td>
<td>0.63</td>
<td>0.58</td>
<td>-</td>
<td>41.7</td>
<td>-</td>
</tr>
</tbody>
</table>

Reverberation time and speech parameters as a function of distance.

The reverberation and speech parameters as a function of distance are presented in figures 9 to 14. The values before and after refurbishment are shown in each figure. For EDT, T20 and D, the values are averaged over the octave bands 250 to 2000 Hz and are given for the positions in the corridor i.e. positions 1, 2 and 3. The speech parameters STI and SII are given for the positions at work stations i.e. position 4 to 8.

Figure 9. EDT as a function of distance from sound source before and after refurbishment. Office: Dicentia - Denmark
Acoustic design of open-plan offices

Figure 10. $T_{20}$ as a function of distance before and after refurbishment. Office: Dicentia - Denmark

Figure 11. $D$ as a function of distance before and after refurbishment. Office: Dicentia - Denmark
Figure 12. STI measured with omni- and directional loudspeaker before and after refurbishment.  
Office: Dicentia - Denmark

Figure 13. SII measured with omnidirectional loudspeaker before and after refurbishment.  
Office: Dicentia - Denmark
Acoustic design of open-plan offices

Figure 14. Privacy index as a function of distance from sound source (omnidirectional). Measurement positions at work stations (4 to 8 in figure 8) and in corridor (1 to 3 in figure 8). Office: Dicentia - Denmark

Sound distribution curves

The sound power levels of the omnidirectional loudspeaker used in the measurements at Dicentia are shown in tables 5 and 6. The sound signal was pink noise.

Table 5. Sound power level of the omnidirectional loudspeaker for measurements before refurbishment.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>80,4</td>
<td>87,3</td>
<td>84,7</td>
<td>79,6</td>
<td>78,5</td>
<td>74,2</td>
<td>86,5</td>
</tr>
</tbody>
</table>

Table 6. Sound power level of the omnidirectional loudspeaker for measurements after refurbishment.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>87,6</td>
<td>94,5</td>
<td>91,9</td>
<td>86,8</td>
<td>85,7</td>
<td>81,4</td>
<td>93,7</td>
</tr>
</tbody>
</table>
The sound distribution curves for A-weighted pink noise along paths A and B according to figure 8 are shown in figures 15 and 16. Sound distribution curves before and after refurbishment are shown in each figure.

**Figure 15.** Sound distribution curves before and after refurbishment for path A. Office: Dicentia - Denmark

**Figure 16.** Sound distribution curves before and after refurbishment for path B. Office: Dicentia - Denmark

The effect of different evaluation intervals calculating DL$_2$ and DL$_4$ is shown in figures 17 and 18. The results for paths A and B in figure 8 are presented both before and after refurbishment.
Acoustic design of open-plan offices

Frequency dependence of room acoustic parameters

The reverberation time $T_{20}$ and the speech clarity $D_{50}$ as a function of frequency are shown in Figures 19 and 20 respectively. The values are averaged over microphone positions 1 to 4 according to figure 8. Results of $T_{20}$ and $D_{50}$ before and after refurbishment are presented in each figure.
Background noise

Background noise was measured linearly in 1/3 octave band and as A- and C-weighted total levels. Measurements were made during normal activity with people in the room and with the room empty and with all office machinery shut down (copying machine, computers, etc.). With the empty office measurements, the ventilation was still on, but the ventilation noise was low and did not affect the speech parameters (STI, SII, D$_{50}$). Measurements for normal activity with people in the room were only performed before refurbishment. Half of the staff were present during these measurements. Background noise was measured in positions 1 to 8 according to
Acoustic design of open-plan offices

Figure 8 except for the case with people in the room. Since it was not possible to measure in all positions with people working, measurements were made only in positions 1, 2, 3, 7, and 8 in this case. The A- and C-weighted background noise levels, averaged over positions, are given in table 7. In figure 21, the background noise levels in 1/3 octave bands are given for the cases with and without activity in the office before refurbishment and for the case without activity after refurbishment. The results are averaged over positions.

Table 7. A- and C-weighted background noise levels. Office: Dicentia - Denmark

<table>
<thead>
<tr>
<th>Empty office before refurbishment, ventilation on</th>
<th>Normal activity, ventilation on</th>
<th>Empty office after refurbishment, ventilation on</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_A (dB)</td>
<td>L_C (dB)</td>
<td>L_A (dB)</td>
</tr>
<tr>
<td>26,6</td>
<td>50,0</td>
<td>52,5</td>
</tr>
</tbody>
</table>

Figure 21. Background noise levels (linear, 1/3 octave bands) in office with different scenarios. Office: Dicentia - Denmark

Conclusions – Dicentia

- Generally, EDT and T20 increased as the distance to the sound source increased.
- Systematic difference between SII and STI. SII generally gives higher values than STI.
- Little effect of the refurbishment on SII and STI.
- Little effect of the refurbishment on PI.
- Significant effect of the refurbishment on DL₂ and DL₇₁.
- Slight increase in DL₂ if the evaluation interval increased.
- DL₂ almost independent of evaluation interval.
Vattenfall Helpdesk – Sweden

Measurement results before and after refurbishment will be shown. Figure 22 on the left shows the source and measurements positions for the room acoustic parameters EDT, $T_{20}$, $D_{50}$, and STI and figure 22 on the right the measuring path for the sound distribution curves. The same positions were used both before and after refurbishment.

Due to technical failure the measurements with the Aculab loudspeaker are not presented.

Reverberation time and speech parameters

Measurements of reverberation time and speech parameters were taken according to ISO 3382 – 1 and IEC 60268-16:2003. STI was calculated from impulse response measurements without any influence of background noise.
The results before and after refurbishment are presented in tables 8 and 9 respectively. The values for the parameters EDT, T\(_{20}\) and D correspond to an average for the octave bands 250 to 2000 Hz.

Table 8. Reverberation time and speech parameters measured at Vattenfall’s Helpdesk before refurbishment. EDT, T\(_{20}\) and D are given as an average for 250 to 2000 Hz.

<table>
<thead>
<tr>
<th>Measurement position (Figure 22)</th>
<th>Distance from source (m)</th>
<th>EDT (s)</th>
<th>T(_{20}) (s)</th>
<th>D (%)</th>
<th>STI omni</th>
<th>STI dir</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.7</td>
<td>0.35</td>
<td>0.45</td>
<td>87</td>
<td>0.81</td>
<td>0.83</td>
</tr>
<tr>
<td>2</td>
<td>5.1</td>
<td>0.34</td>
<td>0.47</td>
<td>87</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>3</td>
<td>7.5</td>
<td>0.52</td>
<td>0.52</td>
<td>73</td>
<td>0.74</td>
<td>0.76</td>
</tr>
<tr>
<td>4</td>
<td>10.4</td>
<td>0.45</td>
<td>0.51</td>
<td>78</td>
<td>0.74</td>
<td>0.75</td>
</tr>
<tr>
<td>5</td>
<td>13.0</td>
<td>0.52</td>
<td>0.50</td>
<td>69</td>
<td>0.73</td>
<td>0.75</td>
</tr>
<tr>
<td>6</td>
<td>6.8</td>
<td>0.50</td>
<td>0.48</td>
<td>78</td>
<td>0.75</td>
<td>0.80</td>
</tr>
<tr>
<td>7</td>
<td>9.7</td>
<td>0.57</td>
<td>0.52</td>
<td>71</td>
<td>0.71</td>
<td>0.75</td>
</tr>
<tr>
<td>8</td>
<td>11.3</td>
<td>0.56</td>
<td>0.52</td>
<td>68</td>
<td>0.71</td>
<td>0.74</td>
</tr>
<tr>
<td>9</td>
<td>15.2</td>
<td>0.57</td>
<td>0.54</td>
<td>61</td>
<td>0.70</td>
<td>0.75</td>
</tr>
</tbody>
</table>

Table 9. Reverberation time and speech parameters measured at Vattenfall’s Helpdesk after refurbishment. EDT, T\(_{20}\) and D are given as an average for 250 to 2000 Hz.

<table>
<thead>
<tr>
<th>Measurement position (Figure 22)</th>
<th>Distance from source (m)</th>
<th>EDT (s)</th>
<th>T(_{20}) (s)</th>
<th>D (%)</th>
<th>STI omni</th>
<th>STI dir</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.7</td>
<td>0.36</td>
<td>0.33</td>
<td>81</td>
<td>0.78</td>
<td>0.78</td>
</tr>
<tr>
<td>2</td>
<td>5.1</td>
<td>0.46</td>
<td>0.35</td>
<td>68</td>
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<td>0.76</td>
</tr>
<tr>
<td>3</td>
<td>7.5</td>
<td>0.61</td>
<td>0.37</td>
<td>40</td>
<td>0.63</td>
<td>0.59</td>
</tr>
<tr>
<td>4</td>
<td>10.4</td>
<td>0.63</td>
<td>0.39</td>
<td>33</td>
<td>0.64</td>
<td>0.57</td>
</tr>
<tr>
<td>5</td>
<td>13.0</td>
<td>0.81</td>
<td>0.41</td>
<td>3</td>
<td>0.56</td>
<td>0.47</td>
</tr>
<tr>
<td>6</td>
<td>6.8</td>
<td>0.42</td>
<td>0.36</td>
<td>74</td>
<td>0.74</td>
<td>0.79</td>
</tr>
<tr>
<td>7</td>
<td>9.7</td>
<td>0.66</td>
<td>0.35</td>
<td>28</td>
<td>0.64</td>
<td>0.62</td>
</tr>
<tr>
<td>8</td>
<td>11.3</td>
<td>0.63</td>
<td>0.40</td>
<td>37</td>
<td>0.64</td>
<td>0.61</td>
</tr>
<tr>
<td>9</td>
<td>15.2</td>
<td>0.82</td>
<td>0.37</td>
<td>4</td>
<td>-</td>
<td>0.42</td>
</tr>
</tbody>
</table>

Reverberation and speech parameters as a function of distance.

The reverberation and speech parameters as a function of distance are presented in figures 23 to 26. For EDT and T\(_{20}\), the values are averaged over the octave bands 250 to 2000 Hz. The values before and after refurbishment are shown in each figure. Measurement positions are shown in figure 22 (left).
Acoustic design of open-plan offices

Figure 23. EDT as a function of distance from sound source before and after refurbishment. Office: Vattenfall Helpdesk – Sweden.

Figure 24. T20 as a function of distance before and after refurbishment. Office: Vattenfall Helpdesk – Sweden.
Figure 25. D as a function of distance before and after refurbishment. Office: Vattenfall Helpdesk – Sweden.

Figure 26. STI measured with omni- and directional loudspeakers before and after refurbishment. Office: Vattenfall Helpdesk – Sweden.
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Sound distribution curves

The sound distribution curves for A-weighted pink noise along paths A and B according to figure 22 are shown in figures 27 and 28. Sound distribution curves before and after refurbishment are shown in each figure.

The sound power level of the omnidirectional loudspeaker used in the measurements at Vattenfall’s Helpdesk is given in table 10. The sound signal was pink noise.

Table 10. Sound power level of the omnidirectional loudspeaker. Office: Vattenfall Helpdesk – Sweden.

<table>
<thead>
<tr>
<th>Distance from sound source (m)</th>
<th>Lp - Lw (dB)</th>
<th>Path A before refurbishment</th>
<th>Path A after refurbishment</th>
<th>free field</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>-15</td>
<td>-20</td>
<td>-15</td>
<td>-15</td>
</tr>
<tr>
<td>3</td>
<td>-10</td>
<td>-15</td>
<td>-10</td>
<td>-10</td>
</tr>
<tr>
<td>4</td>
<td>-5</td>
<td>-10</td>
<td>-5</td>
<td>-5</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>-5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>0</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>7</td>
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<td>10</td>
<td>10</td>
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<tr>
<td>8</td>
<td>15</td>
<td>10</td>
<td>15</td>
<td>15</td>
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<tr>
<td>9</td>
<td>20</td>
<td>15</td>
<td>20</td>
<td>20</td>
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<tr>
<td>10</td>
<td>25</td>
<td>20</td>
<td>25</td>
<td>25</td>
</tr>
<tr>
<td>11</td>
<td>30</td>
<td>25</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>12</td>
<td>35</td>
<td>30</td>
<td>35</td>
<td>35</td>
</tr>
<tr>
<td>13</td>
<td>40</td>
<td>35</td>
<td>40</td>
<td>40</td>
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<tr>
<td>14</td>
<td>45</td>
<td>40</td>
<td>45</td>
<td>45</td>
</tr>
<tr>
<td>15</td>
<td>50</td>
<td>45</td>
<td>50</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 27. Sound distribution curves before and after refurbishment for path A. Office: Vattenfall Helpdesk – Sweden.
Figure 28. Sound distribution curves before and after refurbishment for path B. Office: Vattenfall Helpdesk – Sweden.
The effect of different evaluation intervals calculating $DL_2$ and $DL_f$ are shown in figures 29 and 30. The results for paths A and B in Figure 22 are presented both before and after refurbishment.

Figure 29. $DL_2$ for different evaluation intervals before and after refurbishment for paths A and B in figure 22. Office: Vattenfall Helpdesk – Sweden.

Figure 30. $DL_f$ for different evaluation intervals before and after refurbishment for paths A and B in figure 22. Office: Vattenfall Helpdesk – Sweden.
Frequency dependence of room acoustic parameters

The reverberation time $T_{20}$ and the speech clarity $D_{50}$ as a function of frequency are shown in Figures 31 and 32 respectively. The values are averaged over microphone positions 1 to 9 according to figure 22 (left). Results of $T_{20}$ and $D_{50}$ before and after refurbishment are presented in each figure.

**Figure 31.** Reverberation $T_{20}$ as a function of frequency before and after refurbishment. Office: Vattenfall Helpdesk – Sweden.

**Figure 32.** Speech clarity $D_{50}$ as a function of frequency before and after refurbishment. Office: Vattenfall Helpdesk – Sweden.
Background noise

Background noise was measured linearly in 1/3 octave band and as A- and C-weighted total levels. Measurements were made during normal activity with people in the room and with the room empty with the ventilation off. Measurements for normal activity with people in the room were performed during the course of two working days both before and after refurbishment. The A- and C-weighted background noise levels, averaged over positions, are given in table 11. In figure 33 the background noise levels in 1/3 octave bands are given for the cases with and without activity in the office before and after refurbishment. The results are averaged over measurements positions.


<table>
<thead>
<tr>
<th></th>
<th>Empty office before refurbishment, ventilation off</th>
<th>Normal activity, before refurbishment</th>
<th>Empty office after refurbishment, ventilation off</th>
<th>Normal activity, after refurbishment</th>
</tr>
</thead>
<tbody>
<tr>
<td>LA (dB)</td>
<td>LC (dB)</td>
<td>LA (dB)</td>
<td>LC (dB)</td>
<td>LA (dB)</td>
</tr>
<tr>
<td>33</td>
<td>50</td>
<td>51</td>
<td>58</td>
<td>28</td>
</tr>
</tbody>
</table>

Figure 33. Background noise levels (linear, 1/3 octave bands) in office with different scenarios. Office: Vattenfall Helpdesk – Sweden.

Conclusions – Vattenfall’s Helpdesk

- Generally, EDT and $T_{20}$ increase as the distance to the sound source increases.
- Room acoustic parameters $T_{20}$, $D_{50}$ and STI decreased after refurbishment.
- STI values dependent on loudspeaker directivity.
- Significant effect of the refurbishment on $D_{L2}$ and $D_{Lf}$.
- $D_{L2}$ increase slightly if the evaluation interval increases.
- $D_{Lf}$ almost independent of evaluation interval.
Acoustic design of open-plan offices

Vattenfall Finance department – Sweden

No refurbishment program was implemented. Figure 34 on the left shows the source and measurements positions for the room acoustic parameters EDT, $T_{20}$, $D_{50}$, and STI and figure 34 on the right the measuring path for the sound distribution curves.

Figure 34. The open-plan office with measuring positions (left) and measuring paths for the sound distribution curves (right). Vattenfall’s Finance department – Sweden.

Reverberation time and speech parameters

Measurement of reverberation time and speech parameters was performed according to ISO 3382 – 1 and IEC 60268-16:2003. STI was calculated from impulse response measurements without any influence of background noise.

The values for the parameters EDT, $T_{20}$ and $D$ correspond to an average for the octave bands 250 to 2000 Hz.
Table 12. Reverberation time and speech parameters measured at Vattenfall’s Finance department. EDT, T<sub>20</sub> and D are given as an average for 250 to 2000 Hz.

<table>
<thead>
<tr>
<th>Measurement position (Figure 34)</th>
<th>Distance from source (m)</th>
<th>EDT (s)</th>
<th>T20 (s)</th>
<th>D (%)</th>
<th>STI omni</th>
<th>STI dir</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>0.28</td>
<td>0.44</td>
<td>91</td>
<td>0.85</td>
<td>0.87</td>
</tr>
<tr>
<td>2</td>
<td>4.6</td>
<td>0.37</td>
<td>0.50</td>
<td>82</td>
<td>0.78</td>
<td>0.79</td>
</tr>
<tr>
<td>3</td>
<td>7.2</td>
<td>0.38</td>
<td>0.52</td>
<td>82</td>
<td>0.79</td>
<td>0.83</td>
</tr>
<tr>
<td>4</td>
<td>9.5</td>
<td>0.62</td>
<td>0.57</td>
<td>59</td>
<td>0.71</td>
<td>0.71</td>
</tr>
<tr>
<td>5</td>
<td>12.1</td>
<td>0.60</td>
<td>0.55</td>
<td>66</td>
<td>0.72</td>
<td>0.73</td>
</tr>
<tr>
<td>6</td>
<td>14.3</td>
<td>0.64</td>
<td>0.56</td>
<td>60</td>
<td>0.69</td>
<td>0.69</td>
</tr>
<tr>
<td>7</td>
<td>16.8</td>
<td>0.57</td>
<td>0.58</td>
<td>53</td>
<td>0.70</td>
<td>0.71</td>
</tr>
<tr>
<td>8</td>
<td>9.1</td>
<td>0.46</td>
<td>0.54</td>
<td>77</td>
<td>0.77</td>
<td>0.81</td>
</tr>
<tr>
<td>9</td>
<td>11.8</td>
<td>0.41</td>
<td>0.54</td>
<td>85</td>
<td>0.78</td>
<td>0.83</td>
</tr>
<tr>
<td>10</td>
<td>13.2</td>
<td>0.50</td>
<td>0.58</td>
<td>70</td>
<td>0.74</td>
<td>0.74</td>
</tr>
<tr>
<td>11</td>
<td>19.1</td>
<td>0.51</td>
<td>0.55</td>
<td>71</td>
<td>0.74</td>
<td>0.76</td>
</tr>
</tbody>
</table>

Reverberation and speech parameters as a function of distance.

The reverberation and speech parameters as a function of distance are presented in figures 35 to 38. For EDT and T<sub>20</sub> the values are averaged over the octave bands 250 to 2000 Hz. Measurement positions are shown in figure 34 (left).

![Figure 35. EDT as a function of distance from sound source. Office: Vattenfall Finance – Sweden.](image-url)
Acoustic design of open-plan offices

Figure 36. $T_{20}$ as a function of distance from sound source. Office: Vattenfall Finance – Sweden.

Figure 37. $D$ as a function of distance from sound source. Office: Vattenfall Finance – Sweden.
Figure 38. STI measured with omni- and directional loudspeaker. Office: Vattenfall Finance – Sweden.

Sound distribution curves

The sound distribution curves for A-weighted pink noise along paths A and B according to figure 34 are shown in figure 39.

The sound power level of the omnidirectional loudspeaker used in the measurements at Vattenfall’s Finance department is given in table 13. The sound signal was pink noise.


<table>
<thead>
<tr>
<th>Sound power level, dB rel. $10^{12}$ watt</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>97,5</th>
<th>107,8</th>
</tr>
</thead>
<tbody>
<tr>
<td>125</td>
<td>103,3</td>
<td>105,2</td>
<td>103,9</td>
<td>103,2</td>
<td>100,5</td>
<td>97,5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The effects of different evaluation intervals calculating $DL_2$ and $DL_4$ are shown in figures 40 and 41. The results for paths A and B are presented.
Acoustic design of open-plan offices

Figure 41. DLf for different evaluation intervals for path A and B in figure 34. Office: Vattenfall Finance – Sweden.

Frequency dependence of room acoustic parameters

The reverberation time $T_{20}$ and the speech clarity $D_{50}$ as a function of frequency are shown in Figures 42 and 43 respectively. The values are averaged over microphone positions 1 to 11 according to figure 34 (left).

Figure 42. Reverberation time $T_{20}$ as a function of frequency. Office: Vattenfall Finance – Sweden.
Background noise

Background noise was measured linearly in 1/3 octave band and as A- and C-weighted total levels. Measurements were made during normal activity with people in the room and with the room empty with the ventilation off. Measurements for normal activity with people in the room were performed during the course of two working days.

The A- and C-weighted background noise levels, averaged over positions, are given in table 14. In figure 44 the background noise levels in 1/3 octave bands are given for the cases with and without activity in the office. The results are averaged over measurements positions.

<table>
<thead>
<tr>
<th>Empty office, ventilation off</th>
<th>Normal activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_A (dB)</td>
<td>L_C (dB)</td>
</tr>
<tr>
<td>29</td>
<td>46</td>
</tr>
<tr>
<td>L_A (dB)</td>
<td>L_C (dB)</td>
</tr>
<tr>
<td>48</td>
<td>56</td>
</tr>
</tbody>
</table>
Conclusions – Vattenfall’s Finance department

- Generally, EDT and $T_{20}$ increase as the distance to the sound source increases.
- STI measured with omnidirectional and directional loudspeaker gives similar results.
- $DL_2$ increases slightly if the evaluation interval increases.
- $DL_f$ almost independent of evaluation interval.
Statoil – Norway

No refurbishment programme was implemented. Figure 45 shows the source and measurements paths. Two sound screens were included in path B.

![Diagram of open-plan office with measuring positions and paths]

Figure 45. The open-plan office with measuring positions and measuring paths. Office: Statoil – Norway.

Reverberation time and speech parameters

Measurement of reverberation time and speech parameters was performed according to ISO 3382 – 1, IEC 60268-16:2003, ANSI 3.5-1997 and ASTM E 1130-02. STI and SII were calculated from impulse response measurements with and without the influence of background noise. The effect of background noise was calculated with the software WinMLS 2004. In this calculation the background noise levels in the empty office were used and a speech level of 60 dB(A) at 1 metre.

The effect of using loudspeakers with different directivity when measuring STI and SII is illustrated.

In Figure 45, measurement positions 1 to 8 are in direction A, and 9 to 15 in direction B.

The results are presented in tables 15 and 16 respectively. The values for the parameters EDT, $T_{20}$ and D correspond to an average for the octave bands 250 to 2000 Hz.
Table 15. EDT, $T_{20}$ and D are given as average for 250 to 2000 Hz. No influence of background noise in the parameters. Office: Statoil – Norway.

<table>
<thead>
<tr>
<th>Measurement position (Figure 45)</th>
<th>Distance from source (m)</th>
<th>EDT (s)</th>
<th>$T_{20}$ (s)</th>
<th>D (%)</th>
<th>STI omni</th>
<th>STI dir</th>
<th>SII omni</th>
<th>SII aculab</th>
<th>PI omni (%)</th>
<th>PI aculab (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6</td>
<td>0.36</td>
<td>0.46</td>
<td>87</td>
<td>0.81</td>
<td>0.84</td>
<td>0.93</td>
<td>0.94</td>
<td>7.4</td>
<td>6.3</td>
</tr>
<tr>
<td>2</td>
<td>4.8</td>
<td>0.44</td>
<td>0.45</td>
<td>79</td>
<td>0.78</td>
<td>0.80</td>
<td>0.94</td>
<td>0.94</td>
<td>6.0</td>
<td>5.6</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>0.45</td>
<td>0.53</td>
<td>79</td>
<td>0.77</td>
<td>0.80</td>
<td>0.95</td>
<td>0.94</td>
<td>5.3</td>
<td>5.8</td>
</tr>
<tr>
<td>4</td>
<td>9.4</td>
<td>0.45</td>
<td>0.53</td>
<td>79</td>
<td>0.76</td>
<td>0.78</td>
<td>0.88</td>
<td>0.92</td>
<td>11.9</td>
<td>7.7</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
<td>0.53</td>
<td>0.52</td>
<td>67</td>
<td>0.73</td>
<td>0.75</td>
<td>0.90</td>
<td>0.91</td>
<td>10.0</td>
<td>9.5</td>
</tr>
<tr>
<td>6</td>
<td>15.4</td>
<td>0.60</td>
<td>0.51</td>
<td>61</td>
<td>0.71</td>
<td>0.73</td>
<td>0.85</td>
<td>0.90</td>
<td>14.6</td>
<td>9.9</td>
</tr>
<tr>
<td>7</td>
<td>16.8</td>
<td>0.53</td>
<td>0.55</td>
<td>73</td>
<td>0.73</td>
<td>0.77</td>
<td>0.83</td>
<td>0.87</td>
<td>16.5</td>
<td>13.2</td>
</tr>
<tr>
<td>8</td>
<td>19.0</td>
<td>0.51</td>
<td>0.55</td>
<td>68</td>
<td>0.73</td>
<td>0.76</td>
<td>0.81</td>
<td>0.85</td>
<td>19.1</td>
<td>15.3</td>
</tr>
<tr>
<td>9</td>
<td>2.6</td>
<td>0.25</td>
<td>0.38</td>
<td>94</td>
<td>0.87</td>
<td>0.92</td>
<td>0.92</td>
<td>0.93</td>
<td>7.9</td>
<td>7.5</td>
</tr>
<tr>
<td>10</td>
<td>3.9</td>
<td>0.41</td>
<td>0.38</td>
<td>83</td>
<td>0.81</td>
<td>0.84</td>
<td>0.93</td>
<td>0.93</td>
<td>7.4</td>
<td>7.0</td>
</tr>
<tr>
<td>11</td>
<td>5.8</td>
<td>0.47</td>
<td>0.50</td>
<td>80</td>
<td>0.77</td>
<td>0.80</td>
<td>0.93</td>
<td>0.94</td>
<td>6.8</td>
<td>5.7</td>
</tr>
<tr>
<td>12</td>
<td>11.8</td>
<td>0.67</td>
<td>0.58</td>
<td>64</td>
<td>0.71</td>
<td>0.74</td>
<td>0.84</td>
<td>0.87</td>
<td>15.7</td>
<td>12.9</td>
</tr>
<tr>
<td>13</td>
<td>14.7</td>
<td>0.68</td>
<td>0.54</td>
<td>61</td>
<td>0.70</td>
<td>0.74</td>
<td>0.88</td>
<td>0.87</td>
<td>12.4</td>
<td>12.7</td>
</tr>
<tr>
<td>14</td>
<td>17.3</td>
<td>0.60</td>
<td>0.59</td>
<td>66</td>
<td>0.72</td>
<td>0.73</td>
<td>0.86</td>
<td>0.82</td>
<td>14.0</td>
<td>18.0</td>
</tr>
<tr>
<td>15</td>
<td>18.3</td>
<td>0.59</td>
<td>0.56</td>
<td>62</td>
<td>0.70</td>
<td>0.73</td>
<td>0.86</td>
<td>0.86</td>
<td>14.5</td>
<td>13.5</td>
</tr>
</tbody>
</table>

Table 16. STI, SII and PI calculated including the background noise in the empty office i.e. with ventilation noise on but without people in the room. Office: Statoil – Norway.

<table>
<thead>
<tr>
<th>Measurement position (Figure 45)</th>
<th>Distance from source (m)</th>
<th>STI omni with background noise</th>
<th>STI dir with background noise</th>
<th>SII omni with background noise</th>
<th>SII aculab with background noise</th>
<th>PI omni (%) with background noise</th>
<th>PI aculab (%) with background noise</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6</td>
<td>0.78</td>
<td>0.80</td>
<td>0.92</td>
<td>0.93</td>
<td>6.9</td>
<td>8.0</td>
</tr>
<tr>
<td>2</td>
<td>4.8</td>
<td>0.73</td>
<td>0.74</td>
<td>0.94</td>
<td>0.94</td>
<td>6.2</td>
<td>6.5</td>
</tr>
<tr>
<td>3</td>
<td>7.0</td>
<td>0.70</td>
<td>0.72</td>
<td>0.92</td>
<td>0.91</td>
<td>8.9</td>
<td>7.9</td>
</tr>
<tr>
<td>4</td>
<td>9.4</td>
<td>0.68</td>
<td>0.66</td>
<td>0.86</td>
<td>0.89</td>
<td>11.2</td>
<td>14.3</td>
</tr>
<tr>
<td>5</td>
<td>12.5</td>
<td>0.62</td>
<td>0.61</td>
<td>0.85</td>
<td>0.84</td>
<td>15.6</td>
<td>14.8</td>
</tr>
<tr>
<td>6</td>
<td>15.4</td>
<td>0.56</td>
<td>0.56</td>
<td>0.80</td>
<td>0.83</td>
<td>17.0</td>
<td>19.9</td>
</tr>
<tr>
<td>7</td>
<td>16.8</td>
<td>0.57</td>
<td>0.57</td>
<td>0.79</td>
<td>0.80</td>
<td>19.7</td>
<td>21.2</td>
</tr>
<tr>
<td>8</td>
<td>19.0</td>
<td>0.53</td>
<td>0.52</td>
<td>0.76</td>
<td>0.76</td>
<td>23.8</td>
<td>24.5</td>
</tr>
<tr>
<td>9</td>
<td>2.6</td>
<td>0.87</td>
<td>0.91</td>
<td>0.92</td>
<td>0.92</td>
<td>7.7</td>
<td>8.0</td>
</tr>
<tr>
<td>10</td>
<td>3.9</td>
<td>0.79</td>
<td>0.82</td>
<td>0.92</td>
<td>0.93</td>
<td>7.2</td>
<td>7.5</td>
</tr>
<tr>
<td>11</td>
<td>5.8</td>
<td>0.70</td>
<td>0.71</td>
<td>0.91</td>
<td>0.91</td>
<td>8.7</td>
<td>8.8</td>
</tr>
<tr>
<td>12</td>
<td>11.8</td>
<td>0.57</td>
<td>0.56</td>
<td>0.79</td>
<td>0.80</td>
<td>19.8</td>
<td>20.9</td>
</tr>
<tr>
<td>13</td>
<td>14.7</td>
<td>0.54</td>
<td>0.53</td>
<td>0.81</td>
<td>0.80</td>
<td>19.8</td>
<td>18.6</td>
</tr>
<tr>
<td>14</td>
<td>17.3</td>
<td>0.52</td>
<td>0.47</td>
<td>0.79</td>
<td>0.76</td>
<td>23.7</td>
<td>20.8</td>
</tr>
<tr>
<td>15</td>
<td>18.3</td>
<td>0.52</td>
<td>0.49</td>
<td>0.80</td>
<td>0.79</td>
<td>20.8</td>
<td>19.6</td>
</tr>
</tbody>
</table>
Reverberation and speech parameters as a function of distance.

The parameters EDT, $T_{20}$ and D as a function of distance are presented in Figures 46 to 48. The values for STI, SII and PI measured at the work stations for the positions 1 to 7 are presented in Figures 49 to 53. Results with and without background noise are shown for the latter parameters.

![Figure 46. EDT as a function of distance from the sound source measured along paths A and B. Office: Statoil – Norway.](image)

![Figure 47. $T_{20}$ as a function of distance from the sound source measured along paths A and B. Office: Statoil – Norway.](image)
Figure 48. D as a function of distance from the sound source measured along paths A and B. Office: Statoil – Norway.

Figure 49. STI as a function of distance from the sound source measured along path A. Measurements were performed with and without background noise (ventilation) and with an omnidirectional and a directional loudspeaker. Office: Statoil – Norway.
Figure 50. STI as a function of distance from the sound source measured along path B. Measurements were performed with and without background noise (ventilation) and with an omnidirectional and a directional loudspeaker. Office: Statoil – Norway.
Figure 51. SII as a function of distance from the sound source measured along path A. Measurements were performed with and without background noise (ventilation) and with an omnidirectional and a directional (Aculab) loudspeaker. Office: Statoil – Norway.
Figure 52. SII as a function of distance from the sound source measured along path B. Measurements were performed with and without background noise (ventilation) and with an omnidirectional and a directional (Aculab) loudspeaker. Office: Statoil – Norway.
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Figure 53. PI as a function of distance from the sound source measured along paths A and B. Measurements were performed with and without background noise (ventilation). Aculab loudspeaker was used as a sound source. Office: Statoil – Norway.

Sound distribution curves

The sound distribution curves for A-weighted pink noise along paths A and B according to Figure 45 are shown in Figure 54.
The sound power level of the omnidirectional loudspeaker used in the measurements at Statoil is given in Table 17. The sound signal was pink noise.

Table 17. Sound power level of the omnidirectional loudspeaker. Office: Statoil – Norway.

<table>
<thead>
<tr>
<th>Sound power level, dB rel. $10^{12}$ watt</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>Hz</th>
<th>dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td>99,1</td>
<td>104,6</td>
<td>102,1</td>
<td>98,0</td>
<td>98,7</td>
<td>91,4</td>
<td></td>
<td></td>
<td>104,7</td>
</tr>
</tbody>
</table>
Acoustic design of open-plan offices

Figure 54. Sound distribution curves for paths A and path B in figure 45. The location of the screens in path B is marked. Office: Statoil – Norway.

The effect of different evaluation intervals calculating DL₂ and DL₄ is shown in Figure 55 and 56. The results for paths A and B are presented.
Figure 55. $DL_2$ for different evaluation intervals for paths A and B in figure 45. Office: Statoil – Norway.

Figure 56. $DL_f$ for different evaluation intervals for paths A and B in figure 45. Office: Statoil – Norway.
Frequency dependence of room acoustic parameters

The reverberation time $T_{20}$ and the speech clarity $D_{50}$ as a function of frequency are shown in Figures 57 and 58 respectively. The values are averaged over microphone positions 1 to 15, see table 15.

Figure 59 shows the sound distribution curves for the octave bands 125 Hz to 4000 Hz for path B.

It can be clearly seen that the effect of the screens is greatest from 500 Hz to 4000 Hz. The low frequencies 125 and 250 Hz are hardly influenced by the screens at all.

![Graph of $T_{20}$ vs Frequency](image)

*Figure 57. Reverberation time $T_{20}$ as a function of frequency. Office: Statoil – Norway.*
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Figure 59. Frequency dependence of sound distribution curves measured along the path with screens i.e. path B in figure 45. Office: Statoil – Norway.
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Figure 58. Speech clarity $D_{50}$ as a function of frequency. Office: Statoil – Norway.
Background noise

Background noise was measured linearly in 1/3 octave band and as A- and C-weighted total levels. Measurements were made with the room empty and with the ventilation on. The A- and C-weighted background noise levels, averaged over positions, are given in table 18. Figure 60 shows the background noise levels in 1/3 octave bands averaged over measurements positions.

Table 18. A- and C-weighted background noise levels. Office: Statoil – Norway

<table>
<thead>
<tr>
<th>Empty office, ventilation on</th>
<th>$L_A$ (dB)</th>
<th>$L_C$ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>28</td>
<td>44</td>
</tr>
</tbody>
</table>

![Figure 60. Background noise levels (linear, 1/3 octave bands) in empty office with ventilation on. Office: Statoil – Norway.](image)

Conclusions – Statoil

- Generally, EDT and $T_{20}$ increase as the distance to the sound source increases.
- Omnidirectional loudspeaker gives slightly lower STI values than directional loudspeaker.
- Ventilation noise reduces both STI and SII. STI seems to be more sensitive to the background noise.
• $DL_2$ increases slightly if the evaluation interval increases.
• $DL_f$ almost independent of evaluation interval.

**Association of Finnish Civil Engineers RIL – Finland**

No refurbishment programme was implemented. Figure 61 shows the part of the office that was investigated. Room acoustic parameters and sound distribution curves were measured at the same positions i.e. positions 1 to 4 in Figure 60.

![Figure 61. The open-plan office with measuring positions 1 to 4. Using the directional loudspeaker the orientation corresponds to a working person. Office: RIL – Finland.](image)

**Reverberation time and speech parameters**

Measurement of reverberation time and speech parameters was performed according to ISO 3382 – 1, IEC 60268-16:2003, ANSI 3.5-1997 and ASTM E 1130-02.

STI and SII were calculated from impulse response measurements with and without the influence of background noise.

The effect of using loudspeakers with different directivity when measuring STI and SII is illustrated.

The results of the room acoustic measurements are presented in tables 19 and 20. The values for the parameters EDT, $T_{20}$ and $D$ correspond to an average for the octave bands 250 to 2000 Hz.
Reverberation and speech parameters as a function of distance.

The parameters EDT, $T_{20}$ and D as a function of distance are presented in Figures 62 to 64. The values for STI, SII and PI measured at the work stations at positions 1 to 4 are presented in Figures 65 to 67. Results with and without background noise are shown for the latter parameters.

Table 19. EDT, $T_{20}$ and D are given as an average for 250 to 2000 Hz. No influence of background noise in the parameters. Office: RIL – Finland.

<table>
<thead>
<tr>
<th>Measurement position (Figure 61)</th>
<th>Distance from source (m)</th>
<th>EDT (s)</th>
<th>$T_{20}$ (s)</th>
<th>D (%)</th>
<th>STI omni</th>
<th>STI dir</th>
<th>STI Aculab</th>
<th>SII omni</th>
<th>SII Aculab</th>
<th>PI omni (%)</th>
<th>PI Aculab (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.9</td>
<td>0.40</td>
<td>0.56</td>
<td>84</td>
<td>0.71</td>
<td>0.61</td>
<td>0.50</td>
<td>0.92</td>
<td>0.90</td>
<td>7.8</td>
<td>10.1</td>
</tr>
<tr>
<td>2</td>
<td>7.8</td>
<td>0.67</td>
<td>0.59</td>
<td>61</td>
<td>0.55</td>
<td>0.48</td>
<td>0.43</td>
<td>0.92</td>
<td>0.81</td>
<td>7.7</td>
<td>18.7</td>
</tr>
<tr>
<td>3</td>
<td>11.4</td>
<td>0.74</td>
<td>0.63</td>
<td>42</td>
<td>0.47</td>
<td>0.41</td>
<td>0.36</td>
<td>0.83</td>
<td>0.70</td>
<td>17.2</td>
<td>30.1</td>
</tr>
<tr>
<td>4</td>
<td>13.6</td>
<td>0.83</td>
<td>0.61</td>
<td>47</td>
<td>0.46</td>
<td>0.42</td>
<td>0.33</td>
<td>0.79</td>
<td>0.69</td>
<td>20.8</td>
<td>30.8</td>
</tr>
</tbody>
</table>

Table 20. STI, SII and PI were calculated including background noise in the empty office i.e. with ventilation noise on but without people in the room. Office: RIL – Finland.

<table>
<thead>
<tr>
<th>Measurement position (Figure 61)</th>
<th>Distance from source (m)</th>
<th>STI omni</th>
<th>STI dir</th>
<th>STI Aculab</th>
<th>SII omni</th>
<th>SII Aculab</th>
<th>PI omni (%)</th>
<th>PI Aculab (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.89</td>
<td>0.65</td>
<td>0.51</td>
<td>0.51</td>
<td>0.79</td>
<td>0.65</td>
<td>20.8</td>
<td>35.1</td>
</tr>
<tr>
<td>2</td>
<td>7.76</td>
<td>0.49</td>
<td>0.38</td>
<td>0.39</td>
<td>0.67</td>
<td>0.54</td>
<td>33.2</td>
<td>46.1</td>
</tr>
<tr>
<td>3</td>
<td>11.35</td>
<td>0.26</td>
<td>0.23</td>
<td>0.23</td>
<td>0.49</td>
<td>0.35</td>
<td>50.9</td>
<td>64.8</td>
</tr>
<tr>
<td>4</td>
<td>13.62</td>
<td>0.24</td>
<td>0.27</td>
<td>0.20</td>
<td>0.42</td>
<td>0.31</td>
<td>57.8</td>
<td>68.6</td>
</tr>
</tbody>
</table>

Figure 62. EDT as a function of distance from the sound source measured at positions 1 to 4. Office: RIL – Finland.
Figure 63. $T_{20}$ as a function of distance from the sound source measured at positions 1 to 4.
Office: RIL – Finland.

Figure 64. $D$ as a function of distance from the sound source measured at positions 1 to 4.
Office: RIL – Finland.
Figure 65. STI as a function of distance from the sound source measured at positions 1 to 4. Measurements were performed with and without background noise (ventilation) and with an omnidirectional and a directional loudspeaker. Office: RIL – Finland.

Figure 66. SII as a function of distance from the sound source measured at positions 1 to 4. Measurements were performed with and without background noise (ventilation) and with an omnidirectional and a directional loudspeaker (Aculab). Office: RIL – Finland.
Sound distribution curves

The sound distribution curve for A-weighted pink noise along positions 1 to 4 in Figure 61 are shown in figure 68.

The sound power level of the omnidirectional loudspeaker used in the measurements at Association of Finnish Civil Engineers RIL is shown in table 21. The sound power levels are estimates based on the sound pressure level at 1 metre measured on site. The sound signal was pink noise.

Table 21. Sound power level of the omnidirectional loudspeaker. Office: RIL – Finland.

<table>
<thead>
<tr>
<th>Frequency (Hz)</th>
<th>125</th>
<th>250</th>
<th>500</th>
<th>1000</th>
<th>2000</th>
<th>4000</th>
<th>dB(A)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>100.7</td>
<td>100.0</td>
<td>93.3</td>
<td>87.6</td>
<td>88.3</td>
<td>90.4</td>
<td>97.4</td>
</tr>
</tbody>
</table>
Figure 68. Sound distribution curves for path along positions 1 to 4 in figure 61. Office: RIL – Finland.

The effect of different evaluation intervals calculating DL$_2$ and DL$_f$ is shown in Figures 68 and 69.

Figure 69. DL$_2$ for different evaluation intervals for the path along positions 1 to 4 in Figure 61. Office: RIL – Finland.
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Figure 70. DL₂ for different evaluation intervals for the path along positions 1 to 4 in Figure 61. Office: RIL – Finland.

Frequency dependence of room acoustic parameters

The reverberation time T₂₀ and the speech clarity D₅₀ as a function of frequency are shown in Figures 71 and 72, respectively. The values are averaged over microphone positions 1 to 4 in Figure 61.

Figure 71. Reverberation time T₂₀ as a function of frequency. Office: RIL – Finland.
Background noise

Background noise was measured linearly in 1/3 octave band and as A- and C-weighted total levels. Measurements were made during normal activity with people in the room and ventilation on and in empty room with ventilation on and off, respectively.

The A- and C-weighted background noise levels, averaged over positions 1 to 4 in Figure 61, are given in table 22.

In Figure 73 the background noise levels in 1/3 octave bands are given for normal activity and ventilation on, empty room with ventilation on, and empty room with ventilation off. The results are averaged over positions.

<table>
<thead>
<tr>
<th>Empty office, ventilation off</th>
<th>Empty office, ventilation on</th>
<th>Normal activity, ventilation on</th>
</tr>
</thead>
<tbody>
<tr>
<td>L_A (dB)</td>
<td>L_C (dB)</td>
<td>L_A (dB)</td>
</tr>
<tr>
<td>33.0</td>
<td>48.5</td>
<td>42.4</td>
</tr>
</tbody>
</table>

Table 22. A- and C-weighted background noise levels. Office: RIL – Finland.
Conclusions - Association of Finnish Civil Engineers. RIL

- Generally, EDT and $T_{20}$ increase as the distance to the sound source increases.
- Omnidirectional loudspeaker gives slightly higher values for STI and SII than directional loudspeaker. In this case the directional loudspeaker was not oriented with the main loop in the measurements path.
- Ventilation noise reduces both STI and SII. SII seems to more sensitive to background noise than STI.
- $DL_2$ and $DL_4$ almost independent of evaluation interval.

4. Summary and comparison of measurements

The reverberation time measurements such as EDT and $T_{20}$ are sensitive to the acoustic refurbishment. However, both before and after refurbishment, the reverberation time as a parameter is very dependent on the distance from the sound source. The tendency is for the reverberation time to increase as a function of the distance from the sound source. Even though this could be used in a description of the acoustic conditions, it seems more appropriate to use parameters and measurement procedure directly related to sound distribution curves.

Besides reverberation time parameters, several room acoustic parameters have been tested in this study in order to investigate their suitability in a characterisation of the acoustic conditions in open-plan offices. The speech intelligibility parameters STI and SII were measured both with
directional loudspeakers according to the directives in corresponding standards, and with an omnidirectional loudspeaker.

The following section summarizes the behaviour of the measurement parameters relating to, reverberation times, speech intelligibility and sound distribution parameters.

Reverberation time parameters:

The reverberation time parameters EDT and $T_{20}$ are presented as a function of distance from the sound source in Figures 73 and 74, respectively. The parameters are averaged over the octave band frequencies 250 to 2000 Hz. All offices are shown including the two refurbishment cases. There is a clear tendency of increased reverberation time with increased distance from sound source.

![Figure 73. EDT as a function of distance from sound source. All offices are included.](image)
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Figure 74. T20 as a function of distance from sound source. All offices included.

The values of EDT, T_{20} and D averaged over the octave band frequencies 250 to 2000 Hz and over positions are listed in table 23 for all offices.

Table 23. EDT, T_{20} and D. The values are averaged over the octave bands 250 to 2000 Hz and over the measurement positions. No influence of background noise in the values.

<table>
<thead>
<tr>
<th>Office</th>
<th>EDT (s) Before refurbishment</th>
<th>EDT (s) After refurbishment</th>
<th>T20 (s) Before refurbishment</th>
<th>T20 (s) After refurbishment</th>
<th>D (dB) Before refurbishment</th>
<th>D (dB) After refurbishment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dicentia</td>
<td>0.49</td>
<td>0.34</td>
<td>0.52</td>
<td>0.40</td>
<td>77</td>
<td>89</td>
</tr>
<tr>
<td>Vattenfall Helpdesk</td>
<td>0.44</td>
<td>0.55</td>
<td>0.49</td>
<td>0.37</td>
<td>75</td>
<td>41</td>
</tr>
<tr>
<td>Vattenfall Helpdesk, after refurbishment</td>
<td>-</td>
<td>0.53</td>
<td>-</td>
<td>72</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vattenfall Finance</td>
<td>0.49</td>
<td>-</td>
<td>0.53</td>
<td>-</td>
<td>72</td>
<td>-</td>
</tr>
<tr>
<td>Statoil Finance</td>
<td>0.50</td>
<td>-</td>
<td>0.51</td>
<td>-</td>
<td>74</td>
<td>-</td>
</tr>
<tr>
<td>RIL</td>
<td>0.66</td>
<td>-</td>
<td>0.60</td>
<td>-</td>
<td>59</td>
<td>-</td>
</tr>
</tbody>
</table>

Speech intelligibility parameters:

STI and SII were measured with both an omnidirectional and a directional loudspeaker. Whatever the loudspeaker used, there is a systematic difference between STI and SII, showing lower values for STI. Both STI and SII are dependent on the type of loudspeaker. A directional loudspeaker gives higher values than an omnidirectional one. However, the loudspeaker
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according to ASTM E 1179 for SII measurements gives values quite similar to those relating to an omnidirectional loudspeaker. The only exception from these statements is the result from the Finnish office (RIL). However, in this case, the directional loudspeaker was not directed in the measurement path, thereby redirecting the main loop of the directional loudspeaker. In the other offices the directional loudspeaker was directed with the main loop in the measuring path. This result shows the importance of well-specified measurement procedures in order to be able to compare results from different offices.

In Figures 75 and 76 the STI and SII values are shown as a function of the distance from the sound source. The STI was measured with the directional loudspeaker in accordance with IEC 60 268-16 and SII with the Aculab loudspeaker in accordance with ASTM E 1179-87.

![Figure 75. STI in all the offices measured along work stations and without ventilation noise.](image-url)
The STI and SII values averaged over positions are given in Table 24.

Table 24. STI and SII for all offices. The values are averaged over measurement positions.

<table>
<thead>
<tr>
<th>Office</th>
<th>STI (SII) Before refurbishment, no influence of background noise</th>
<th>STI (SII) After refurbishment, no influence of background noise</th>
<th>STI (SII) Ventilation off</th>
<th>STI (SII) Ventilation on</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dicentia</td>
<td>0.73 (0.89)</td>
<td>0.72 (-)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vattenfall Helpdesk</td>
<td>0.78 (-)</td>
<td>0.63 (-)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Vattenfall Finance</td>
<td>0.76 (-)</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Statoil</td>
<td>-</td>
<td>-</td>
<td>0.78 (0.90)</td>
<td>0.64 (0.85)</td>
</tr>
<tr>
<td>RIL</td>
<td>-</td>
<td>-</td>
<td>0.48 (0.78)</td>
<td>0.35 (0.46)</td>
</tr>
</tbody>
</table>

Figure 76. SII measured along work stations and without ventilation noise.
The Privacy Index as a function of distance from sound source is presented in Figure 77.

![Figure 77. Privacy Index PI as a function of distance from sound source.](image)

It is noticeable that the Privacy index, calculated by equation 2, in none of the offices reaches values above 80%, a level which is considered as ‘acceptable’ speech privacy (Bradley 2003). In the type of offices included in this study it is questionable if it is a realistic design goal to try to achieve privacy between closely-situated work stations.

**Sound distribution parameters:**

The sound distribution curves for all offices including the cases after refurbishment are presented in Figure 78. The values correspond to A-weighted sound pressure levels.
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Figure 78. Sound distribution curves for all offices.

From these curves, the sound distribution parameters $DL_2$ and $DL_f$ have been calculated by equations 2 and 3 according to ISO 14257. $DL_2$ is estimated by the slope of a regression line over the range from 3 to 16 metres. In some of the offices a slightly shorter evaluation interval had to be used due to the size and shape of the offices (see figure 78). Normally the slope becomes steeper at greater distances due to the scattering effect of furnishings. Consequently, the $DL_2$ value will depend on the evaluation interval. In most offices an interval of 3 to 16 metres seems appropriate from a practical point of view. $DL_f$ was calculated as an average over the measurement positions and for the same distance as $DL_2$. The $DL_2$ and $DL_f$ values are presented in table 25.
Table 25. DL₂ and DL₆ evaluated over the range 3 to 16 meters from the sound source position.

<table>
<thead>
<tr>
<th>Office scenario</th>
<th>DL₂ (dB)</th>
<th>DL₆ (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dicentia, before refurbishment, along path A, see figure 8</td>
<td>4.7</td>
<td>8.4</td>
</tr>
<tr>
<td>Dicentia, after refurbishment, along path A, see figure 8</td>
<td>6.2</td>
<td>4.4</td>
</tr>
<tr>
<td>Dicentia, before refurbishment, along path B, see figure 8</td>
<td>5.8</td>
<td>6.8</td>
</tr>
<tr>
<td>Dicentia, after refurbishment, along path B, see figure 8</td>
<td>7.6</td>
<td>1.2</td>
</tr>
<tr>
<td>Vattenfall Helpdesk, before refurbishment, along path A, see figure 22</td>
<td>4.8</td>
<td>7.2</td>
</tr>
<tr>
<td>Vattenfall Helpdesk, after refurbishment, along path A, see figure 22</td>
<td>8.2</td>
<td>0.0</td>
</tr>
<tr>
<td>Vattenfall Helpdesk, before refurbishment, along path B, see figure 22</td>
<td>5.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Vattenfall Helpdesk, after refurbishment, along path B, see figure 22</td>
<td>8.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Vattenfall Finance department; along path A, see figure 34</td>
<td>5.5</td>
<td>9.1</td>
</tr>
<tr>
<td>Vattenfall Finance department, along path B, see figure 34</td>
<td>5.8</td>
<td>6.5</td>
</tr>
<tr>
<td>Statoil, along path A, see figure 22</td>
<td>5.7</td>
<td>7.4</td>
</tr>
<tr>
<td>Statoil, along path B, see figure 22</td>
<td>6.2</td>
<td>3.9</td>
</tr>
<tr>
<td>RIL</td>
<td>5.4</td>
<td>5.1</td>
</tr>
</tbody>
</table>

The effect of the refurbishment at the Helpdesk office at Vattenfall and at Dicentia has clearly influenced both DL₂ and DL₆. The significant effect on DL₆ is noticeable. The parameter DL₆ is related to the decrease in sound pressure levels in the offices.

Knowing DL₂ and DL₆ and specifying a target value for acceptable speech level L_c at a work station, the distance needed between the person talking and the work station is given as

$$d_c = 10^{0.3(L_{speech} + DL_6 - L_c)/DL_2}$$  \( (4) \)

where d_c is the distance of comfort, L_{speech} is the level of speech and L_c is the acceptable speech level at the work station.

This (comfort) distance gives an indication of how to proceed in the acoustic design work relating to absorbent materials, screens, furnishing etc. and acts as guidance for the architects. By defining fixed values of L_{speech} and L_c, equation 4 is a way of converting DL₂ and DL₆ to a one-figure value.

An example of how to use equation 1 is given in table 26. In this example the target value is 35 dB(A) and the speech level 55 dB(A). The formula 4 is valid for the evaluation distance 3 to 16 metres and the values of DL₂ and DL₆ are in accordance with the calculations in table 25 above.
Table 26. The values in the table show the distance needed to reach a speech level of 35 dB(A) at a speech level of 55 dB(A) at 1 metre. The DL\textsubscript{2} and DL\textsubscript{f} values correspond to the Dicentia and Vattenfall Helpdesk offices before and after refurbishment as shown in table 25. The evaluation interval 3 to 16 metres has been used in the calculation of DL\textsubscript{2} and DL\textsubscript{f}.

<table>
<thead>
<tr>
<th>Offices</th>
<th>Distance to reach a speech level of 35 dB(A) at a speech level of 55 dB(A) at 1 metre</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dicentia before refurbishment at work stations (path B)</td>
<td>&gt; 16 m (eq. 4 gives 24 m)*</td>
</tr>
<tr>
<td>Dicentia after refurbishment at work stations (path B)</td>
<td>7 m</td>
</tr>
<tr>
<td>Vattenfall Helpdesk before refurbishment at work stations (path A)</td>
<td>&gt; 16 m (eq. 4 gives 50 m)*</td>
</tr>
<tr>
<td>Vattenfall Helpdesk after refurbishment at work stations (path A)</td>
<td>5 m</td>
</tr>
</tbody>
</table>

* The valid range of equation 4 is limited to the range used for calculation of DL\textsubscript{2} and DL\textsubscript{f}. If equation 4 gives a value outside this range, this value is often an over-estimate of the distance due to the increased slope of the sound distribution curves at greater distances, see figure 78.

5. Conclusion of questionnaires and measurements

Questionnaires

As mentioned above, the effect of the reduction of sound disturbance due to acoustic treatment of the open-plan offices (the helpdesk office at Vattenfall and Dicentia) is quite considerable. Even though the number of respondents was quite limited, the answers do indicate a change, which leads to the possible conclusion that the acoustic treatment has had a positive impact on the acoustic climate.

One interesting discovery occurs when correlating question no. 47 with 37.5. and no. 48 with 37.6. All the open-plan offices investigated show a discrepancy between how well each work station is protected from disturbing sounds in the office (telephone and conversation) and the relation to sound disturbance at a subjective level. For instance, 79% of the staff at Vattenfall’s helpdesk office consider that their work stations are not well screened off as regards their colleagues’ conversation, working apart. But only 40% of the same staff consider that the noise from their colleagues has a negative impact. It can be added that 60% of the staff consider the acoustic environment, from a general point of view, as being “bad” or “very bad”. One hypothesis here is that some of the staff are less sensitive to sound disturbance than their colleagues.

Another interesting discovery occurs when scrutinizing the questionnaires from Vattenfall’s finance office. 100% of the staff consider that their work stations are not well screened off as regards their colleagues’ conversation, working apart. But 0% of the same staff consider that their colleagues’ noise has a negative impact on their possibility to accomplish their task. Moreover, only 20% of the staff consider the acoustic environment, from a general point of view, to be “bad” or “very bad”.

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As stated above (see 3.1), the architectural design of the helpdesk office and that of the finance office at Vattenfall are almost identical, yet 60% of the staff at the helpdesk office consider the acoustic environment to be “bad” or “very bad”, compared with only 20% at the finance office. Therefore, when correlating and evaluating these data, aspects dealing with sensitivity to sound disturbance at the finance office may not be the main factor. Instead, the hypothesis is that the major reason for people being more disturbed at the helpdesk office depends on the work itself: the helpdesk function implies talking on the telephone, which is in fact a major source of disturbance in open-plan offices. At the finance office, on the other hand, the staff are less disturbed since their assignments are not so noise-related. It can be added that there were more people (20) in the helpdesk office, than in the finance office (16).

The above results from the questionnaires focus on subjective data that deal with speech (conversation between colleagues and on the telephone).

**Measurements**

The aim of this study was to investigate suitable room acoustic parameters to achieve overall characterisation of the acoustic conditions in open-plan offices. Important properties for these parameters are that they should reflect the subjective sensation of the acoustic conditions as well as the effect of a different room acoustic design. The intention is not to make a detailed analysis for neighbouring work stations but to investigate the degree of privacy.

The room acoustic parameters EDT, $T_{20}$, STI, SII, $D_{50}$, $DL_2$ and $DL_f$ have been measured in five open-plan offices. In two of the offices a refurbishment programme was implemented. The acoustic characterisation of open-plan offices is a complex task that can be performed at different levels of detail. However, for an overall characterisation of the acoustics in order to evaluate the suitability of the office as a workplace, the simplicity and robustness of the parameters and the corresponding method of measurement is crucial.

The influence of interior design on sound propagation over distance is a crucial factor as regards the overall impression of the acoustic environment and its suitability as an efficient work environment. Parameters related to sound propagation like $DL_2$ and $DL_f$ are therefore appropriate for open-plan spaces. A refurbishment programme was performed in two open-plan offices. It has been shown that $DL_2$ and $DL_f$ are sensitive to the acoustic treatment carried out and also that they reflect the improvement of the subjective judgment concerning the acoustic environment in general. Moreover, these parameters can be converted into a (comfort) radius indicating the distance needed to achieve a certain reduction of the sound level from a sound source. This application could serve as a practical tool for the acoustic planning of open-plan offices. \The reverberation time parameters EDT and $T_{20}$ also reflect the effect of the acoustic treatment. However, the values of EDT and $T_{20}$ will depend on the distance from the sound source. Consequently, using reverberation parameters as room acoustic descriptors for open-plan offices requires a measurement procedure that takes into account the spatial variation.

It is important to keep in mind that effective acoustic design of an open-plan office depends on several factors, not only building acoustic measures. Consideration of the activity in question during the planning of the open-plan office is essential for effective acoustic design.
For overall acoustic evaluation of an open-plan office we propose the following measurement procedure:

- Measurement parameters $DL_2$ and $DL_f$. These values can be converted into a single number value by equation 4.
- Source and measurements positions are chosen along work stations.
- Pink noise is used as a sound signal and A-weighted sound pressure levels are measured.
- Height of sound source and microphone should be 1.20 metres.
- Omnidirectional loudspeaker and microphones should be used.
- Evaluation range for $DL_2$ and $DL_f$ should be 3 to 16 metres.

6. Discussion – Acoustic design and measurement method

One noticeable finding in this project relates to the importance of functional criteria regarding activities. The comparative study between the two open-plan offices at Vattenfall – the finance office and the helpdesk office – proves that problems associated with the working environment are clearly connected to what the staff are doing. At the finance office the staff considered the working environment relatively comfortable, while the helpdesk office staff considered the environment much more uncomfortable. This is because the helpdesk activity (mainly telephone conversations) generates a disturbing sound environment as compared to the finance office, where the staff are mostly involved with paperwork.

Regarding communication, the screen walls installed at Vattenfall proved the importance of visual contact between the staff. In this case, one section of the screen wall is transparent, in order to facilitate visual contact. However, the mistake was to mount the transparent section at the higher level. This meant that the staff had to stand up in order to get visual contact. This mistake was subsequently adjusted.

The aim of the acoustic measurement method proposed is to evaluate the overall acoustic conditions in an open-plan office. The parameters used are supposed to reflect the basic acoustic conditions objectively. Suitable values for the parameters will depend on the type of activity that carried on in the office. The intention is not to analyse the privacy conditions between neighbouring work stations so this means that the method is not directly applicable for use in the type of open-plan office often referred to as cubicles where the intention is to create privacy between adjacent work stations. The measurement method has been developed for use in open-plan offices with an open architectural design where openness is one of the functional demands of the office.
7. Future research

The effect of considering a holistic approach as suggested in the introduction of this report.

Two important aspects that have not been investigated in this project concern rearrangement of work stations and movement criteria.

Rearrangement of work stations is definitely an effective measure for improving the sound environment. In fact one of the main purposes of open-plan is for its spatial structure to facilitate the possibility of organisational variations over time. However, there is a lack of knowledge of the effects of reorganisation of work stations. Very often it results in deterioration of the sound environment. Regarding the open-plan offices at Vattenfall and Dicentia, the actual organisation of the work stations is not ideal. A further step would thus be to perform a research project into the rearrangement of work stations with regard to physical as well as subjective acoustic measures.

The second aspect, movement criteria, concerns the internal infrastructure of open-plan offices in terms of the structuring of passages, corridors and entrances. One major source of disturbance is when staff walk past their colleagues. From a configurative point of view, each work station may be regarded as a spatial unit and so one important aspect concerns the spatial relation between the work stations. Another crucial aspect deals with the positioning of facilities such as copying machines, toilets, communal areas etc. Accordingly, this aspect is central to future research.

There is a need for further measurements to be performed in open-plan offices using the suggested method in order to gain experience of appropriate values for different type of offices and corresponding activities. This knowledge is of course indispensable as a basis for further recommendations and guidelines with regard to architects and end users.
8. References

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Questionnaires