Abstract
On account of LN Akustikmiljö AB, the sound energy absorption of various rooms was estimated using two methods; by measuring the steady-state sound pressure levels in the rooms when excited by a reference sound source and by measuring the reverberation time. The reason for the comparison was that the reverberation time was not always a satisfactory measure of the acoustical performance of rooms, even though it was the only requirement in Swedish standard SS 25268:2007[1]. Thus, it was suggested to try alternative methods to measure the acoustical performance of the rooms.

Measurements were performed in 18 rooms with varying volume and acoustical treatment. The equivalent absorption area of each room was calculated from both methods. Comparison between the two methods showed large differences in the equivalent absorption area; however which value was the best representation of the actual real situation is a complex problem, which varies with the dimensions and acoustical treatment of the room and the frequency band and will need further research.
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1 Introduction

According to Swedish Standard SS 25268:2007[1], requirements on rooms are stated in the longest allowed reverberation time. The reverberation time is used mainly to describe the decay of sound energy in the room and thereby giving a measure of the noise tendencies of the room, but can also be used as an indication of other acoustical qualities, such as speech intelligibility and musical quality. For example is stated that for *Utrymmen för gemensam undervisning (gymnasium)* (enclosures for communal education (high school/college)), the reverberation time for *sound class A* is allowed to reach a value of 0,6 seconds maximum. This requirement is set since the sound quality and noise tendency of the room are not considered to meet the requirements of sound class A for longer reverberation times. However, a certain value of the reverberation time does not perfectly correspond to for example certain noise tendency or speech intelligibility. The design of the room will play an important part for the behaviour of the sound field, since the properties of the surfaces within the enclosure will affect early reflections and diffusion of the sound field, which in turn affects, for example, the speech intelligibility. These aspects cannot be described by the reverberation time.

Two rooms with different construction and acoustical treatment can have the same reverberation time but still differ in other acoustical qualities. The reverberation time is a measure of the time it takes for the sound energy to decay by a certain level. The process of the energy decay is usually more complex than what the reverberation time can show. For example, the delay of the early reflections and their magnitude and frequency content will have an impact on sound qualities such as the speech intelligibility. The reverberation time is thus not enough to fully describe the acoustics of a room, a requirement on solely the reverberation time is misleading. More acoustical parameters would be helpful, either to complement the reverberation time, or substitute it altogether. One such parameter could be the *room constant, which is a measure of the difference between the sound power level of a sound source and the resulting steady-state sound pressure level in the room*. Though the room constant and reverberation time are measured as different parameters with different methods, they can both be used to calculate another parameter (for example the equivalent absorption area) of the room and then be compared.

The subject of this project is to research if the room constant could work as another valid method when specifying requirements on rooms, either as a substitute or as a compliment to the reverberation time.

In order to research the room constant as an alternative to the reverberation time, measurements will be done in rooms of varying size and design with different degrees of acoustical treatment.

This master thesis work was performed as a project for LN Akustikmiljö AB and supervised by Lennart Nilsson at LN Akustikmiljö AB and Hans Bodén at KTH, during the fall of 2011.
2 Theory

2.1 Energy methods in room acoustics

Describing the very complex sound field of a room excited with sound energy in a lot of frequencies is practically impossible to do exact with mathematics, except in certain low frequency cases. For low frequencies there might be standing waves, creating modes. How low depends on the crossover frequency, defined by the dimensions of the room. In the lower frequencies, the modes are few and the state of the room can be described by the sum of the different modes, so called deterministic prediction. For higher frequencies, the number of modes will be much larger and an exact mathematical solution is impossible to calculate. Also, the eigenfrequencies of the modes will vary slightly even with small temperature differences, which further aggravates the deterministic prediction. Another approach must be used.[3]

If we disregard the individual waves, we can instead regard the field as built up from independent plane sound waves whose interaction with surfaces and different mediums is similar to that of light as described by the theory of optics. The field will then be characterized by the total energy, instead of the character of the waves. This has the advantage that it will be possible to give a good approximation of the energy state of the room, without using complex mathematics. However, since we disregarded the character of the individual waves, it will no longer be possible to describe interference or diffraction of sound.[3]

If the dimensions of the room are large in relation to the wavelengths of the frequencies being studied, the number of modes will be high and analysis of the room is possible only with energy based methods. To specify ‘large’ in relation to the wavelength, Helmholtz number is used. Helmholtz number is dimensionless and describes the size of a system in terms of wavelengths. If Helmholtz number is in the range of \( \pi \) (in radians, half a wavelength), then there are likely only a few eigenmodes dominating the behaviour of the system and it is possible to achieve an exact description of the field by deterministic prediction. If Helmholtz number is large \((\gg \pi)\), the system is large in relation to the wavelengths and energy based methods must be used to describe the field.[3] Another way of defining for which frequencies energy based methods are valid is to use the definition of the crossover frequency between different modal shapes in the room,

\[
 f_c = 3400 \cdot \sqrt[3]{\frac{T_{60}}{V}} 
\]

(0)

where \( T_{60} \) is the reverberation time for the frequency band in question and \( V \) is the volume of the room. For frequencies larger than \( 4 \cdot f_c \), energy based methods are valid.[1 6] In this project we rely solely on energy based methods.

Now, consider an isolated acoustic system, kind of like an energy reservoir. \( E(t) \) denotes the total energy in the system and \( W(t) \) denotes acoustic power. Sound sources will add the power \( W_{in} \) to the system, but at the same time some power \( W_{dis} \) will be dissipated through losses within the system. Since the system was assumed to be isolated, the change in energy over time must be
\[
\frac{dE}{dt} = W_{\text{in}} - W_{\text{dis}} \quad (1)
\]

If we assume linearity, a loss factor \( \eta \) can be used to describe the dissipated power

\[
W_{\text{dis}} = \eta \omega E \quad (2)
\]

Insertion into the energy balance gives

\[
\frac{dE}{dt} + \eta \omega E = W_{\text{in}} \quad (3)
\]

**2.2 Sabine’s formula**

If the room is excited to a steady state with broadband noise, white noise for example, which is suddenly interrupted, the decay of the energy within the room can be measured. This can be used in order to calculate the loss factor, which in turn can be used to calculate the damping of the room. If we interrupt the source at \( t = 0 \), \( W_{\text{in}} \) will be equal to zero for \( t > 0 \). This gives

\[
\frac{dE}{dt} + \eta \omega E = 0 \quad (4)
\]

which has the solution

\[
E(t) = E_0 e^{-\eta \omega t}, \ t > 0 \quad (5)
\]

where \( E_0 \) is the energy in the system excited to the steady state.

If we use the definition for the reverberation time \( T_{60} \), which means we want to use the time it takes for the energy to decrease a factor \( 10^{-6} \), a decrease of 60 dB, as a measure of the rooms damping, the equation turns into

\[
10^{-6} = e^{-\eta \omega T_{60}} \Rightarrow T_{60} = \frac{6 \ln 10}{\eta \omega} \quad (6)
\]

With energy methods, it is assumed that the waves can be added on an energy basis and that they can be considered to be uncorrelated. It is also assumed that the field is an **ideal diffuse field**

With an ideal diffuse field it is assumed that all plane waves which are incident towards a point have the same magnitude and are uniformly distributed over all incident angles. It is also assumed that the energy density in all points is the same. In practice, this means that the energy density must be the same in all points in the room and that all absorbing material must be uniformly distributed over all surfaces of the room.\[^1\]

In classical acoustics, the **diffuse intensity** is defined as

\[
I_d = \frac{e_{\text{dc}}}{4} \quad (7)
\]
where $\varepsilon_d$ is the energy density of the sound field in the enclosure and $c$ is the speed of sound in the medium (air in all cases in this report). It is valid as an approximation for all kinds of wave fields enclosed in a 3-D system.

If a plane wave with the intensity $I_n$ hits a surface with area $S$ and absorption factor $\alpha(\theta_n)$ at angle $\theta_n$, the dissipated power will be

$$W_{n,\text{dis}} = \alpha(\theta_n) I_n S \cos \theta_n$$  \hspace{1cm} (8)

If we sum the contribution of all plane waves incident from the diffuse field, the dissipated power will be

$$W_{\text{dis}} = I_n S \int_0^{\pi/2} \alpha(\theta) \sin(2\theta) d\theta = I_n S \alpha_d = \{\text{eq 7}\} = \frac{\varepsilon_d c S}{4} \alpha_d$$  \hspace{1cm} (9)

where $\alpha_d$ is the absorption factor at diffuse incident.

If there are several absorbers in the room, that is, several areas with various absorption factors, the dissipated power will be

$$W_{\text{dis}} = \frac{\varepsilon_d c S}{4} \sum_m \alpha_{d,m} S_m$$  \hspace{1cm} (10)

where

$$\langle \alpha_d \rangle = \frac{\sum_m \alpha_{d,m} S_m}{S}$$  \hspace{1cm} (11)

is the average absorption factor of the room and $S$ is the total area of the room (walls, floor and ceiling).

From equations (2) and (9) we now have an expression for the loss factor

$$\eta = \frac{W_{\text{dis}}}{\omega E} \left\{ \frac{W_{\text{dis}}}{\frac{\varepsilon_d c S}{4} \langle \alpha_d \rangle} \right\} \Rightarrow \eta = \frac{c \langle \alpha_d \rangle S}{4 \omega V}$$  \hspace{1cm} (12)

If we insert the loss factor into the expression we got for $T_{60}$ in equation (6), we get

$$T_{60} = \frac{6 \ln 10}{\omega} \cdot \frac{4 \omega V}{c \langle \alpha_d \rangle S} \approx 0.161 \frac{V}{(\alpha_d) S}$$  \hspace{1cm} (13)

This formula is called Sabines formula after W. C. Sabine who found the formula empirically around year 1900. The formula was first derived and published by W. S. Franklin in 1903. It is probably one of the most important formulas in classical/statistical acoustics.[3]

In practice, the desired reverberation time and the room volume is usually known. From the formula, it is then possible to calculate the resulting equivalent absorption area, $A$, as the sum of the products of the absorption factor $\alpha_d$ and the surface of the area over which $\alpha_d$ is applied, $S$

$$A = \sum_m \alpha_{d,m} S_m$$  \hspace{1cm} (14)
The air absorption of sound energy can be significant in large rooms, especially at higher frequencies. The air absorption depends on the temperature and humidity of the air. If the air absorption is to be included in the equivalent absorption area, the formula for $A$ will be

$$A = 4mV + \sum m a_{d,m}S_m$$  \hspace{1cm} (15)$$

where $m$ is the energy air absorption coefficient and $V$ is the volume of the enclosure$^{[10]}$.

Insertion into Sabine’s formula gives

$$A = 0,161 \frac{V}{t_{60}}$$  \hspace{1cm} (16)$$

The equivalent absorption area can be described as the total area of material with absorption factor equal to 1 in the room. The unit of $A$ is called $m^2 Sabine^{[3]}$.

2.3 Limitations of Sabine’s formula

It is very important to be aware of the assumptions made when deriving Sabine’s formula and what the consequences of those assumptions are. First of all, it is assumed that the sound field is an ideal diffuse field. A room will have a sufficiently diffuse field if the absorbing material is uniformly distributed over all surfaces, if no walls are parallel and most internal surfaces are divided into parts. For most rooms, none of these assumptions are correct. Usually, there are parallel pairs of walls, the floor and ceiling are parallel and there is absorbing material only in either the ceiling or on the floor. It can be assumed that the sound field in most rooms is not an ideal diffuse field. Depending on the room, Sabine’s formula might still give results that closely resemble the reality, but it is not granted.$^{[5]}$

In the case of a room having most of its absorbing material concentrated to one surface, usually the ceiling, the reverberant field will be longer between the walls than between the floor-ceiling. This results in a two-dimensional diffuse field rather than a three-dimensional one as assumed, which in turn results in the real reverberation time being longer than calculations with Sabine’s formula would give.$^{[3]}$

The sound field can be divided into waves propagating parallel to the absorber (for example, the ceiling-absorber) and waves propagating perpendicular to the absorber. Diffusing surfaces, such as chairs and tables, will divert energy from the parallel waves to the perpendicular waves and vice versa. If there were very little diffusing surfaces in the room, the reverberation time would be determined by the energy decay time of the waves traveling parallel to the ceiling (wall-to-wall), since that is usually the path with least absorption and longest energy decay.$^{[6]}$

In a room the sound intensity tends to be greater for the paths with low absorption factors (wall to wall), than for the paths with higher absorption factor (floor to ceiling).$^{[7]}$
In Sabine's formula, it is also assumed that the sound energy within the room is homogeneous, which means the energy density at all points in the room is the same. For this to be valid, the energy decay cannot be too quick, since then the energy density close to absorbing surfaces would be different to the energy density in the middle of the room. This means that the time it takes for the energy to distribute over the room in order for the energy density to be the same in all points must be shorter than the reverberation time.\[\text{\textsuperscript{3}}\]

Sabine stated that a window or a hole in the wall (that is, a surface reflecting no energy), which could be likened to a material with 100% sound absorption, had an absorption factor of 1.0. After a quick glance at Sabine's formula (13) however, it can be seen that a reverberation time of zero seconds would require an absorption factor of value approaching infinity. Sabine himself measured absorption factors of higher than one, for example a factor of 1.26 at 1024 Hz for a felt material.

For a given material, the Sabine absorption factor per area unit will also vary with the placement (different impedances for different placements) and size of the absorbent in the room.

In [13], Cops, Vanhaecht and Leppens demonstrated the large discrepancies of measurement results of absorption factors over the range 125-4000 Hz, done in reverberation rooms and following the standard measurement procedures. The absorption factor of the material will vary with the sound field to which it is exposed, which means parameters such as the dimensions of the test room and the placement of the absorbing material, the sound source(s) and the microphone(s) will all affect the reproducibility of the results. For example, when measurements were conducted on a Rockwool absorbent placed with three different positions on the floor, for the frequencies below the 400 Hz third octave band, the discrepancies increased from 10%, to 100% for the lower frequencies.\[\text{\textsuperscript{13}}\]

Beranek in [7] showed this was the case for an audience in many different concert halls; the absorption of the audience was proportional to the seating area (with edge corrections) rather than the number of seats in the audience. Beranek suggests that when using the Sabine formula for calculating reverberation times in a room, the Sabine absorption factors of the used materials should have been determined in a similar room as the one in consideration. The absorption factors should also not be restricted to a value between 0 and 1 but instead be allowed to take any value between zero and infinity.\[\text{\textsuperscript{7}}\]

In [11], Ducourneau and Planeau found that it is necessary to take into consideration the relative placement of the source and the absorbing material and achieved better accuracy when calculating the reverberation time from the absorbing materials if the “solid angles representing the equivalent area of the panels as viewed by the source” were used instead of the actual area of the absorbing material. This was mainly important when the absorbing material was placed close to the source, since the first reflections will have a great influence on the reverberation time.\[\text{\textsuperscript{11}}\]
2.4 Further research on room acoustics

Several researchers have worked on developing Sabine’s formula, trying to make it more versatile or better suited for certain conditions. Eyring presented his formula in 1930, which is similar to Sabine’s formula, but is deriving the total absorption from the number of reflections at the boundaries and the absorption at each reflection. An average absorption factor for each boundary is used. Beranek in [7] describes it as with the Eyring equation it is assumed all surfaces are simultaneously impacted by the initial sound wave, whereas with the Sabine equation it is assumed that a sound wave travels around the room, impacting surfaces one after another. Millington and Sette, in 1932 and 1933 respectively, derived an equation similar to Eyring’s, but instead of using an average absorption factor for each surface, various averages of absorption factors for various portions of each wall were used.[4][5]

In 1959, Fitzroy published a paper in which he stated that it is important to take into consideration the geometrical aspects of a sound field. He found that in a rectangular room the sound field tends to settle into a pattern of simultaneous oscillations along three axes, vertical, transverse and longitudinal. He suggests that a rectangular room can be separated into three sets of parallel boundaries, and the average absorption factor of each boundary pair will decide the energy decay for the sound waves travelling along that specific axis. Thus, Fitzroy’s formula does not depend on the assumption of uniform distribution of the absorption within the room. However, the division of the sound field along three axes will not be valid if there are a lot of diffusing surfaces in the room; this case however would instead be advantageous for Sabine’s formula. [4][5]

Tohyama and Suzuki published a paper [ref] in 1986 where they presented the idea that in many rooms, the diffuse field is two-dimensional rather than three-dimensional and thus calculations of reverberation time assuming a two-dimensional acoustic field would give better results. The two-dimensional field theory is interesting for rooms where the absorption material is concentrated to only one (or a pair of parallel) boundary surface(s), for example rooms with hard walls and absorption material only in the ceiling and/or on the floor.[4][5]

In [6], E. Nilsson suggests that for two-dimensional diffuse fields, different loss factors could be introduced for the waves propagating parallel and perpendicular to the absorbers. There would also be a coupling loss factor between the two groups, for the power flow from one group to the other due to scattering reflections or diffuse surfaces, furniture for example. The diffusive effect/scattering of the furniture will depend on the frequency of the sound waves, in [6] it is concluded that the power flow from one group to the other is of importance mostly at lower frequencies (under 500 Hz) and that it can be neglected at higher frequencies.

One might wonder, with Sabine’s formula empirically derived over one hundred years ago, and with further development of newer formulas, why is it that Sabine’s formula still has widespread use when estimating reverberation times and absorption factors? Part of it might be because of the formula being very simple, requiring only easily acquired parameters and that in many cases, it gives a good enough approximation of the desired parameters. According to Beranek
[7], unless the sound field is nearly completely random and for average absorption values lower than 0.4, the Sabine formula is probably more correct than the Eyring formula. In [3] it is stated that in general, for an average absorption factor below 0.3, Sabine’s formula can be used with good results.

2.5 Measures reverberation time, T60, T30 and T20

The reverberation time of a room is the time it takes for the sound energy to decay by a certain factor. Usually the factor $10^{-6}$, a decrease of 60 dB, is used, denoted as $T_{60}$. However, to acquire a valid measurement, one would need a difference of at least 60 dB between the peak level of the excitation and the background noise. In practice, it is desired to have at least 10 dB of margin to the background noise. Furthermore, the reverberation time is measured from 5 dB below the peak, which means the difference between the peak level and the background noise has to be at least 75 dB to achieve a good measure of $T_{60}$. This applies to sine-wave excitation. If white noise is used as the noise source, an additional 10 dB of headroom will be required, since white noise incidentally will have peaks of up to 10 dB over the average level.

Instead of $T_{60}$, $T_{30}$ or $T_{20}$ can be used. With $T_{20}$ for example, the time it takes for the sound energy to decay by 20 dB is measured and then interpolated to get an approximate value of $T_{60}$. This has the advantage of being able to measure the reverberation time even with some background noise present, since the difference between the peak level and the background noise only has to be greater than 35 dB (45 dB for white noise) for $T_{20}$, or 45 dB (55 dB for white noise) for $T_{30}$. These requirements on headroom make $T_{20}$ the only practically useable option for measurements outside laboratories.

For the interpolation to be correct, it has to be assumed that the first 20 dB of energy decay and the following 40 dB decay has the same slope. The reverberation time is well defined if the reverberation curves are straight lines, as they should be for an empty room with uniform distribution of absorbing material.[8] If a large portion of the energy decay is happening within a certain time frame of the reverberation time, the interpolation from $T_{20}$ to $T_{60}$ would give some errors.

For measurements, $T_{20}$ has become the standard for several reasons; the early part of the decay has the strongest influence on the perceived reverberation time, the early part of the decay is the most appropriate to use when estimating the steady-state sound level in a room from the reverberation time and, perhaps most importantly, the signal-to-noise ratio, usually a concern in field measurements, needs to be only at least 35 dB (or 45 dB if a white noise source is used).[2]

For measurements using the Swedish standard SS 25268:2007, the room has to include furniture or other diffusing surfaces in order to make the sound field diffuse. The details of this are not further specified in the standard.[1]

The sound pressure level from noise sources, speech intelligibility, intimacy, perception of musical quality, and more, are in various degrees dependent on the reverberation time. This has lead to the reverberation time being the parameter
used when specifying requirements on rooms according to different standards.[2]
The reverberation time is a very important parameter when studying the
acoustics of music halls and auditoriums. In some other cases, industrial machine
halls for example, the reverberation time is not as relevant. This does not imply
that the sound absorption of the room is irrelevant. More important than the
reverberation time is the room constant, which would be better suited for
specifying such requirements on the room.[9]
According to De Ruiter in [9], the speech intelligibility, preferred speech levels
and other subjective parameters regarding speech depend not so much on the
reverberation time but rather on the amount of sound absorption per person
present in the room.[9]

In rooms with acoustical treatment mainly in the ceiling, the absorber which
gives the shortest reverberation time will not necessarily give the lowest
measured steady state sound pressure level in the room, which would be the
case if the ideal diffuse field theory was correct in that room. Thus, when treating
the room, it has to be taken into consideration what is most important; a shorter
reverberation time or a lower static sound pressure level.
This behaviour can be explained by the fact that the reverberation time is
depending mainly on the energy decay of the sound waves moving parallel to the
absorbers, while the steady state sound pressure level depends mainly on the
sound waves moving perpendicular to the absorbers. This would be the case in a
room with only ceiling treatment and very few diffusing surfaces. This is
especially noticeable at higher frequencies.[6]
When working with noise control, the main concern is usually the static sound
pressure level. Thus, in noise control, the room constant is a more important
parameter than the reverberation time. Of course, assuming an ideal diffuse field,
the relationship between the two is well defined. But as mentioned earlier, that
assumption is rarely perfectly true. A method of measuring the sound absorption
of a room without relying solely on the reverberation time would be necessary.[9]

2.6 Reverberation time and room characteristics
For good speech intelligibility, a shorter reverberation time is preferred. While a
completely dead room will have good speech intelligibility, some reverberation,
especially the effect of early reflections, is desired since the effects of early
reflections will actually amplify the speech, increasing the speech intelligibility
over greater distances. The room constant is also important for the speech
intelligibility, since a very high absorption, though providing a short
reverberation time, will also decrease the sound level further from the source. In
the case of a two-dimensional sound field, the absorptive material might not
reduce the reverberation time as effectively as calculations would lead one to
believe.

For music, the intelligibility of detail is important, but so is the longer decay rate
of the sounds. Reverberation will add a sense of room to the music, making it
larger and warmer. Different reverberation times are important for different
kinds of music. For music where percussive sounds are important, a shorter
reverberation time is better, since a long reverberation time will smear out the
definition between transient sounds. For orchestral music, organ music and
choir music, a longer reverberation time (around 2 s) is usually desired.
2.7 Early decay rate
As described earlier, the reverberation time is simply a measure of the time it takes for the sound energy to decay by a certain factor, usually 60 dB. The reverberation time does not tell us if a major part of the energy-decay happens early or late within the time frame of the total decay.
The decay time of the first 10 dB will have a strong influence of the perceived reverberation time. Another way to describe this is that the first 10-15 milliseconds of the decay will have a strong influence on the perceived reverberation time. Thus two rooms with equal measured reverberation times can be perceived as having different reverberation times. This is a drawback of the reverberation time when it is used for specifying the requirements on a room, as in the standard SS 25268:2007[1] since there is no strict relationship between the real value of the reverberation time and the perceived reverberation time.
The early decay time, usually abbreviated EDT, which is a measure of the time it takes for the first 10 dB of the sound energy to decay, can be used as a complement to $T_{60}$.
In [15], Hirata suggested that the initial decay rate of the decay curves could be used to estimate the equivalent absorption area. This was further investigated by Tohyama in [14], who concluded that the equivalent absorption area could be derived from the ‘initial decay rate of the time derivative of the ensemble and space-averaged decay curve’, however Tohyama stated further studies would be necessary in order to develop any experimental methods based on the results.[14]

In a small room where the early reflections occur very close in time to the source sound, the EDT will be long, whereas in a larger room, where the early reflections will occur farther apart in time from the source sound, the EDT might be shorter.

2.8 Early reflections
The sound field is strongly influenced by the first reflections on the walls.[11]
Thus, the early reflections play an important part in the way the acoustics of a room is perceived and is a subject still under research. The direction, amplitude, frequency content and time delay (from the direct sound) of the early reflections will either improve or impair the sound quality. None of these qualities can be completely derived from just the reverberation time, still they are very important.

Even though the early decay rate and the early reflections are not part of this study, they are important subjects in psychoacoustics and in explaining how the acoustics of an enclosure is perceived.

2.9 Room constant
*The room constant is, just like the reverberation time, a measure of the amount of damping in a room.*
There are methods of measuring the sound energy absorption of a room without relying on the reverberation time.
Instead of measuring the time it takes for the sound energy to decay a certain ratio, the room constant compares the emitted sound power level of a source within the room to the sound pressure level in the room. The sound field within the room can be described as the sum of the direct sound and the reverberant sound. Since the sound pressure level will vary within in the room due to the varying distance from the source, surfaces and possible standing waves, many measurements has to be made in different positions in the room in order to achieve an average of the sound pressure level of the room. For accuracy, it is important to measure within the reverberant field, which basically means measurements has to be done at a distance from the source greater than the critical distance. The critical distance is usually defined as the distance from the source at which the sound pressure level of the reverberant field is 10 dB higher than the sound pressure level of the direct sound. It is important to measure in the reverberant field in order to be able to neglect near-field effects of the source. This requirement will however introduce some practical problems in small rooms, where it is not possible to measure outside the near-field.

From the measurements, the room constant can then be calculated as

\[ K = L_W - L_p \]  

(17)

Where \( K \) is the room constant, \( L_W \) is the sound power level of the source and \( L_p \) is the measured average of the sound pressure level within the room.

Measurement of the room constant is usually done with help of a reference sound source (RSS), which is a source that can emit a constant and precise known sound power level. One type of RSS is a radial fan driven by an over-dimensioned electrical motor. This results in an omnidirectional source, which will emit a very stable sound. The emitted sound power level for different octave- and third octave-bands are specified by the manufacturer of the RSS.

In order to compare the measured values of the room constant to the measured values of the reverberation time, the equivalent absorption area of the rooms must be calculated.

If we assume that the energy lost when the direct sound is reflected at the walls of the room is the same as the energy injected into the reverberation field. Furthermore, we assume that the reverberant field is an ideal diffuse field. From equation (9) we can then describe the dissipated power as

\[ W_{dis} = \frac{\varepsilon_d e^{(\alpha_d)S}}{4} \]  

(18)

where \( \varepsilon_d \) is the dissipated energy density. However, we must also take into account the energy absorbed and lost as heat at the first reflection. Thus the dissipated power is described as

\[ W_{dis} = W_{dir} - W_{dir}(\alpha_d) = W_{dir}(1 - (\alpha_d)) \]  

(19)
where $W_{dir}$ is the power of the direct field emitted from the source and $\langle \alpha_d \rangle$ is the average absorption factor of the room. This assumption is only true for an isotropic source and for a room with uniform distribution of the absorption. The former is true for an omnidirectional source such as the RSS, but the latter is not always true, especially for higher frequencies, since there in many acoustically treated rooms is absorption material only in the ceiling.

The relation between sound intensity and energy density for a plane harmonic wave is given by

$$I = \varepsilon c$$  \hspace{1cm} (20)

The energy passing through a spherical surface with radius $r$ is given by

$$\mathcal{W} = I_r (r) 4\pi r^2 = \varepsilon c 4\pi r^2$$  \hspace{1cm} (21)

Now, the energy density of the direct field, at distances where the sound waves can be considered to be plane waves, is given by

$$\varepsilon = \frac{\mathcal{W}}{4\pi cr^2}$$  \hspace{1cm} (22)

The placement of the source within the room will affect its directivity. This must also be accounted for. By multiplying $\varepsilon$ with the directivity index $\Gamma$, we get

$$\varepsilon_{dir} = \frac{\Gamma W_{dir}}{4\pi cr^2}$$  \hspace{1cm} (23)

where $\varepsilon_{dir}$ is the energy density of the direct field. The total energy density is the sum of the energy density of the direct field and the dissipated energy density,

$$\varepsilon_{tot} = \varepsilon_{dir} + \varepsilon_d$$  \hspace{1cm} (24)

$$\begin{array}{l}
\varepsilon_d = \frac{4 W_{dis}}{c (\alpha_d) S} \\
W_{dis} = W_{dir} (1 - \langle \alpha_d \rangle)
\end{array}$$

$$\Rightarrow \varepsilon_{tot} = \frac{\Gamma W_{dir}}{4\pi cr^2} + \frac{4 (1 - \langle \alpha_d \rangle) W_{dir}}{c (\alpha_d) S}$$  \hspace{1cm} (25)

To express the equation in terms of pressure, we use the relation

$$\varepsilon = \frac{\bar{p}^2}{\rho_0 c^2}$$  \hspace{1cm} (26)

thus

$$\bar{p}^2_{tot} = \rho_0 c^2 \varepsilon_{tot} = \rho_0 c W_{dir} \left[ \frac{\Gamma}{4\pi r^2} + \frac{4 (1 - \langle \alpha_d \rangle)}{(\alpha_d) S} \right]$$  \hspace{1cm} (27)

Expressed in sound pressure and power levels

$$L_{p}^{tot} = L_{W}^{dir} + 10 \log \left[ \frac{\Gamma}{4\pi r^2} + \frac{4 (1 - \langle \alpha_d \rangle)}{(\alpha_d) S} \right]$$  \hspace{1cm} (28)
The first term in the brackets is the contribution from the near-field. For measurements in the reverberant field this term can be neglected. The last term in the brackets is the contribution from the reverberant field and can be approximated to

\[
\frac{4}{(a_d)s^2} = \frac{4}{A}
\]

for small values of \(a_d\), usually for \(a_d < 0.3\), which is usually the case for normally treated rooms (exceptions would be anechoic and hemi-anechoic rooms).

Since we defined the steady-state room constant as \(K = L_W - L_p\), we now have

\[
K = -10 \log \left[ \frac{\Gamma}{4\pi r^2} + \frac{4(1-(a_d))}{(a_d)s^2} \right] \approx 10 \log \left[ \frac{A}{4} \right]
\]

Now, the equivalent absorption of the room, \(A\), can be calculated from the measured value of \(K\),

\[
A_K = 4 \cdot 10^{K/10}
\]

Now, we have two means of calculating the equivalent absorption area from two different types of measurements.

\[
A_T = 0.161 \frac{V}{T_{60}}
\]

\[
A_K = 4 \cdot 10^{K/10}
\]

where \(A_T\) is the equivalent absorption area of the room calculated from the measured reverberation time \(T\) and \(A_K\) is the equivalent absorption area of the room calculated from the measured room constant \(K\). The unit is \(m^2\) Sabine.\[3\]

The room constant is simply a measure of how the sound pressure level in the room relates to the emitted sound power. As such, it does not take into consideration the decay time of the sound energy or how it happens. Instead, it tells us how loud the source will be in the room in question. In general, a smaller room will have a smaller room constant than a larger room, giving a lower value of the absorption area, since in a small room, the average distance between the source and the observer is smaller than in a larger room. In a larger room the average distance between the source and the observer will be longer, the room constant will be higher and the room will have much larger areas of absorption as well as a larger volume of air absorbing sound energy.

For noise control, the reverberation time and room constant might not go hand in hand as closely as in the case of speech intelligibility or music. For example, in an industrial hall with machines emitting a constant noise, the reverberation time of the room would not be sufficient to tell us about the noise levels in the hall. Instead, the room constant, which describes the relation between the
emitted sound power level of the machines and the resulting sound pressure level in the room, might be a more appropriate parameter.

2.10 Limitations of the room constant method
Just as with the reverberation time using Sabine’s formula, calculating the equivalent absorption area from the room constant involves some assumptions. Just as with Sabine’s formula, an ideal diffuse field is assumed. For equation (33), derived above, it was also assumed the near-field could be neglected. However, in smaller rooms, there will always be some influence from the direct sound. The emitted power of the RSS will depend on the placement in the enclosure, which was taken into consideration with the directivity index $\Gamma$. By neglecting that term, it is assumed the placement of the RSS should not matter, but in most ‘normal’ rooms outside laboratories, the placement of the RSS will, in varying degrees, determine the power it emits.
3 Method – Measurements and analysis

3.1 Measurement of reverberation time, excitation method

Now we know that the absorption of sound energy of a room can be measured and described by two different parameters, the reverberation time $T$ and the room constant $K$. The method of measurement is different for the two parameters, but by calculating the equivalent absorption factor from both of them, the results of the two methods can be compared.

For measuring the reverberation time, the necessary frequencies of the room must be excited to a sufficient level above the background noise. In practice, two different methods can be used; the interrupted noise method and the integrated impulse response method.

With the interrupted noise method, a loudspeaker emits white or pink noise for a few seconds in order to fully excite all the frequencies in the room. Then the noise is suddenly interrupted and the reverberation time is calculated from the decay curves obtained by recording the decay of the sound pressure level.

With the impulse response method, an impulse is used as excitation at one point in the room and the reverberation time is calculated from the decay curves obtained by recording the decay of the sound pressure level at another point in the room. It is important that the impulse as closely as possible resembles a Dirac impulse (very sharp transient) and that it excites all the necessary frequencies, which is not always easy, especially in the lower frequency bands.[2][8]

There should be no people in the room when performing the measurements, since human bodies will add significant absorption to the room, as well as introduce extra background noise in some cases. However, the room may still be considered as unoccupied with up to two people present in the room, which makes measurements easier to perform.

The amount of sound energy absorbed by the air will depend on the temperature and relative humidity of the room, especially for larger halls. For smaller rooms, the air attenuation can usually be neglected. According to SS 3382, the air absorption can be neglected if the reverberation time is shorter than 1,5 s at 2 kHz and shorter than 0,8 s at 4 kHz, and there is no need to measure the temperature and relative humidity.

For the measurements, initially shutting a book was used as impulse excitation. However, the size of the book limited the energy that could be excited in the 63 Hz and 125 Hz octave bands.

Thus, other methods had to be evaluated. Balloons, though providing a good impulse with sufficient energy at the lower octave-bands, were not an option since at least 24 impulses were to be performed in each of circa 20 rooms and thus would be too time- (and balloon-) consuming.
The interrupted noise method, with use of a Brüel & Kjær Sound Source 4224 was another option, but the weight of the device in conjunction with limited access to it, made it less optimal for the measurements. The book-shutting-method was improved by acquiring book with larger mass and surface (the infamous ELFA-catalogue) and instead of shutting it, it was slammed to the floor. This proved to provide enough energy even in the lower octave bands.

Figure 1. The book-shutting method. In the lower frequency bands, the sound pressure level of the impulse peak was too low, below 60 dB at 63 Hz and around 70 dB at 125 Hz. This did not provide enough headroom to the background noise.

Figure 2. The method with the larger and heavier catalogue slammed to the floor. Here, the sound pressure level of the impulse peak was above 80 dB in all octave-bands between 63-4000 Hz.

However, one has to be careful with this method and make sure not to set any structures, such as tables or blackboards, or even the floor, in vibration, since
they could then emit sound and thus contribute to making the measured reverberation time seem longer. Usually, the input impedance of a concrete floor is high enough for neglecting the extra sound from vibrations created at the impact.

The microphone used must be omnidirectional connected to some form of recording equipment, either for direct or later analysis. The instrument used, Brüel & Kjær 2260, has a built in amplifier, filter set and system for displaying all required measurement results.

Depending on the requirements on the measurements, the number of source and microphone positions used during the measurements varies. For rooms with complicated geometry, more measurements positions must be used. The standard SS 3382[2] specifies the number of microphone- and source-positions, as well as number of measurements in each position, required to achieve either survey, engineering or precision grade measurements.

Microphone- and source-positions were chosen to comply with precision grade measurements, however, SS 3382[2] states that the impulse response method is good only for survey grade measurements. For the purpose of the measurements of this report, survey grade should be enough. The source-position should be chosen at the position where noise will usually be emitted in the room. For small rooms, at least one source-position should be in the corner of the room. The microphone-positions should be at least half a wavelength apart from each other and at least a quarter wavelength from any reflecting surface. They should also not be too close to the source, where ‘too close’ depends on the volume of the room and the reverberation time.[2]

Measurements were done in octave-bands in the range 125-4000 Hz. For a given number of measurement positions, octave-band measurements give higher accuracy than third-octave band measurements.[2] At first, also the 63 Hz octave band was intended to be included in the measurements, however, neither the RSS or the impulse excitation could excite enough energy in that octave-band, especially in larger rooms.

According to the measurement standards, the temperature of the air in the enclosure shall be in the range 10-30 °C. In this range, the influence of the humidity can be ignored. During all measurements, the temperature was within this range.

3.2 Measurement of room constant
Measurement of the room constant requires two specific tools; a sound pressure level meter, in this case the Brüel & Kjær 2260 and a reference sound source (RSS), in this case a Brüel & Kjær 4204. In order to comply with current measurements standards, the amount and locations of the source- and microphone-positions must follow certain guidelines similar to those used when measuring reverberation time.
Guidelines for the number of measurement points required are given by ISO 3745. The number of measurement points must be chosen so that the difference (in decibels) between the highest and lowest measured sound pressure levels in any frequency band of interest is numerically smaller than half the number of measurement points. For example, if the maximum difference in SPL between measurements in any frequency band is 3 dB, the number of measurement points must med at least 6. The microphone positions should be spread out randomly and at different heights within the reverberant field. For each position a time average of the SPL is measured. The measurement time at each position must be at least 30 seconds for the frequency bands centred on or below 160 Hz. For the frequency bands on or above 200 Hz, a measurement time of 10 seconds is sufficient. In some cases corrections must be made for the background noise. However, if the level of background noise is more than 20 dB below the SPL with the source running, no corrections are required. This would prove to be the case for all measurements. [8]

3.3 Data analysis
The measurement data was analysed with help of Brüel & Kjær 7815 Noise explorer, Brüel & Kjær 7830 Qualifier, MatLab and Excel. The equivalent absorption area was calculated from the measurement data of both the reverberation time and the room constant in order to compare the results of the two methods.

Figure 3. Room FB55, 125 Hz, position 12. Computation of T20 by interpolation. The red line is a straight line fitted to the sound pressure level in a 20 dB interval, starting 5 dB below the peak level. This is automatically done for all octave-bands in the interval 125-4000 Hz and for all 24 measurement positions. The energy decay is not a perfectly straight line at the lower frequency octave-bands, due to
the sound field not being ideally diffuse, early reflections and background noise (which is more common in lower frequencies).

Figure 4. Room FB55, 2 kHz, position 12. At 2 kHz, the energy decay is a much straighter line and the value of T20 is probably a good approximation of T60.

Figure 5. Room FB55, position 12. The decay curves for T20 for the different octave-bands for one specific measurement position. The curves are straighter at higher frequencies, meaning the value of T20 is a better representation of T60.
3.4 Test objects

In order to analyse the differences between the two measurement methods, it is desired to keep the varying parameters between the different rooms at a minimum, preferably only changing one parameter at a time. That way, it will be easier to come to conclusions about how different room parameters affect the two measurement methods. Rooms were chosen such that there were groups of rooms that were similar in some aspects but differed in size, construction and acoustical treatment.

- **Q11, Q22, Q33**: Treatment in the ceiling, porous absorbers positioned with a spacing of 20-40 cm from the ceiling (Q33 20 cm, Q22 & Q11 40 cm). Rubber mat on floor. One pair of parallel walls with hard surfaces, one pair with windows on one side and hard walls with smaller windows on the other side.
• **M23, M24:** Hard (stone) floor. Hard walls, windows in one wall. Wooden ribs in ceiling.

*Figure 8. Q33.*

*Figure 9. M23.*
• **M33, M35**: Rubber mat on floor, hard walls, windows in one wall. Porous absorbers in ceiling, 7.5 cm of fibre.

![Figure 10. M33.](image)

• **M37, M38**: Rubber mat on floor, hard walls, windows in one wall, treatment in ceiling, ca 7 cm porous absorber with 1 cm spacing to the ceiling.
• **M1, M2, M3**: Hard (stone) floor. Hard (concrete) ceiling. Plate absorber (wooden casing with fibre) on one wall, windows on parallel wall. One wall with perforated bricks filled with fibre on one wall, parallel to untreated brick wall.
• **F1**: Large auditorium. Sloped seating, upholstered seats. Wooden seats and tables, wooden walls, also concrete walls and concrete ceiling. Not much acoustical treatment, quite lively and *musical* acoustics.

*Figure 12. M1.*
**Figure 13. F1.**

- **FB41, FB52, FB55:** Rubber mat on floor. Treatment in the ceiling, porous absorbers, ca. 7 cm thick, positioned with no spacing to ceiling.

**Figure 14. FB41.**

- **Meeting room, Kontorsplatsen:** Small meeting room. Hard walls, treatment in ceiling (porous absorbers), hard floor.

- **Group room 6, M-huset:** Small meeting room. Hard walls, window on one wall. Rubber mat on floor.
For later comparison of measurement results, the rooms could be sorted into groups:

- **Q11, M23, M24, M35, M37, FB41**: Similar size (volumes ca. 190-245 m\(^3\)), different construction/acoustical treatment.
- **Q22, FB55**: Similar size (volumes ca. 300-330 m\(^3\)), different construction/acoustical treatment.
- **Q33, M3, M33, FB52**: Similar size (volumes ca. 400-500 m\(^3\)), different construction/acoustical treatment.
- **Q11, Q22, Q33**: Similar construction/acoustical treatment, different size.
- **M1, M2, M3**: Similar construction/acoustical treatment, different size.
- **M37, M38**: Similar construction/acoustical treatment, different size.
- **FB41, FB52, FB55**: Similar construction/acoustical treatment, different size.
- **F1**: Large hall (ca. 2500 m\(^3\)).
- **Meeting room Kontorsplatsen, Group room 6 M-huset**: Small rooms (30-60 m\(^3\))
4 Results

The equivalent absorption area was calculated from both the measured sound absorption and the reverberation time in order to achieve one comparable parameter between the two measurement methods.

Following are graphs comparing the two calculated equivalent absorption areas for each room.
Figure 15. Q11

Figure 16. Q22

Figure 17. Q33
Figure 18. M23

Figure 19. M24
Figure 20. M33

Figure 21. M35
Figure 22. M37

Figure 23. M38
Figure 24. M1

Figure 25. M2

Figure 26. M3
Figure 27. FB41

Figure 28. FB52

Figure 29. FB55
Figure 30. Mötesrum, Kontorsplatsen (lite märkliga resultat, denna mätningen bör nog göras om)

Figure 31. Grupprum 6, M-huset

Figure 32. F1
The reverberation time for M35 and M37 is similar in all octave-bands between 125 and 4000 Hz. The room constant is similar at lower frequencies, however, at higher frequencies, they differ with up to 2 dB. If only studying the reverberation time, one might say the acoustics of both rooms are similar, but from the room constant, it is clear that M35 will have a lower static sound pressure level given any sound source. The same can be said about Q11 and M23, only in their case, the room constant differs mostly at lower frequencies.

Figures 33 and 34.
Comparing Q33 and M3, the reverberation time in the 250 Hz octave-band is ca 0.94s in both rooms. The room constant however differs with 2.6 dB. The reason for this might be the larger volume of M3. The room constant for room FB52 has a large dip around 500 Hz, which cannot be seen in the reverberation time.
Figure 37 and 38. Q11 and Q22 have similar reverberation times over all frequency bands. Interesting is the 4 kHz-band, where they have very similar reverberation time, but the room constant differs with 2.2 dB. Both rooms have similar construction and treatment, the only major differing parameter being the volume of the room. The volume seems to affect the steady-state sound pressure levels at high frequencies more than it affects the reverberation time. This is probably because of larger distance between observer and source and larger air absorption.
Figure 39 and 40. The room constant displays a dip in the 500 Hz octave band which is not displayed in the reverberation time measurements. However, this dip might be an error in measurements due to the reference sound source not being omnidirectional and actually being most directional in the 500 Hz octave band. The B&K 4204 has a directivity index of almost 8 dB in the 500 Hz octave band.\textsuperscript{18}
Figure 41. Relative difference between $A(K)$ and $A(T)$, calculated from $A(K)$ divided by $A(T)$, for some of the rooms. As can be seen, the results are similar in the 500 Hz octave band, but differs to varying degrees in the other frequency bands, especially in the lower frequencies.
5 Discussion

As can be seen there are large differences between the equivalent absorption areas achieved from the two measurement methods, sometimes as large as 100%.

For a certain amount of equivalent absorption area, if the absorbing material is not uniformly spread out, resulting in a 2D diffuse field rather than a 3D diffuse field, the measured reverberation time will be longer than calculations based on the construction would give. The other way around, calculation of the equivalent absorption area $A$ from the measured reverberation time will thus give a lower value of $A$ than the ‘real’ value. However, as mentioned in the theory part, it is not really possible to compare the measured value of the total equivalent absorption area to a ‘real’ value, since there is no defined absolute value of the absorption factor.

The room constant measurements indicate a higher value of $A$ than the reverberation time measurements. Which value is the best representation of the real value of the equivalent absorption area? This brings back the problem of the absorption factor of the materials used in the construction of the room. As stated by Beranek in [7], the absorption factor of a certain material does not have an absolute value that is valid in all situations; instead, the absorption factor will depend on the way the material is placed in the room and the way it interacts with the sound field. Discrepancies between standard-procedure measurements of the absorption factor are large, especially in the lower frequency bands[13], thus, saying for example that $A_T$ is a better representation of the reality than $A_K$ is not trivial and rather than saying one method is better than the other it would be more appropriate to use each method where it is the most relevant with regards to the acoustical performance of the room.

In rooms with little treatment and sound field approaching an ideally diffuse field, the values of $A_K$ and $A_T$ should be closer than in the rooms with more treatment, based on the assumption that for an ideal diffuse field, the two methods should give similar results. For example, in rooms M23 and M24, which had hard walls and floor and practically no acoustical treatment, the values of $A_K$ and $A_T$ were indeed closer to each other than in, for example, rooms FB41, FB52 and FB55, which had a softer floor and heavier treatment in the ceiling. That there still were differences between $A_K$ and $A_T$ in M23 and M24 can probably be contributed to the presence of chairs and tables, resulting in non-uniform distribution of absorbing surfaces, as well as flat parallel walls.

The values of $A_K$ are in some cases, especially in larger rooms, much higher than the values of $A_T$. Probably the values of $A_T$ are a better indicator of the reality here, since the values of $A_K$ in for example M1, M2 and M3 seem unrealistically high considering the treatment of the rooms and the total surface area on the enclosure. The reason for the high value of $A_K$ might be that the RSS is not providing enough energy to excite a steady-state field at the lower frequencies, thus a high value of the room constant $K$ will be measured. Another reason could be that sound waves could be ‘trapped’ in the seating area in those rooms, much more than in the other rooms, but this should affect the results of both methods.
It should also be remembered that the direct-field term was neglected from equation (30). In smaller rooms, where the direct field will influence the measurement, this term perhaps should not be neglected. The emitted power of the RSS will depend on the placement in the room. Part of this was accounted for by the directivity index \( \Gamma \), which was neglected.

In many of the rooms, the values of \( A_K \) and \( A_T \) were closest in the 500 Hz octave-band (see figure 41). This seemed to occur to such a degree (11 of 18 rooms) that the phenomenon would be interesting to study further. When Sabine empirically derived his famous formula for the reverberation time (equation 16), he used a tone one octave higher than the middle \( C \) of an organ as excitation, resulting in an excitation frequency of 512 Hz\(^{[17]} \). The technology of the time and for a long time onwards did not make measurements over a broad frequency spectrum possible, and the same excitation frequency was used in Sabine’s further research “in the absence of any good reason for changing”\(^{[17]} \).

Until modern digital signal processing technology arrived, reverberation time was measured only at 500 Hz. Does the results of Sabine’s formula have best accuracy at 500 Hz? Since Sabine’s empirical value was derived at that frequency that would be a fair assumption. However, when Franklin a few years later theoretically derived the same formula, it was independent of the frequency.

Both measurement methods make the assumption of an ideal diffuse field. Thus, even though this assumption has some flaws when measuring in normal rooms, as described in the theory part, none of the methods can be deemed more suitable with regards to the assumption; both will have errors due to the sound field not being ideally diffuse.

Taking into consideration the possibility of a 2D diffuse field, better results should be acquired by using a modified reverberation time formula, such as Fitzroy’s formula, as described by Neubauer in [4] and [5]. How much better will depend on the character of the sound field and on the average absorption factor of the enclosure; for average absorption factors below 0.3, Sabine’s formula is said to give satisfactory results.\(^{[3]} \)

Rooms with the same type of construction and acoustical treatment seem to have the same shape of the curves of \( A_K \) and \( A_T \). See for example Q11 vs. Q22 vs. Q33, M23 vs. M24, M33 vs. M35 and M37 vs. M38 in figures 15-23. The volume of the room seems to affect mainly the magnitude of the equivalent absorption area. This seems correct, since given the rooms have the same kind of acoustical treatment (similar amount of absorbing material per surface area), the room with the larger volume will also have the larger equivalent absorption area.

In general, a larger enclosure will have greater room constant and a smaller enclosure will have smaller room constant. This is due to the influence of the direct sound; in a large enclosure, it is possible to measure in solely the reverberant field, in a small enclosure, the direct field will have a greater impact on the measurements, leading to a smaller difference between the emitted sound power of the RSS and the measured sound pressure level.

Also, in a large room or hall, the air absorption will be significant at higher frequencies, further increasing the room constant. Taking into consideration the
air absorption in the calculations should change the values slightly in the higher frequency-bands; however since this applies to both methods (in current calculations the air absorption was not accounted for in any of them), the main reason for the differences is probably due to the influence of the direct sound rather than the air absorption.

Is the reverberation time method as sensitive to enclosure volume as the room constant method? From a practical point of view, taking into consideration that it is easier to excite energy with the impulses rather than using a steady state source as the RSS, the reverberation time method has an advantage if the access to and mobility of equipment is a concern, since the reverberation time method by simple means can excite enough energy with the impulse excitation.

According to [12], for low average surface absorption coefficients, the steady-state sound pressure level is less sensitive to non-uniform distribution of absorbing surfaces than the reverberation time. The steady-state sound pressure level is more sensitive to a lot of diffusing surfaces than the reverberation time. A high degree of diffusion gives better results with reverberation time approximation, a high degree of specular reflections give better results with steady-state sound pressure level approximation. The only situation where steady-state sound pressure level approximation and reverberation time approximation are both of high accuracy is in an empty, regularly shaped room with specularly reflecting surfaces and uniform surface absorption. This is the case in a reverberation room or similar, but not in the case of most other rooms, like the ones measured in here.[12]

In the measurements where two rooms had very similar reverberation times but different values of the room constant for a certain octave-band, the room with the larger volume had the highest room constant (See figures 35 and 36, rooms Q33 and M3). Given the rooms are designed with the same treatment, the rooms with the largest surface area would have the largest equivalent absorption area. The room with the largest volume would be the least influenced by the direct sound and have the largest contribution of air absorption. At 250 Hz, for the given rooms (Q33 and M3) however, the air absorption can be neglected. How can the differences in measured static sound pressure differ with up to 2.6 dB, given the rooms have similar dimensions? In the case of M3, at floor level there were many obstructing surfaces; the seats and benches will absorb and reflect a lot of direct sound. In Q33, having chairs and tables with thin metal legs, the direct sound was not obstructed the same way, thus a higher static sound pressure level was measured. If measurements were done solely in the far-field, only the reverberated sound were measured, but for each reflection to a surface, sound energy will be lost and this likely happened in a much higher degree in M3 than in Q33.

In figures 39 and 40, the equivalent absorption area calculated from the room constant displayed a dip in the 500 Hz octave band which could not be seen in the reverberation time measurements. However, this dip might be an error in measurements due to the reference sound source not being omnidirectional and
actually being most directional in the 500 Hz octave band. The B&K 4204 has an
directivity index of almost 8 dB in the 500 Hz octave band.[18]

The measurement of the room constant with a reference sound source should
only be used in enclosures within a certain range of size. Too small enclosure
(say approximately <200 m³) and the direct sound will impact the
measurements; too large enclosure (>500 m³) and the RSS will not be able to
provide enough energy to excite the sound field to a steady-state. The issue with
being close to the source applies to the reverberation time method as well,
though with impulse excitation, it is possible to excite enough energy without
expensive or cumbersome equipment such as the RSS, thus making
measurements possible in larger enclosures.

So in which cases is it preferable to use the room constant method? In the cases
where two rooms measure almost identical reverberation time, but clearly still
there is a difference in noise tendency or speech intelligibility, the room constant
makes it possible to give an indication on which room performs best. An example
of this can be seen in rooms M35 and M37 (figures 33 and 34), where both
rooms have similar reverberation times in all octave-bands, but M35 has a lower
measured steady-state sound pressure level, thus will perform better when it
comes to noise tendency. Also, a high value of the room constant will result in a
lower level of the early reflections, which are of great importance for the speech
intelligibility.

Say for example both rooms fulfil the requirements set in the standard for sound
class A, but still the acoustics in M37 are not satisfactory. An extra requirement
on the room constant could be introduced in order to avoid this problem. The
standard could, for rooms where noise control is important, include a
requirement on the room constant, in order to make sure the steady-state sound
pressure levels in the room meet a certain requirement.
6 Conclusion

The reverberation time and Sabine’s formula make some assumptions that seldom agree with the real situation. How problematic the errors of these assumptions are depends on the situation and the required accuracy of the results. In most cases with normal rooms, classrooms for example, Sabine’s formula can give good enough results. Problems might occur in rooms with special requirements or rooms with complex construction and acoustical treatment. When special requirements are set for the room, it should be taken into consideration what is most important for the acoustics of the room; a short reverberation time, or a high damping of the steady-state sound pressure level, since these two parameters, though in many cases closely linked, do not always go hand in hand.

As seen by the measurements, the reverberation time and room constant went hand in hand in most cases. In these cases, either method would work and the reverberation time method, with Sabine’s formula, is probably the easiest way of achieving satisfactory results.

In some cases, e.g. in the comparison between rooms M35 and M37, it can be seen that even though the rooms compare similarly with regard to the reverberation time, they perform differently with regards to steady-state sound pressure levels. If one of the rooms would prove to have unsatisfactory acoustical performance, even though it fulfilled the requirements on reverberation time, an additional requirement on the room constant would be helpful.

When calculating the equivalent absorption area from the reverberation time with Sabine’s formula, it should be realised that the actual ‘real’ value of the equivalent absorption area is slightly higher due to the distribution of absorbing materials being uneven. The room constant method gave a higher value of the equivalent absorption area in most cases, though sometimes also unrealistically high. It could be assumed that the actual ‘real’ value of the equivalent absorption area lies somewhere in between the results of the two methods. It would be interesting to investigate which results better represent the equivalent absorption area for the different octave-bands.

In rooms where there are important requirements on the performance of the room with regard to noise tendency, there is the risk that even though the reverberation time requirements are fulfilled, the steady-state sound pressure level is too high. In such rooms, solely the reverberation time is not a guarantee of good acoustical performance and an extra requirement on the room constant should be used to complement or replace the requirement on the reverberation time. In situations where two rooms measure almost identical reverberation time but still perform differently with regards to noise tendency or speech intelligibility, the room constant makes it possible to give an indication on which room performs best.
7 Further investigations
The same kind of measurements as conducted in this report could be done in more rooms to obtain results of a wider variety of room-types. If the room constant is to be used in the standard when specifying requirements on rooms, an investigation on what the requirements should be for different classes of different rooms should be conducted. It would also be interesting to further investigate the relation between the results of the two methods in the 500 Hz octave band. Methods of measuring the absorption of the room other than the reverberation time and room constant would be interesting to compare to the results of the measurements in this report; one such method could be using the early decay rate.

8 Thanks
I would like to thank the following people for providing me with the knowledge and practical help necessary for me to complete this report.

Lennart Nilsson at Akustikmiljö AB for proposing an interesting subject for this thesis, for supervising it and providing helpful input and insights on the subject and for lending measurement equipment.

Hans Bodén at Markus Wallenberg laboratoriet at KTH for supervising the project and providing practical help.

Simon Edwinsson, Johan Ekebergh and Yvet Martin at Akusikmiljö AB for helpful input and insights on the subject.

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Ingemar Ohlsson and Audio Data Lab for giving me access to their reference sound source.

Thommas Carlsson at KTH for helping me with access to rooms at KTH and for specifications of these rooms.
9 References


## Appendix: Measurement data

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### Mötesrum kontorsplatsen

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