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Open windows with good sound insulation

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Content

1. Preface

Based on a previous project on supply air windows (“Optimizing the sound insulation of supply air windows”) and an increasing demand for knowledge on sound insulation for open windows, a project titled ” Development of windows with sound insulation in the open position” has been executed. In general, three different window types will be investigated:

I. Further development of the supply air window
II. ”Ordinary window med an internal solution
III. ”Ordinary window with an external solution

A significant number of laboratory tests have been performed with the various window types, as mock-up solutions, as well as more complete proto type solutions, and a few field measurements. This report accounts for the performed measurements and subsequently drawn conclusions.

The project has been carried out by DELTA – a part of FORCE Technology (DELTA) in collaboration with HSHansen a/s. The Danish Environmental Protection Agency has subsidised the project within the subsidy scheme ”Grøn Teknologi” (Green Technology).

The project group includes Lars Sommer Søndergaard (Project manager), Rune Egedal and Morten Bording Hansen from DELTA. Furthermore, Henrik S. Olesen and Dan Hoffmeyer – also DELTA – have participated in preparing the project application and they have participated in a few technical discussions during the project. From HSHansen a/s, Preben Knutsson and Michael Milert Hansen participated. The measurements have been carried out by Lars Sommer Søndergaard, Rune Egedal, Morten Bording Hansen and David Duhalde Rahbæk from DELTA. HSHansen a/s has undertaken manufacturing and assembly of the used windows.

The project has had an attached focus group, consisting of Frank Pedersen and
Jens Schultz Hansen, The Danish Environmental Protection Agency,
Preben Knutsson, HSHansen a/s, and
Lars S. Søndergaard, DELTA – a part of FORCE Technology.

This report is a translation of the Danish report: “Åbne vinduer med god lydisolation”, Miljøprojekt nr. 1940, Maj 2017. The translation has been performed by
Mari Lindum, Inge Lis Kjær and Lars Sommer Søndergaard,
DELTA – a part of FORCE Technology.

2. Summary and conclusions

This report covers the project " Udvikling af vinduer med god lydisolation i åben tilstand "("Development of windows with good sound insulation in the open position") conducted by DELTA and HSHansen a/s. The project is co-funded by the Danish Environmental Protection Agency under the development program "Grøn Teknologi 2013" ("Green Technology 2013"). The project is based on a previous project on "supply air windows" ("Lydmæssig optimering af "Russervinduer"") ("Optimizing the sound insulation of supply air windows") [1].

An ordinary window in an open position has low sound insulation which for some situations is not sufficient to meet the Danish requirements for indoor noise levels. The primary project objective is to research alternatives to an ordinary open window that has both a wide range of sound insulation, but which is also diverse as regards dimensions, absorption material locations and structural additions such as an external solution.

Based on an initial literature search in the project, three different window types are assessed: I) Further development of the "Supply air window" II) "The ordinary window" with an internal solution and III) "The ordinary window" with an external solution.

A considerable number of laboratory measurements with various types of windows was conducted as mock-up solutions and as more completed prototype solutions. The laboratory measurements were additionally supplemented by field measurements. The report presents the measurements and the subsequent conclusions.

An optimised version of the "Supply air Window" with particular focus on sound insulation for low frequencies has been developed. In contrast to previously developed solutions, perforated casings tuned to dampen the low frequency part of the spectrum are developed.

A window that fits in a standard window opening with an internal solution has been developed. With reference to a single window, improvements are seen in several steps: Firstly, by adding an additional window (i.e. overall double construction), secondly, by adding a sliding window into the cavity, and finally by adding absorption in the cavity of the window.

A window that fits in a standard window opening with an external solution has been developed. It does not necessarily imply any changes to be made on the window hole or the window itself. The solution is based on an external design in the form of an attached sound-lock, which is connected to a window frame that opens out into the sound-lock.

Comparative field and laboratory measurements are conducted on a supply air window to investigate any differences between field and laboratory measurements. There is higher sound insulation for field measurements than for laboratory measurements, especially for frequencies below 250 Hz. The difference in R_w+C_{tr} is 2-4 dB. An explanation could be the difference in sound incidence. Hence it might be possible that the difference could be greater for window types in which the opening does not face the noise source.

For the project, it can be concluded that three window types have been investigated, ranging widely in sound insulation, dimensions and design/solution principle. For the three window types, the laboratory sound insulation as R_w+C_{tr} was measured to 26, 12 and 17 dB, respectively, with an opening area of 0.35 m^2. Laboratory sound insulation as R_w+C_{tr} for an ordinary open window are in the range of 5-8 dB with an opening area of 0.35 m^2.

3. Sammenfatning og konklusioner

Rapporten omhandler projektet ”Udvikling af vinduer med god lydisolation i åben tilstand” gennemført af DELTA og HSHansen a/s. Projektet er medfinansieret af Miljøstyrelsen under udviklingsprogrammet ”Grøn Teknologi 2013”. Projektet bygger videre på et tidligere projekt om ”russervinduer” (”Lydmæssig optimering af ”Russervinduer”) [1].

Et almindeligt vindue har i åben tilstand en lav lydisolation, der for en del situationer ikke er tilstrækkelig til at opfylde kravene for indendørs støjniveau. Det primære formål med dette projekt er at finde alternativer til et almindeligt åbent vindue, der både spænder bredt lydisolationsmæssigt, men også spænder bredt i forhold til dimensioner og placering af absorbenter og konstruktionsmæssige tilføjelser såsom en udvendig løsning.

I projektet undersøges på baggrund af indledende litteratursøgning tre forskellige vinduestyper: I) Videreudvikling af ”russervinduet” II) ”Almindeligt vindue” med indvendig løsning og III) ”Almindeligt vindue” med udvendig løsning.

Der er gennemført et betydeligt antal laboratorieforsøg med de forskellige vinduestyper både som mockup-løsninger, som mere færdige prototypeløsninger og enkelte feltmålinger. Rapporten redegør for de udførte målinger og heraf afledte konklusioner.

Der er udviklet en optimeret udgave af ”russervinduet”, her med specielt fokus på lydisolation for det lavfrekvente frekvensområde. I modsætning til tidligere er der udviklet perforerede karme, som er tunet til specifikt at håndtere den lavfrekvente del af spektret.

Der er udviklet et vindue, der passer i et almindeligt vindueshul med en indvendig løsning. Med reference i et enkelt vindue ses forbedringer i flere step: først ved tilføjelse af et ekstra vindue (dvs. en samlet dobbeltkonstruktion), dernæst ved tilføjelse af et skydevindue i hulrummet og til sidst ved at tilføje absorption i karmkonstruktionen.

Der er udviklet et vindue, der passer i et almindeligt vindueshul med en udvendig løsning,,og dermed ikke nødvendigvis fordrer, at der foretages ændringer på vindueshullet eller vinduet. Løsningen er baseret på en udvendig konstruktion i form af en påmonteret lydsluse, der har forbindelse til en vinduesramme, som åbnes ud i slusen.

Der er udført sammenlignende felt- og laboratoriemålinger på et russervindue for at undersøge eventuelle forskelle mellem disse. Der ses en højere lydisolation for feltmålingerne end laboratoriemålingerne, specielt for frekvenser under 250 Hz. Forskellen i R_w+C_{tr} er 2-4 dB. En forklaring kunne være forskellen i lydindfald, og det kan derfor ikke afvises, at forskellen kunne være større for vinduestyper, hvor åbningen i konstruktionen ikke vender mod støjkilden.

For det samlede projekt kan det konkluderes, at der er arbejdet med tre vinduestyper, der spænder vidt i både lydisolation, dimensioner og konstruktion/løsningsprincip. For de tre vinduestyper er opnået en laboratoriemålt lydisolation for R_w+C_{tr} på hhv. 26, 12 og 17 dB, hvor et almindeligt åbent vindue har en lydisolation for R_w+C_{tr} på 5-8 dB.

4. Background

4.1 What is the present situation?

In the Danish Environmental Protection Agency's guideline 4/2007: ”Støj fra veje” (Noise from roads) [30] as a new thing in Danish legislation, requirements have been made that a fixed noise level limit for traffic-noise will have to be met indoor with open windows. The noise level must be met with windows, opened to an opening area of 0.35 m^2. With a moderately/high outdoor noise level from traffic, this cannot be met with a traditional window in open position, but requires special noise reducing window solutions.
Furthermore, in 2007 requirements were also set forth for windows on indoor noise from trains and companies.

Based on the above, in corporation with HSHansen a/s, DELTA conducted a project titled ”Lydmæssig optimering af ”Russervinduer”” (Optimizing the sound insulation of supply air windows) [1] under the Danish Environmental Protection Agency's programme ”Subsidies for environmental-efficient technology 2008”.

Windows with good sound properties in the open position are particularly useful in connection with facade restoration or replacement of windows in e.g. existing residential properties, even if these are not included by the new requirement. The outdoor level of traffic noise may be high in these situations, e.g. 70-75 dB.

The below tables 1 and 2 derive from the working report from the Danish Protection Environmental Agency “New national mapping of road noise” (”Ny national kortlægning af vejstøj”) (tables 3.1 and 3.4) [21]. From the tables it is seen that in Denmark, 785,000 homes are exposed to noise levels above the indicated permissible value of 58 dB, and 190,000 homes are exposed to extreme noise levels above 68 dB and approximately 115,000 homes are exposed to noise levels above 70 dB.

Table 1 Number of noise exposed homes in 2007 distributed in 5-dB intervals exclusive of rural areas

dB	Metropolitan area	Denmark all	Total
55-59	138780	143524	282304
60-64	122498	158871	281369
65-69	67492	129981	197473
70-74	47021	59586	106607
≥ 75	2766	5538	8304
≥ 55	378557	497500	876057
≥ 65	117279	195105	312385
≥ 58	314000	413673	727673
≥ 68	77290	108437	185728

Table 2 Number of noise exposed homes in 2007 distributed in urban categories

	Above 58 dB	Above 68 dB
Cities up to 1,000 inhabitants	28072	2088
1,000-5,000 inhabitants	56619	9447
5,000-20,000 inhabitants	55481	6593
20,000-100,000 inhabitants	152762	52262
Over 100,000 inhabitants	100861	36888
Metropolitan area – other	19877	1159
County of Copenhagen	85799	11690
Copenhagen and Frederiksberg municipalities	228200	65600
Rural districts	57922	5260
Total	785594	190987

4.2 The project ”Optimizing the sound insulation of supply air windows”

The first accomplished project” Optimizing the sound insulation of supply air windows”” had the purpose of listing design guidelines, to optimize the sound insulation of supply air windows. A design guide was prepared, based on a significant number of laboratory measurements. This project was documented in three reports and two papers [1], [2], [3], [31], [32]. Extracts from the conclusions are shown below:

”Initially, a literature search was carried out to determine relevant references in the field. The result of the relatively extensive literature search is that basically no previous systematic investigations of sound insulation have been performed for this type of window”.

”The sound insulation’s dependency on parameters such as the window dimensions, the *open area of the openers, the pane construction and various materials placed in the window cavity, have been investigated, based on a significant number of laboratory tests. Furthermore, the significance of the window assembly was examined, i.e. the distance from the window’s upper edge to the ceiling and the ceiling’s absorption properties.”*

”The project’s main conclusion is that the most important parameters of significance to the supply air window’s sound insulation is the window-height, the opening area of the vents and the location of noise-absorbing material in the window cavity. Furthermore, the distance to the ceiling is important, especially if the ceiling is sound absorbing. It is seen that when the sound insulation for an open traditional window is compared with that of a supply air window with similar opening area, the supply air window has a sound-insulation expressed as R_w+C_{tr}, which, depending on the supply air window’s form and composition, is usually 8-16 dB better than that of the traditional window. Thus, it may be concluded that the supply air window holds obvious sound advantages compared to those of a traditional window in the open position”.

”The lowest sound insulation for the supply air window is usually in the frequency area 100-250 Hz. It is difficult to improve the sound insulation in this frequency area, e.g. by use of sound absorbers, since the window space area is often limited. It turns out that with window frame absorbers with a thickness of 20 mm and 40 mm, as applied in this project, significant improvement of the sound insulation in the frequency area above 500 Hz has been detected, however only limited effect is achieved at lower frequencies. Thus, it would be relevant to investigate the possibility of designing special sound absorbers for use in supply air windows.

As an alternative solution for improvement of the sound insulation, especially in the low frequency area around the pane's resonance-frequency, the possibility of applying active noise reduction, might be examined further."

"Based on the results of this report, a guideline has been prepared, titled "Design-guide for determining the sound insulation of supply air windows".

From the conclusion it is seen that it would be appropriate to continue working on the supply air window, especially with focus on improving the sound insulation in the low-frequency area 100-250 Hz.

4.3 Demand for solutions apart from the supply air window

There is a need to assess and/or develop alternative solutions to the air supply window, as the window's sound insulation, in certain situations, is better than what is required, and thus may turn out to be an unnecessary and expensive solution.

Since the implementation of the requirement on indoor noise with open windows, as mentioned under section 4.1, it has, from time to time, been mentioned by various authorities, projects and window manufacturers that know-how and documentation along with alternative and inexpensive possibilities are needed in the field. A range of window possibilities is called for, so that in the situations, when only slightly better sound insulation than what an ordinary open window can present, is required, you are not forced to choose a very expensive solution with better sound insulation than necessary.

As a guide for the noise requirements regarding open windows, the Danish Environmental Protection Agency's reference laboratory for noise measurements has prepared an informative memo on "Indoor noise levels with open windows" [20].

5. Purpose and delimitation

The purpose of this project is partly to optimize the supply air window, primarily at low frequencies, and partly to propose/develop alternative solutions, either based on new principles or based on improvement of traditional windows' sound insulation, in the open position. The investigated constructions through the project must be described and tested in such a manner that they are close to being as production matured as possible.

As mentioned under section 4.1 it has not been entirely without difficulty to implement the new noise requirement with open windows. The requirement applies when designing new homes and offices in areas with severe traffic noise levels (58-68 dB), which have not previously been allowed. Especially in connection with urban regeneration, hole-filling and revitalisation of existing urban areas, the new possibilities will be relevant. Thus, it is important that the new requirement for the indoor noise level does not block out innovative possibilities, if it turns out to be difficult, perhaps impossible to find window solutions with sufficiently satisfactory sound properties in the open position. Based on this, it is important to move one step further in the development of windows with satisfactory sound insulating properties.

Regarding improvement of the supply air window's noise reducing abilities at low frequencies, the aim is to try with special sound absorbers in the window cavity. The absorbers must be especially optimized on high sound absorption in the low frequency area. Therefore, more atypical absorber types are tried out, e.g. narrow banded absorbers, such as e.g. slit or perforated types as well as absorbers based on the Helmholz resonator principle.

In situations where the need for sound reduction is lower than that provided by the supply air window, alternative solutions are developed/investigated, based on improvement of traditional windows with various indoor and outdoor sound shutters, perhaps combined with sound absorbers.

This project therefore investigates three overall types of windows, which will be dealt with in each work package:

- The supply air window – focusing on the low frequency sound insulation (work package 1)
- An ”ordinary open window” focusing on internal initiatives (work package 2)
- An ”ordinary open window” focusing on external initiatives (work package 3)

This project is based on windows, made with frames of aluminium. However, it is assumed that other existing window types (wood wood/alu, aluminium, steel and plastic) may be constructed in a similar way as the constructions investigated with high degrees of freedom and variation in design and mechanical preparation.

HSHansen a/s supplied and mounted the mock up-models and the prototype structures and they were in charge of the composition and adjustment in the laboratory.

6. Literature search

6.1 Approach

For the project ” Optimizing the sound insulation of supply air windows’” [1] a literature search has been conducted to determine whether previous relevant investigations of supply air windows sound properties have been carried out.
In the present project, a renewed literature search is conducted to determine if, since the search during the first air supply window project, new knowledge and information has become available. And focus on the literature search is directed at the three work packages in the project.

The literature search has been conducted by searching various scientific databases for papers, articles, journals and books. Conferences such as Euronoise, Internoise, ICA and NoiseCon have been reviewed for relevant publications. Referrals from the literature search in [1] have been reviewed to determine whether scientists have found new knowledge since then.
The literature search covers three work packages, where “Work package 1” focuses on solutions aimed at improvement of the low frequency sound insulation of the supply air window, especially various types of absorbers and resonators. For ”Work package 2”, the literature search is aimed at internal sound shutter solutions with natural ventilation. The literature search for ”Work Package 3” is aimed at external sound shutter solutions with natural ventilation, but with focus on various absorbers and other noise reducing solutions.

General denominations applied in the search are:

- Plenum Window
- Dual airflow window
- HSIVW (High Sound Insulation Ventilating Windows)
- Acoustic ventilated windows
- Recessed Window
- Hafencity Fenster
- Acoustic window shutters
- T-shaped acoustic resonator
- Acoustic resonators in windows
- Helmholtz resonator in windows
- Low frequency acoustic resonator
- Micro perforated absorbers in windows

Furthermore, searches have been conducted on the previously used denominations: Ventilation window, Supply Air Window, Exhaust Air Window, Air Flow Window og Air Vented Window.

6.2 Results

The result of the literature search will be summarised for each work package.

6.2.1 Work package 1

In ”Work package 1” focus is on improvement of the supply air window’s low frequency properties. In that connection, references have been found for acoustic resonators with the purpose of improving the sound insulation in the low frequency area.

6.2.1.1 T-shaped acoustic resonator

In references [4] and [5], the effect of the tuned T-shaped acoustic resonator in a square glass double structure for soundproofing in the frequency area 203 Hz-346 Hz is investigated. With a T-shaped resonator tuned to 203 Hz, improved sound insulation up to 14 dB is obtained. The use of several resonators with alternately tuned frequencies is examined in references [4] and [6] to achieve broadband proofing. In reference [8] results of a resonator array aimed at proofing several resonance frequencies in a cavity with proofing at 5-7 dB in the low frequency area 145 Hz-249 Hz are seen. References [4] and [6] prove that placing of the resonators is of great significance. In reference [6] is seen a difference of 5 dB in the sound pressure level at various locations of resonators tuned to proofing of 145 Hz within the cavity. It is important to observe that references [4], [5], [6] and [8] deal with resonators in contained areas/cavities and that the alternating state between an open and closed cavity in the supply air window might have to be handled differently. For dimensioning of resonators, we refer to references [7] and [9].

6.2.1.2 Helmholtz resonator

Reference [10] examines the effect of the Helmholtz resonators' soundproofing properties in a double panel structure. The article provides several conclusions based on simulations, among which is that the use of optimised Helmholtz resonators in a double structure will improve the sound insulation by 8 dB in the frequency area 50 Hz-150 Hz by use of 1 resonator and by 10 dB by use of 3 resonators. It may be concluded that the use of Helmholtz resonators is very solid to the sound entrance angle. The maximum sound insulation variation is for 0,3 dB.

In reference [11] is presented the possibility of a dual Helmholtz resonator, which instead of locating two resonators for soundproofing of two frequencies, is a double Helmholtz resonator in one construction, which will soundproof two frequencies.

6.2.1.3 Quarter-wave resonator

Reference [12] examines the effect of quarter-wave resonators in a ventilation window, however the relevance of this is limited, as the improvement of the sound insulation is within the frequency area 500 Hz - 4 kHz. The necessary physical dimensions also involve that application of a lower frequency proofing by using quarter-wave resonators is not optimal.

6.2.1.4 Hafencity Fenster – German supply air window construction

Reference [13] deals with a project from Hamburg with a window structure, which resembles a supply air window. The structure/design of the Hafencity window is different than that of the supply air window, as the outdoor air enters through the top of the structure and is led further into the room from the bottom of the window. The requirements for the opening of the Hamburg Hafencity structure is 4 cm [22]. The measurements of the Hafencity window have been conducted with an opening area of 0,064 m^2 and 0,11 m^2.

To compare it with the supply air window a result from [1] is used, in this case a supply air window with an opening of 0.14 m^2. The supply air window obtained the sound insulation R_w (C; C_{tr}) at 18 (0; -2) dB. The Hafencity window obtaines the sound insulation R_w (C; C_{tr}) at 33 (-1; -4) dB with an opening area of ≈0.06 m^2 and sound insulation of R_w (C; C_{tr}) at 31 (-2; -6) with and opening area of ≈0.11 m^2, respectively. The sound insulation for the Hafencity window in the low frequency area 100 Hz-250 Hz is between 20-30 dB, which is 10-20 dB better than that of the supply air window in this frequency area. The measurements have been performed as per DIN EN ISO 140-3 with a window area of ≈3 m^2.

6.2.1.5 Plenum window

Reference [14] is a study of a window type, which resembles a horizontal supply air window. The study has been conducted on a model in the dimensions 1:4 and it investigated the significance of the noise entrance angle. The results of the study show a difference of up to 7 dB(A) in sound insulation, depending on the entrance angle of the noise.

6.2.2 Work packages 2 and 3

6.2.2.1 Margretheholm – external removable sound shutter

In reference [15], tests have been made with an external sound shutter solution, which, when the window opens, will turn the shutter to a position in front of the opening. An opening area of minimum 0,35 m^2 will be maintained, when the sound shutter is at an angle of 45 degrees on the window. In a test, where the opening area is 0.39 m^2, an R'_w-value of 19 dB is measured.

6.2.2.2 Folehaven – external slidable sound shutter

In reference [16], tests have been made with an external sound shutter for windows that open inwards. The sound shutter is mounted as a glass box on the outside of the existing window. The sound shutter is mounted on a guide-rail, and it is optional whether it slides to the side or in front of the window. In one of the external positions, the sound shutter covers half of the two-winged underlying window. In the other external position, the sound shutter covers the entire two-winged window. At the sides of the sound shutter, there is an approximately 3 cm crevice, which ensures natural ventilation. The opening area is not 0.35 m^2. The sides of the sound shutter are covered in sound-absorbing material. In a scenario, with an open underlying window, and the sound shutter drawn out in front of the entire window, there will be a level difference between the outside (69 dB(A)) and inside (51 dB(A)) at 18 dB(A).

6.2.2.3 Experience with sound insulating open windows in residential areas exposed to traffic noise

The Danish Research Building Institute’s Birgit Rasmussen has prepared a report [17] and a paper [18], describing the need for sound insulating open windows in existing domestic areas with severe noise loads from traffic. Based on these and the authorities’ requirements for new homes, and experience and comparisons from a number of Danish cases with sound insulating open windows, recommendations are provided for initiatives for further development of window solutions, which in the open position will provide much better sound insulation than ordinary open windows.

6.3 Updated literature search

The abovementioned literature search has been performed in the initial phases of the project. Throughout the project period, newer literature has been discovered, which has been applied, where relevant.

7. Window type 1: “The supply air window”

Illustration 7A. Photo of ”Supply air window” with perforated boards in the frame.

The supply air window is an already known construction that has been examined in a previous project for the Danish Environmental Protection Agency [1]. Through this project it was demonstrated that satisfactory effects may be obtained by adding absorbers to the inside frames of the structure. However, it also turned out that the achieved effect was limited to the high frequencies, and this complicated the possibility of improving the R_w+C_{tr}. This project included test with fully or partly absorber covered windows and a thicker/deeper absorber to raise the level of low frequency absorption and thus the R_w+C_{tr}.

The previously performed measurements, form the basis for further development of the supply air window, as performed in this report. In this report, focus in on further developing the construction so that it will become more absorbing of frequencies below 200-315 Hz**.**

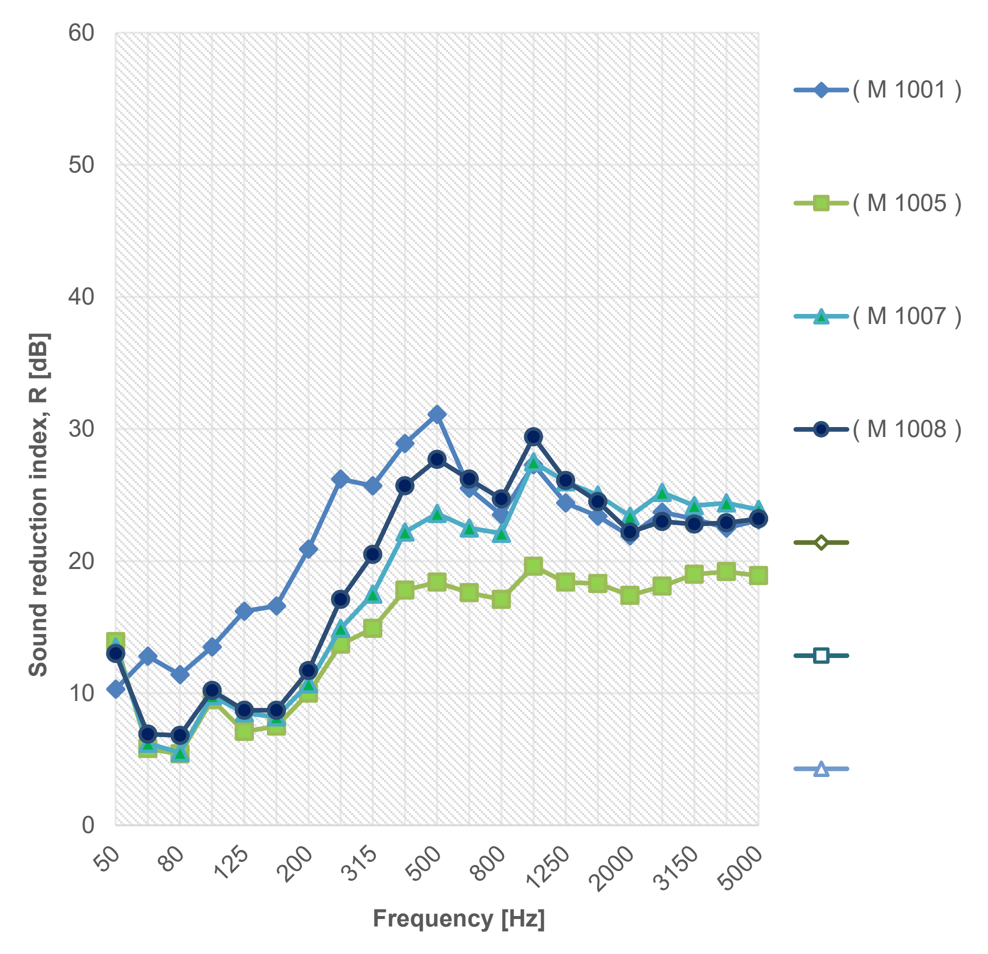
7.1 Solution principle with improved frame absorber

Optimization of the construction's effect of the low frequency sound insulation has been based on the original supply air structure. Focus is on a solution, which will not influence the efficient air flow area of the construction. To avoid blockage of the air flow area, the frame structures will be optimized based on low-frequency noise reduction.

Initially, tests were made as to how a deeper frame absorber would affect the low-frequency area. This was determined by opening the surrounding cavity wall and thus exposing the mineral wool between the two wall halves. Comparative measurements were conducted, as the cavity wall was shut off, and absorber had been put up, based on the previous report [1]. As in the previous project, the plate absorber Sund® Miljöundertak (SUND®) is applied as absorber in a thickness of either 20 mm or 40 mm.

In general, the results of the measurements will be presented in an figure as FIGURE 1. The figure depicts the sound reduction index, as stated in a graph in 1/3-octaves. Furthermore, the measurement number is shown to the right. Under the graph is shown a brief description of the measurement and the single number quantity R_w og R_w+C_{tr}. The description of the laboratory setup is clarified in Appendix 2. All single number quantities for the measurements are stated with measurement number in Appendix 3.

FIGURE 1. Investigation of the effect of open frame (to the cavity wall) versus closed frame with or without SUND® absorber. The opening area is always 0.35 m^2.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1001	24	24	Open to cavity with mineral wool
M 1005	18	16	Closed to cavity w. plasterboard plates
M 1007	23	19	Closed to cavity w. plasterboard plates + 20 mm SUND®
M 1008	24	20	Closed to cavity w. plasterboard plates + 40 mm SUND®

It is clear from the measurements in FIGURE 1, that significantly more absorption is introduced by opening up directly to the cavity wall. As expected, it is also seen that the measurements, in the location that is closed off to the cavity wall, converge to approximately 250-315 Hz, after which, depending on the absorber's thickness, the high frequency reaches the same level, as a measurement taken in an open part to the cavity wall insulation (in this case the mineral wool in the double plaster board wall). This initial measurement forms the basis for solutions focusing on the further development of the supply air window. An open cavity wall is not realistic for the final solution, hence focus is on altering the frames so that they become tuned to low-frequency areas and thus ideally illustrate an open cavity wall. Focus is on the following solutions:

- Increased frame depth with room for porous absorber with perforated frames.
- Helmholtz resonators located in the frame, tuned to specific frequencies.

7.2 Possible implementation

In order to have a deeper frame absorber, which might resemble the open cavity wall, boxes are designed, which fits inside the cavity wall, see Illustration 7B.

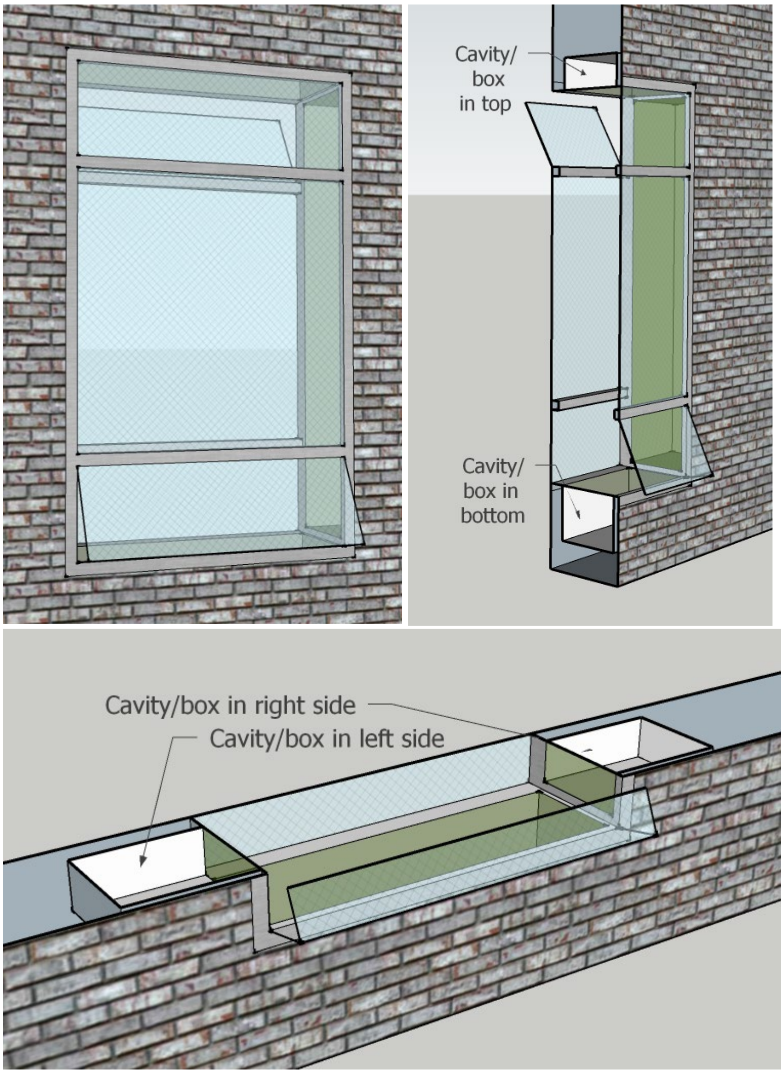


Illustration 7B. Sketch of the window and frame construction for the supply air window. Top left is showing the whole construction. Top right is showing a vertical cross section in the construction, where the boxes in top and bottom is shown. Bottom is showing a horizontal cross section of the construction, where the boxes in the sides is shown.

The boxes are made to combine absorption materials and to make sure that the actual cavity wall is closed off. The box must be of a suitable depth, so that the absorbers may be tuned to the desired frequency range.
It is desirable that the absorbers are effective from 315-500 Hz and below. This implementation will involve that the window does not grow in size but maintains the dimensions, which have previously been applied. To make such a solution easier to install, the boxes might be incorporated as part of the window structure so that on the side there would be two opaque boxes, mounted on the window. A box solution is being examined in the laboratory. This solution is being installed in all four frames, and in this way, it is possible to make use of the extra frame width on all 4 sides. In the laboratory, the maximum obtainable depths have been selected for the boxes (limited by the actual set-up in the laboratory). This means that the depth of the sides is 410 mm, for the bottom it is 300 mm and for the top it is 170 mm. These dimensions will form the basis of the further calculations.

7.3 Calculation of absorbers

As mentioned in section 7.1, two types of absorbers have been selected for implementation, i.e. a resonator-based solution and a combined solution, consisting on porous material together with perforated plates. Below is shown the results of the calculations for the various types of absorbers.

7.3.1 Resonator calculations

In the literature study in section 6.2.1, various resonators are mentioned, among those the so-called ”T- shaped resonators” and the usual Helmholtz resonators. As it is important to avoid unnecessary occupation of space in the frame, further work is performed on the most compact of the two solutions, which in this case is the ”T-shaped resonator”. The resonator is built up of 4 elements: a neck (branch 1), a T-joint and two end pieces, of which one is short (branch 2) and the other is long (branch 3), as can be seen in illustration 7C. These elements are adjusted to tune the resonator to the desired frequency.

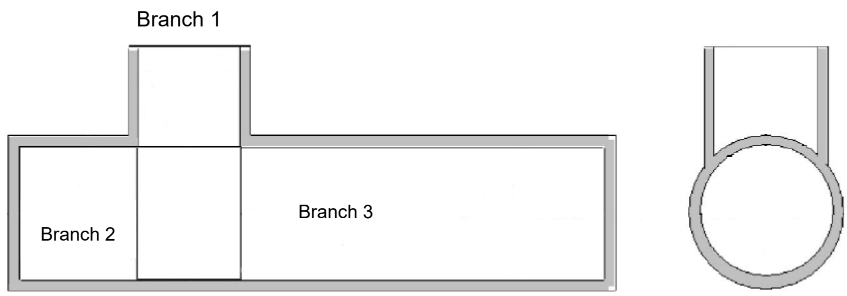


Illustration 7C. T-shaped resonator principle. [7]

To make the calculations and in the end, also the implementation easy, it has been chosen to work with three predefined elements and one adjustable element, all with the same diameter. With reference to illustration 7C, the lengths of branches 1 and 2 are maintained as well as the size of the T-joint, whereas the length of branch 3 is adjustable.

The calculations are performed based on the publications found in the literature study (see section 6.2.1). Lengths are calculated for branch 3 with various diameters on the entire resonator in order to find optimal conditions for location and necessary space. In Table 3 the calculations for a set-up with a diameter of ø50mm for all three branches is depicted. The calculations are based on finding a suitable size of resonator. Thus, calculations for various resonance frequencies and various diameters of the resonator-construction have been carried out. The resonator frequency is the frequency, on which the resonator will have a noise reducing effect

Table 3. The lengths of branches 1 and 2 are fixed at 50 mm. The length of branch 3 is calculated and given in metres.

Diameter/Frequency	100 Hz	150 Hz	200 Hz	250Hz	300 Hz	350 Hz	400 Hz
ø12 mm	0.79 m	0.51 m	0.36 m	0.28 m	0.22 m	0.17 m	0.14 m
ø16 mm	0.79 m	0.50 m	0.36 m	0.27 m	0.21 m	0.17 m	0.13 m
ø20 mm	0.79 m	0.50 m	0.35 m	0.27 m	0.21 m	0.16 m	0.13 m
ø25 mm	0.78 m	0.49 m	0.35 m	0.26 m	0.20 m	0.16 m	0.12 m
ø32 mm	0.77 m	0.49 m	0.34 m	0.25 m	0.19 m	0.15 m	0.11 m
ø50 mm	0.75 m	0.47 m	0.32 m	0.23 m	0.17 m	0.12 m	0.08 m
ø63 mm	0.74 m	0.45 m	0.30 m	0.21 m	0.15 m	0.10 m	0.05 m

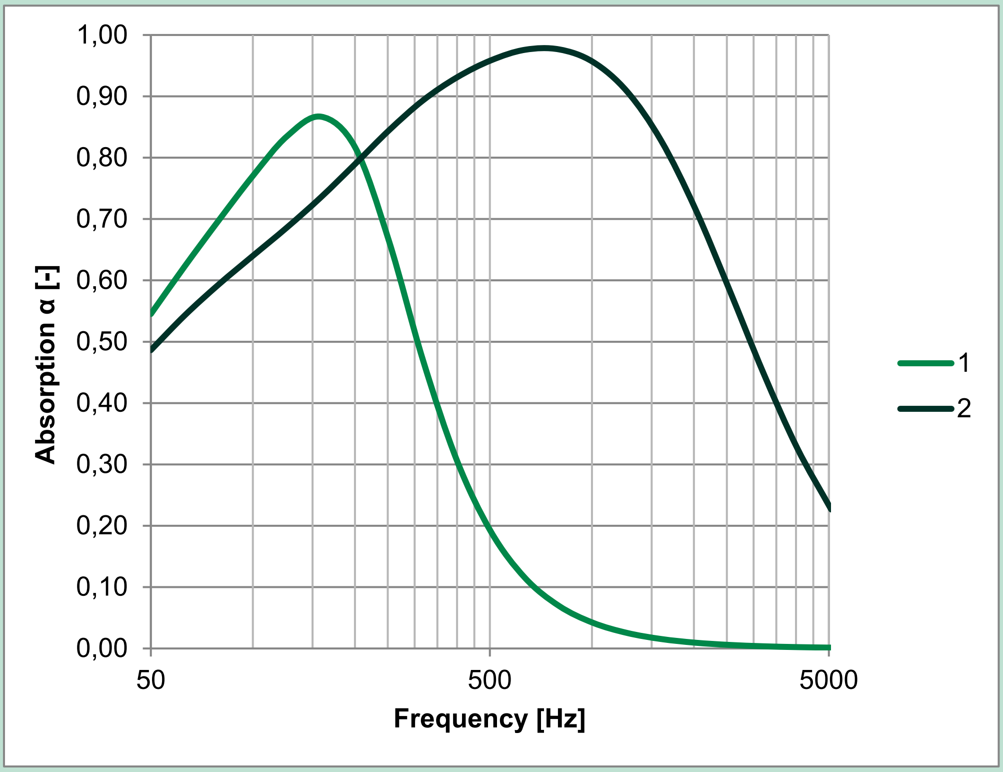
The calculated values form the basis of the resonator dimensioning for use in the construction. To make the resonators easier to tune, branch 3 is made as long as possible, but with the possibility of inserting a fuse, which will adjust the length, without cutting the branch length.

7.3.2 Perforated absorber calculations

The perforated solution is already known, as today it is used for ceilings especially, but also for other purposes. As with the resonators, the principle is based on that of Helmholtz. As opposed to the abovementioned, this solution contains more holes, and to lower the frequency there is a demand for larger cavities, as opposed to what applies for the calculated resonators (T-shaped resonator). This provides the opportunity of tuning the perforated plates to a wider spectrum, so that the actual absorption is not as small-banded as for the resonator.
The calculations are based on [23], which describes the design process for perforated absorbers. Basis is formed on reducing frequencies below 350 Hz and at the same time doing it for as wide a range as possible with the dimensions available at the laboratory. To achieve a wider frequency area, for which the absorption is high, two perforation degrees have been calculated up through the window. The calculations only apply for perpendicular incidence. Furthermore, the perforated plates have been made in 13 mm plasterboards, with a hole radius of 5 mm. Depending on the degree of perforation, the distance between the holes varies. For the low degree of perforation, the distance from centre to centre of the holes is 50 mm, whereas for the high degree, it is 15 mm. This results in degrees of perforation of 3,14 % and 34,91 %, respectively. In Illustrations 7E and 7F, the various degrees of perforation mounted in the window, are depicted.

In FIGURE 2 the absorption coefficient is calculated in the areas, where the frame depth is 410 mm. The frame is filled with mineral wool with an air flow resistance of 9000 Rayls/m. Calculations for two degrees of perforation are shown. It is seen from the calculations that in the area from 100 Hz to 1750 Hz, a combined absorption coefficient of more than 0.8 is to be expected.

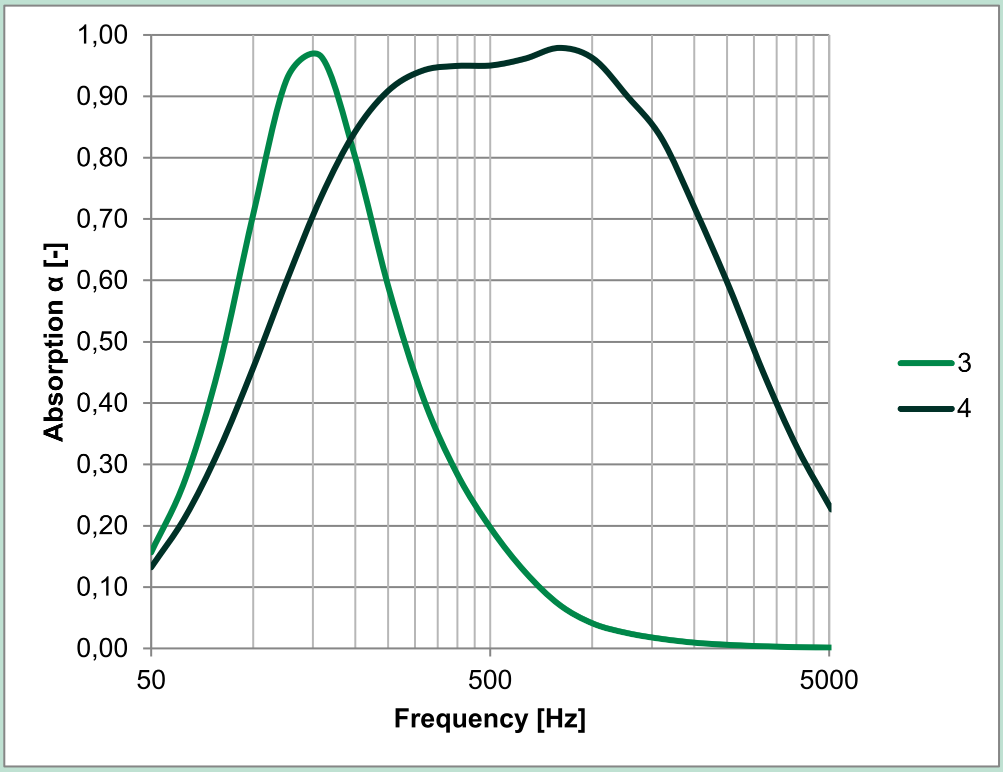
FIGURE 2. Calculation of absorption coefficient depending on degree of perforation with 410 mm mineral wool.



Calculation no	Description (Degree of perforation and depth of cavity)
1	3.14 % 410 mm mineral wool
2	34.91 % 410 mm mineral wool

In FIGURE 3 is seen a similar calculation as FIGURE 2. In this case, a calculation is made for a cavity of 170 mm, filled with mineral wool with an air flow resistance of 9000 Rayls/m. The calculation applies to the uppermost frame, since no higher depth than the 170 mm is available. It is seen, depending on the degree of perforation chosen, that low frequency absorption may be obtained in a small banded frequency area or absorption in a broader band at higher frequencies. Since the width of the uppermost frame is only 1250 mm, this does not work with combined absorption, as is the case on the sides.

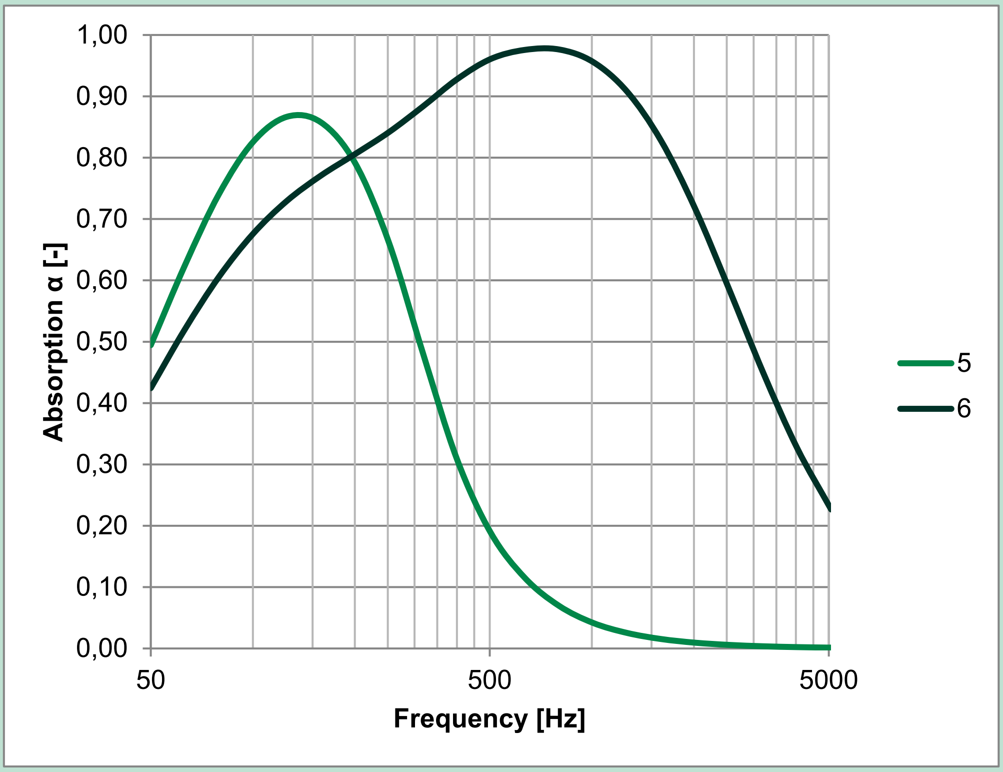
FIGURE 3. Calculation of absorption coefficient depending on degree of perforation with 170 mm mineral wool.



Calculation no	Description (Degree of perforation and dept of cavity)
3	3.14 % 170 mm mineral wool
4	34.91 % 170 mm mineral wool

In FIGURE 4, the calculation is shown for a cavity of 300 mm filled with mineral wool with an air flow resistance of 9000 Rayls/m. As opposed to FIGURE 3 it is seen that the absorption value for the two degrees of perforation take on a wider form, but with not as high an absorption coefficient. The calculation has been carried out for the lowermost frame of the window, for which the maximum depth is 300 mm.

FIGUR 4. Calculation of absorption coefficient depending on degree of perforation with 300 mm mineral wool.



Calculation no	Description (Degree of perforation and dept of cavity)
5	3.14 % 300 mm mineral wool
6	34.91 % 300 mm mineral wool

It is possible to alter the absorption values by e.g. applying a porous material with higher air flow resistance than applied. It is furthermore possible to work with e.g. semi-filled cavities, which combine air with a porous material. Calculations have been carried out, for which the mineral wool has not filled the entire cavity. The depicted calculations are for the combination that has mostly been applied throughout the project.

7.4 Laboratory measurements

In the laboratory, measurements have been performed for the two types of solutions; a solution based on the T- shaped resonators and a solution based on perforated plates with porous filler in the cavity behind the frame. The measurements with resonators have been carried out in the window size (width x height) 1250 mm x 2100 mm. The measurements with perforated plates and porous frame have been performed on three different sizes of the supply air window, 1250 mm x 2100 mm, 1250 mm x 1500 mm and 900 mm x 2100 mm, respectively.

Illustration 7D. Photos of the window with inserted resonators. The Left photo depicts the resonators mounted in the vertical frame, while the right photo shows the resonators mounted in the horizontal frame (the bottom).

In Illustration 7D mounting of the resonators to the frame is depicted. The resonators are constructed in ordinary plastic drain pipe material, sealed with silicone. Where possible, the resonators are placed as per the vertical waves occurring in the window in the closed position at the selected resonator frequencies.

Illustration 7E. Photo of the window with 34.91 % perforated frame installed. The photo shows the upper corner.

Illustration 7F. Photo of the window with respectively 34.91 % (upper) and 3.14 % (lower) perforated frame. The photo shows the lower part of the window.

In illustrations 7E and 7F the window is seen mounted with perforated plates with porous filler. The two illustrations are depicted for the window with the dimensions (width x height) 1250 mm x 2100 mm. In these illustrations, the sides are coated with 34.91 % perforation at the top and 3.14 % perforation at the bottom. Top- and bottom frames are 34.91 % and 3.14 % perforated, respectively. The perforated plates are, as mentioned previously, made of 13 mm plaster boards.

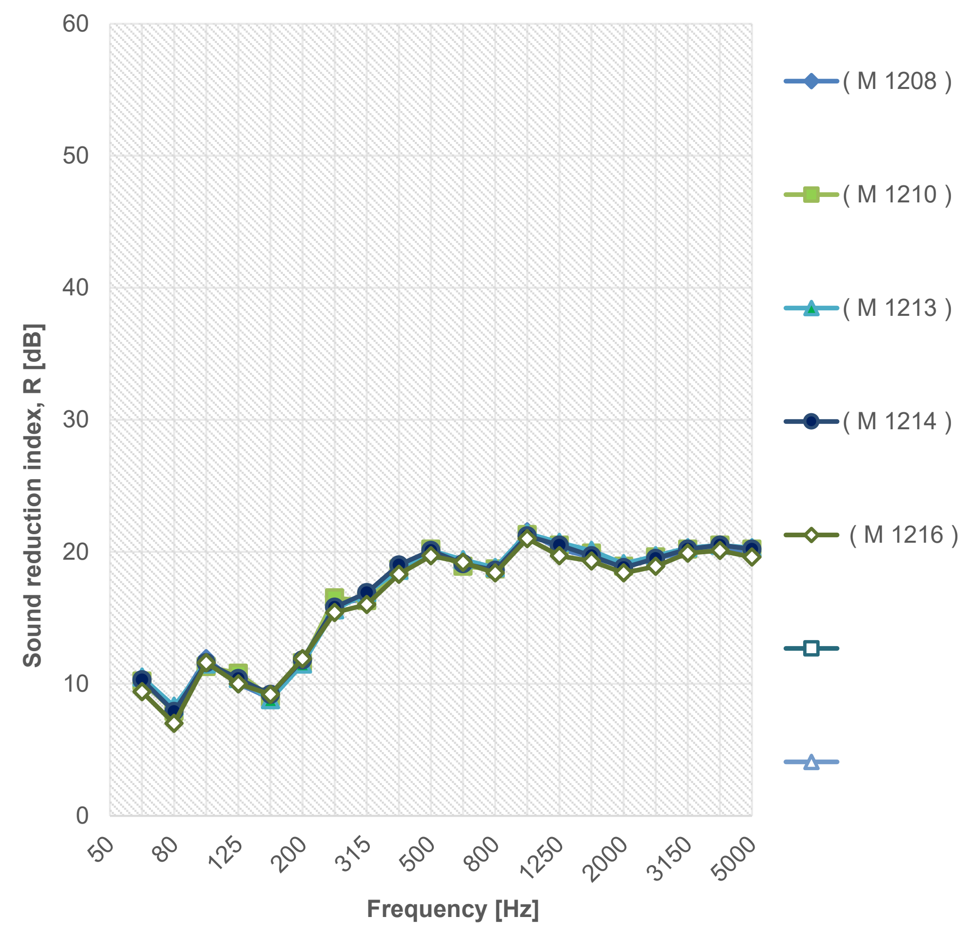
The set-ups depicted in the illustrations are examples of possible setups. The measurements have been performed with various set-ups and combinations. Apart from the perforated plates, experiments have also been conducted with the use of absorber on the outside of the perforated plates.

7.4.1 Resonator solution

The resonator solution sees the window as a closed box with regards to the placing of the resonators. As best possible, it has been tried to position the resonators from the quarter wave lengths, corresponding to the frequency, to which the resonaters have been tuned. Furthermore, locations at sash bars and in corners have been tried out. This is seen from FIGURE 5, where it has been tried with a large number of resonators tuned to the same frequency and two subsequent 1/3-octave frequencies, and compared to the solution without resonators there is no difference in the R_w+C_{tr} between this and the solution, where the frame has been closed off by a plaster board. The resonators are all tuned to the higher part of the low frequency spectrum 200 Hz and 315 Hz, respectively. During the laboratory tests, measurements have been tried performed with a stationary source (as opposed to the movable loudspeaker, which is usually applied in the laboratory) and measurements with narrow banded noise. No noticeable effect is seen for these measurements. However, there is a slight difference when testing is performed with pure tones at the actual frequencies for the resonators. FIGURE 6 depicts the measurements performed at a lower frequency for the resonators. As for the measurements in FIGURE 5, there is no improvement of the R_w+C_{tr} compared to the reference level, for which the frame is plaster board. It is possible that the placing of the resonators has not been optimal. Thorough simulation of the acoustic part of the window in the open and closed positions will contribute to selecting the optimum location for the resonators. However, such simulation has not been possible within the limits of the project, but might contribute to an improvement of the sound insulation.

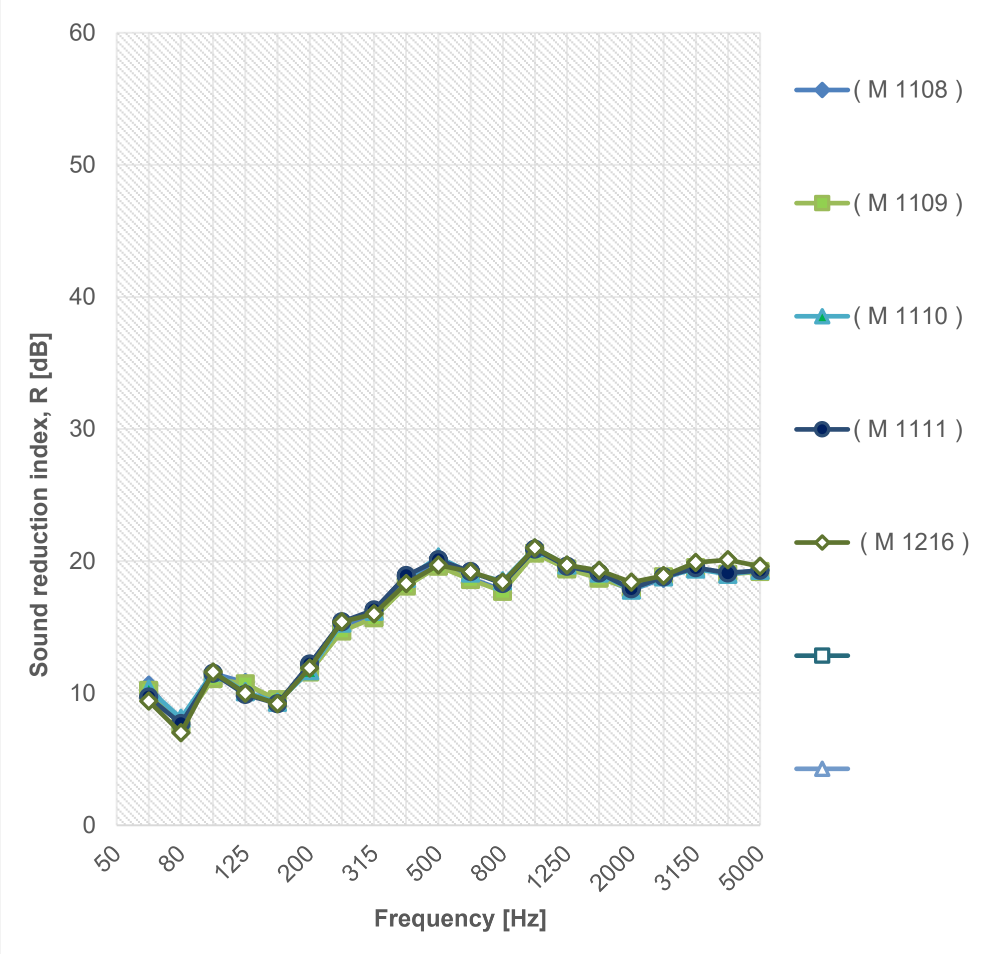
The previously achieved results of these measurements are comparable with the results obtained in the previous supply air window project without absorbers. [1].

FIGUR 5. Open window 0.35 m². Different resonator setups mounted with plaster board plates.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1208	20	18	4 resonators in the sides, tuned at 200 Hz
M 1210	20	18	6 resonators in the sides, tuned at 200 Hz
M 1213	20	18	6 resonators in the sides, 2 tuned at 315 Hz and 4 tuned at 200 Hz
M 1214	20	18	6 resonators, 2 in the top frame, tuned at 315 Hz and 4 in the sides, tuned at 200 Hz
M 1216	19	18	Closed with plaster board plate against the boxes.

FIGUR 6. Open window 0.35 m². Different resonator setups mounted either at the top or at the bottom of the window.

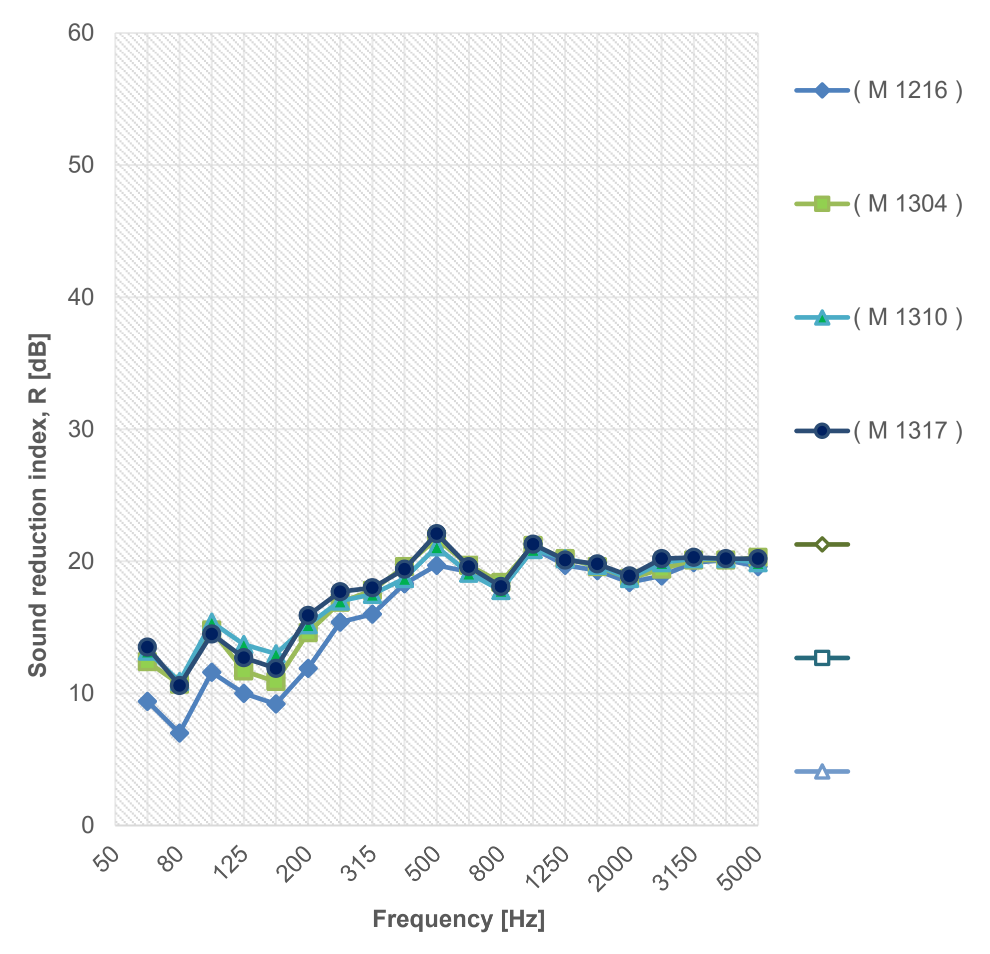


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1108	19	17	2 resonators in bottom, tuned at 80 Hz
M 1109	19	17	1 resonators in the left side of the bottom, tuned at 80 Hz
M 1110	19	18	2 resonators in the top, tuned at 80 Hz
M 1111	19	18	2 resonators in the top, tuned at 200 Hz
M 1216	19	18	Closed with plaster board plate against the boxes.

7.4.2 Perforated solution

As described in section 7.3, calculations have been carried out for perforated absorbers with various degrees of perforation. Initially, measurements with a constant degree of perforation were performed. Furthermore, tests have been performed with and without mineralwool in the cavity and partial perforation in the frames only. In FIGURE 7, measurements conducted with a constant degree of perforation of 3.14 % are seen. Initially, there are perforated plates at the sides with mineral wool cavity fill, subsequently, supplementing perforated plates have been mounted at the top and bottom, with the same degree of perforation still, but with air and mineralwool in the cavity.

FIGURE 7. Open window 0.35 m^2. Perforated plates with a degree of perforation of 3.14 %, different filling in the cavity and frames with different degrees of perforation.

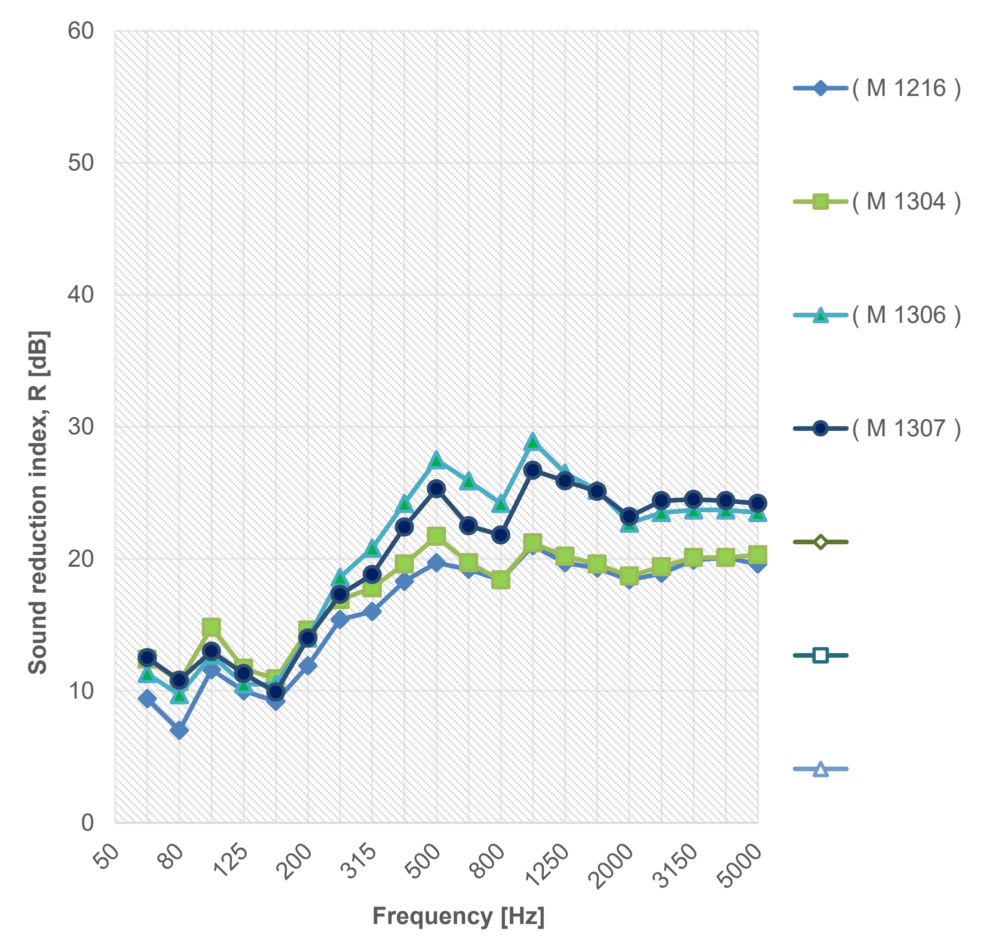


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1216	19	18	Closed with plaster board plate against the boxes.
M 1304	20	19	Sides perforated 3.14 %, cavity filled with mineral wool
M 1310	20	19	Top and bottom perforated 3.14 %, cavity with air, sides perforated 3.14 %, cavity with mineral wool
M 1317	20	19	Top and bottom perforated 3.14 %, cavity with mineral wool, sides perforated 3.14 %, cavity with mineral wool

From the calculations it is seen that there must be higher absorption from approximately 500 Hz down to 50 Hz with a degree of perforation at 3.14 %. From FIGURE 7 is seen that the sound reduction index from 500 Hz and below for the perforated measurements is increased compared to the standard solution with an ordinary plaster board. It is also seen that for 500 Hz and above there is convergence between the reference measurement and the perforated measurements, which indicates that the calculated effects from the perforated measurements are what is seen in the measurement. It is also seen that the R_w and R_w+C_{tr} have increased by 1 dB compared to the reference measurement. It is a limited increase but it has been found by regulating the low frequency area for the window, only.

In the previously performed supply air window project it has been demonstrated that ordinary porous absorbers in the frame are beneficial to absorption on frequencies above 500 Hz. Measurements are performed where absorbers are affixed on the outside of the perforated plates to increase absorption at higher frequencies. The same absorber as in the previously performed project (SUND®) is applied. FIGURE 8 depicts the measurements performed with a fixed degree of perforation of 3.14 % at the sides. Measurements have been made with and without SUND® absorbers in the frames. It is seen from the measurements that the frequency area above 500 Hz is increased, without dissapearence of the low frequency benefit found by perforating the plates. However, there is a slight loss in the low frequency area, compared to when there is no absorber. It is seen that for both the 20 mm and 40 mm frame absorbers, is achieved an R_w of 24-25 dB as compared to 19 dB and an R_w+C_{tr} of 21 compared to 18 dB, which is an increase of 3 dB compared to the solution without absorber.

FIGURE 8. Open window 0.35 m^2. Perforated plates with a degree of perforation of 3.14 %, only the sides are perforated, the frames are either lined with SUND ® or without.

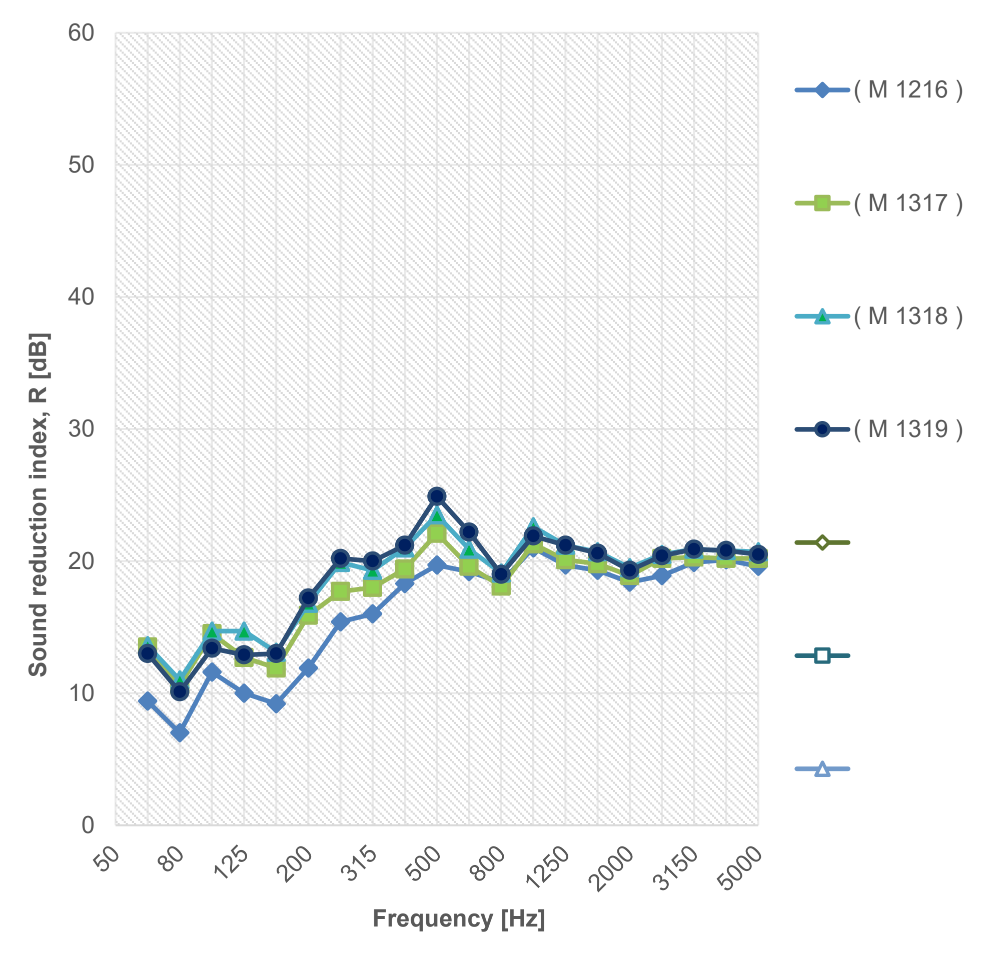


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1216	19	18	Closed with plaster board plate against the boxes.
M 1304	20	19	Cavity filled with mineral wool
M 1306	25	21	Cavity filled with mineral wool, lined with 40 mm SUND®
M 1307	24	21	Cavity filled with mineral wool, lined with 20 mm SUND®

The measurements that have been carried out so far, have all been with the same degree of perforation. In section 7.3.2 calculations with a higher degree of perforation than the 3.14 % have also been performed. The idea with the higher degree of perforation is to cover a wider frequency area of the absorber. By combining the two degrees of perforation, higher coverage is achieved and thus an expected better sound reduction index.

FIGURE 9 depicts measurements performed with and without a combined degree of perforation. It is seen that the measurements for the lowest and the highest frequencies coincide. It is also seen that measurements where either the top or the bottom has the highest degree of perforation, higher absorption has been obtained for the middle frequencies, than when the window is only mounted with a degree of perforation of 3.14 %. With a degree of perforation of 34.91 % at either top or bottom, 1 dB extra as obtained in the R_w+C_{tr} compared to an overall total perforation degree of 3.14 %. Furthermore, an increase of 2 dB for the R_w+C_{tr} is achieved compared to that of a structure without perforated frames.

FIGURE 9. Open window 0.35 m^2. The sides are perforated 3.14 %. The top and bottom frame is perforated with either a degree of perforation of 3.14 % or 34.91 %.

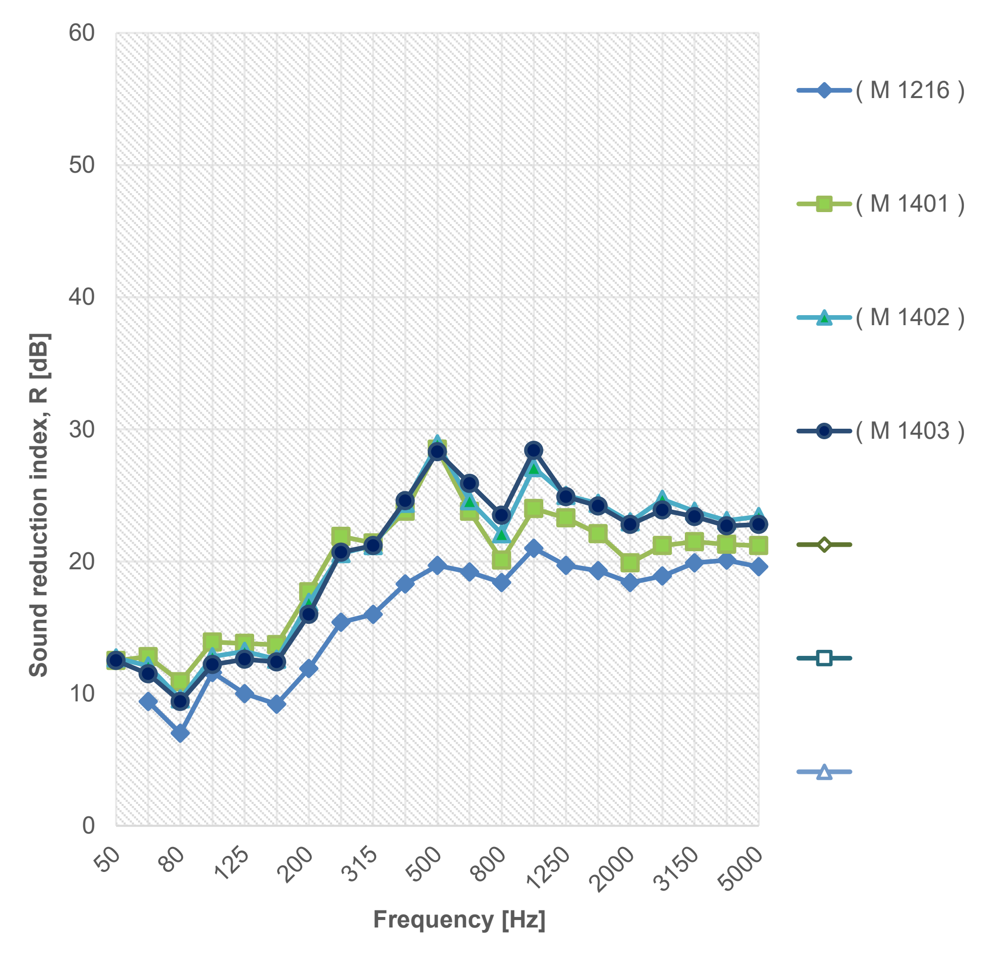


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1216	19	18	Closed with plaster board plate against the boxes.
M 1317	20	19	Top and bottom perforated 3.14 % to the cavity with mineral wool, the sides are perforated 3.14 % to the cavity with mineral wool.
M 1318	21	20	Bottom perforated 34.91 % to the cavity with mineral wool, top and sides perforated 3.14 % to the cavity with mineral wool.
M 1319	21	20	Top perforated 34.91 % to the cavity with mineral wool, bottom and sides perforated 3.14 % to the cavity with mineral wool.

It has been attempted to obtain a better distribution between the perforated areas. Instead of solely placing the high degree of perforation at the top or bottom, it is also inserted in the side frame at approximately 2/5 of the frame length. As seen from simulations of the window's acoustic area, better placing of the various absorbers may be obtained. However, in these measurements the intention is to show the principle, only, not to optimize the placing. In FIGURE 10 the measurements are seen performed with a combined degree of perforation, and a porous absorber inserted in the perforated plates. By inserting a higher degree of perforation at the frame sides, in combination with a higher degree of perforation at the bottom, the area with increased absorption is extended from not only being at low frequencies, but to apply to the entire area.

Porous absorber is implemented on the frames to obtain better noise reduction at the higher frequencies. As previously seen, the area above 500 Hz is increased, whereas some of the effect disappears from the perforated plates in the low frequency areas, however they still function, which is seen when the measurements are compared to a non-perforated solution. It is also seen that with 20 mm as well as with 40 mm SUND® the same result is achieved with an R_w value of 25 dB and an R_w+C_{tr} of 22 dB, in total an increase of the R_w+C_{tr} of 4 dB compared to a non-perforated solution. This solution may be seen as the optimal solution for surfaces, in which to place absorber, as all glass surfaces have been kept without absorber.

FIGURE 10. Open window 0.35 m^2. The sides are perforated 3.14 % 3/5 of the frame, the remaining 2/5 are perforated 34.91 %. The top is perforated 3.14 % and the bottom 34.91 %.

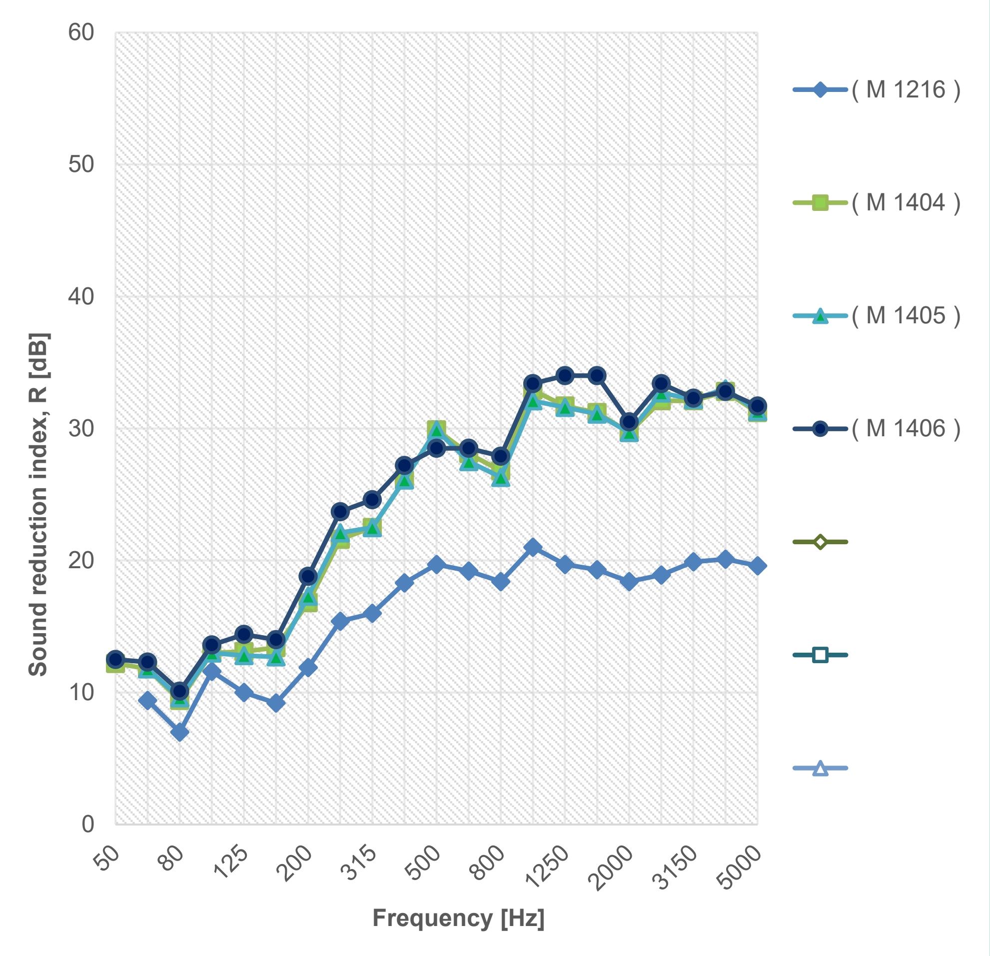


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1216	19	18	Closed with plaster board plate against the boxes.
M 1401	20	19	Perforated, cavity filled with mineral wool
M 1402	25	22	Perforated, cavity filled with mineral wool, 20mm SUND®
M 1403	25	22	Perforated, cavity filled with mineral wool, 40mm SUND®

Some urban areas may necessitate a very high sound reduction index. To demonstrate the full potential of the window, measurements have been performed with absorber placed on some of the transparent surfaces. In order to still work with a solution that allows light in, and ensures that the solution remains comfortable for the user, only tests with absorber placed on the vents and on the opposite side of the vents have been performed, see Illustration 7G. In FIGURE 11 it is seen that by implementing absorber on the vent and on the opposite window is obtained an R_w of 29 dB and an R_w+C_{tr} of 24 dB. It is also seen that there is no difference whether 40 mm or 20 mm is mounted on the frames. Finally, a measurement has been conducted for which the opposite sides of the vents have been filled as much as possible with absorber. This solution must be seen as an absolute maximum measurement for which it is still possible to see through the window. By this is achieved an R_w of 30 dB and an R_w+C_{tr} of 26 dB – in total an improvement compared to the window without absorber of 11 dB for the R_w and 8 dB for the R_w+C_{tr}.

Illustration 7G. Left side: photo taken from the inside showing absorber lined on the vent and the glass on the opposite side of the vent. Right side: photo taken from the outside showing absorber lined on the vent and the glass on the opposite side of the vent.

FIGURE 11. Open window 0.35 m². The sides are perforated 3.14 % 3/5 of the frame, the remaining 2/5 are perforated 34.91 %. The top is perforated 3.14 % and the bottom 34.91 %. All cavities (boxes) are filled with mineral wool.



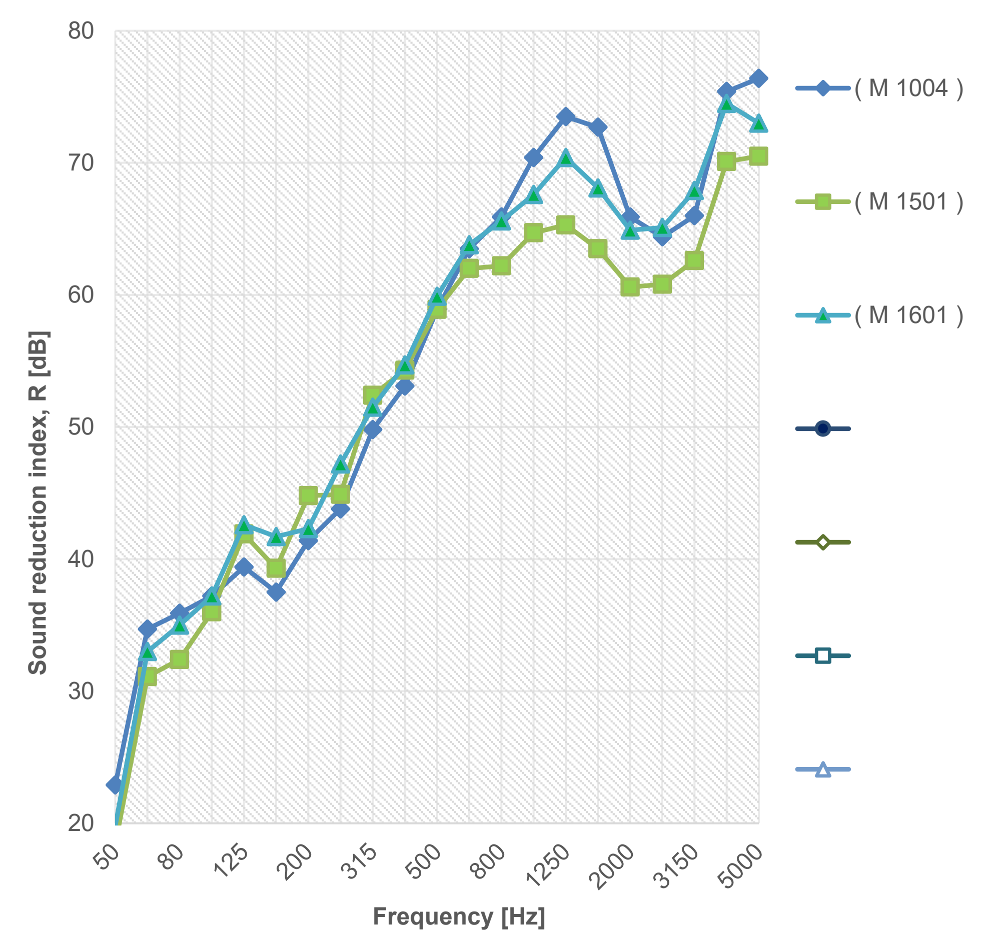
M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1216	19	18	Closed with plaster board plate against the boxes.
M 1404	29	24	Perforated, 40 mm SUND® on the frames, 20 mm SUND® on vents and on glass opposite the vents
M 1405	29	24	Perforated, 20 mm SUND® on the frames, 20 mm SUND® on vents and on glass opposite the vents
M 1406	30	26	Perforated, 40 mm SUND® on the frames, 20 mm SUND® on vents plus 80 mm at the top plus 40 mm at the bottom on the glass opposite the vents

7.4.3 Variation of outer dimensions

All measurements shown in FIGUR 5-FIGURE 11 have been performed on a window with the same dimensions (width x height) 1250 mm x 2100 mm (2.63 m^2). This solution requires rather a lot of space, and thus it is tested which possibilities exist with windows constructed as the supply air window, however with other dimensions. Measurements have been carried out on windows with the dimensions (width x height) 1250 mm x 1500 mm (1.88 m^2) and 900 mm x 2100 mm (1.89 m^2).

Initially, measurements have been performed with closed windows. This has been done to see if there is a profound difference between the windows in general. In FIGURE 12 is seen the measurements of the various windows in the closed position, without any absorber having been added to the window. It is seen that the windows are similar in the low frequency area. It is also seen that from 500 Hz , the smallest of the three windows has the lowest sound reduction, while the two constructions with the same height, but different width are somewhat the same.

FIGURE 12. Closed window. Different dimensions of the supply air window. The measured sound reduction index has not been corrected for flanking transmission.

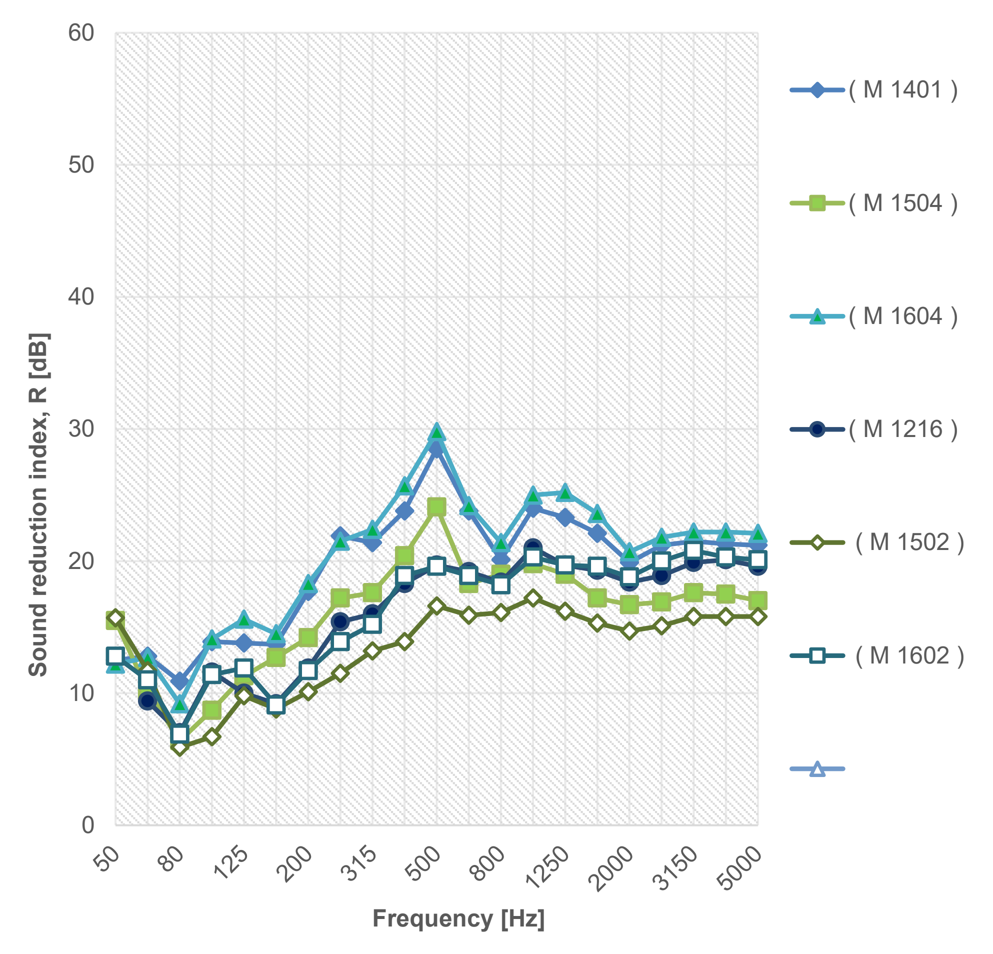


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1004	57	50	Closed, with plasterboard plates at the boxes, no absorbers, 1250 mm x 2100 mm
M 1501	58	51	Closed, with plasterboard plates at the boxes, no absorbers, 1250 mm x 1500 mm
M 1601	59	52	Closed, with plasterboard plates at the boxes, no absorbers, 900 mm x 2100 mm

The various dimensions are desired compared in the open position. However, due to the construction of the narrow high window, it is not possible to fully compare the measurements, as the window can only open 0.28 m^2.

FIGURE 13 displays the measurements performed on three different windows. These have been based on a solution without added absorber and a solution with perforated plates and porous absorber. As with the measurement for the closed position, it is seen that the two tall constructions differ. They perform approximately 3 dB better R_w+C_{tr} compared to the short, wide window. However, it must be assumed that the degree of opening of 0.28 m^2 for that one window is of significance. Even though this is taken into consideration, there is a tendency that the higher the construction, the better the window performs, as the sound must travel a longer distance.

FIGURE 13. Open window 0.35/0.28 m². Influence of perforated absorbers in different dimensions.

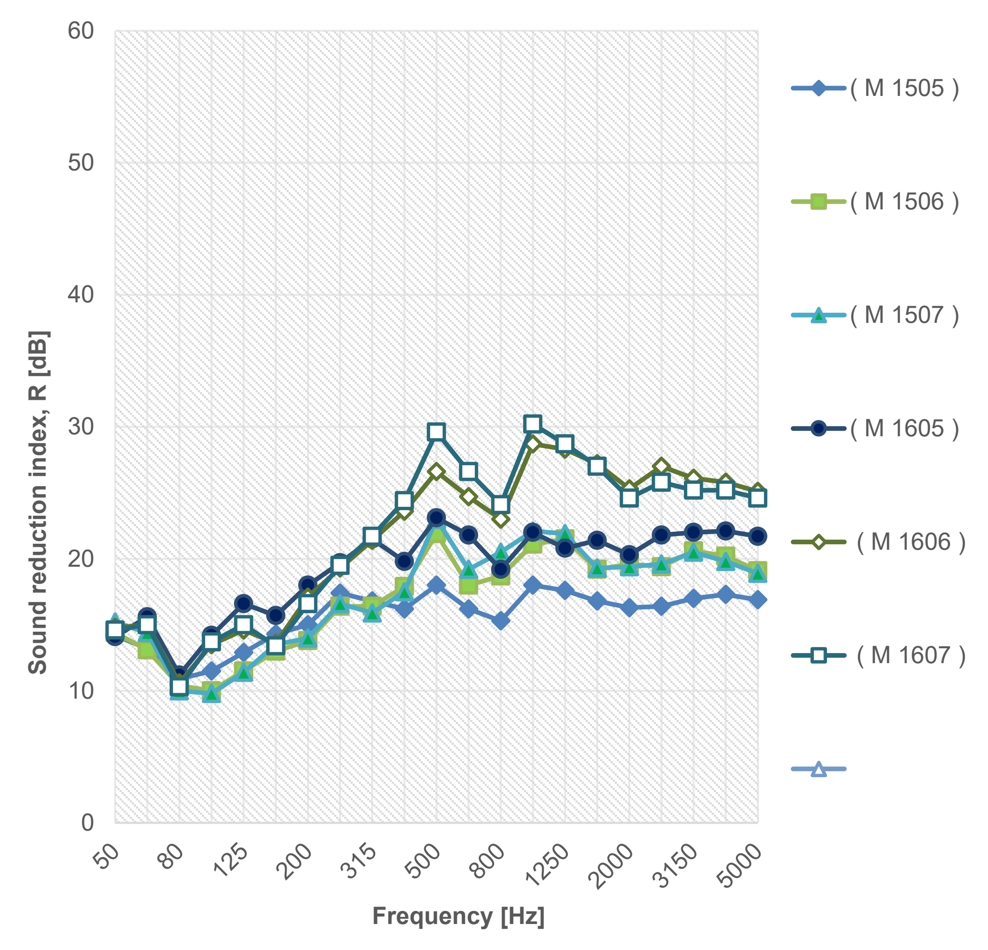


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1401	22	21	Perforated bottom 34.91 %, top 3.14 %, sides 3/5 perforated 3.14 % and 2/5 perforated 34.91 %. Cavity/box filled with mineral wool. 1250 mm x 2100 mm
M 1504	18	18	Perforated bottom 34.91 %, top 3.14 %, sides 1/3 perforated 3.14 % and 2/3 perforated 34.91 %. Cavity/box filled with mineral wool. 1250 mm x 1500 mm
M 1604	23	22	Perforated bottom 34.91 %, top 3.14 %, sides 3/5 perforated 3.14 % and 2/5 perforated 34.91 %. Cavity/box filled with mineral wool. 900 mm x 2100 mm
M 1216	19	18	Closed with plaster board against the boxes.1250 mm x 2100 mm
M 1502	16	15	Closed with plaster board against the boxes.1250 mm x 1500 mm
M 1602	20	18	Closed with plaster board against the boxes. 900 mm x 2100 mm

For the measurements displayed in FIGURE 13, as for other measurements, applies that in order to increase absorption at higher frequencies, porous absorber is affixed on the frames. This leads to the measurements as presented in FIGURE 14. It is seen from the measurements of the tall, narrow window and for the short window that high absorption is achieved at the higher frequencies.

It is also seen that there is a comparable benefit by applying the absorber for the tall as well as the short windows. This will obtain an increase of 5 dB for the R_w and 3 dB for the R_w+C_{tr}, respectively, for the tall window and 3 dB for the R_w and 3 dB for the R_w+C_{tr} respectively for the short window. This is probably due to the fact that the amount of added absorber relative to area, is close to being the same.

FIGURE 14. Open window 0.35/0.28 m². Different dimensions of the supply air window with perforated absorbers and SUND®.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 1505	17	17	Perforated bottom 34,91 %, top 3.14 %, sides 1/3 perforated 3.14 % and 2/3 perforated 34.91 %, cavity filled with air, 1250 mm x1500 mm
M 1506	20	18	Perforated bottom 34.91 %, top 3.14 %, sides 1/3 perforated 3.14 % and 2/3 perforated 34.91 %, cavity filled with air, 20 mm SUND® on the frame,1250 mm x 1500 mm
M 1507	20	19	Perforated bottom 34.91 %, top 3.14 %, sides 1/3 perforated 3.14 % and 2/3 perforated 34.91 %, cavity filled with air, 40mm SUND® on the frame,1250 mm x 1500 mm
M 1605	21	20	Perforated bottom 34.91 %, top 3.14 %, sides perforated 3/5 3.14 % and 2/5 perforated 34.91 %, cavity filled with air, 900 mm x 2100 mm
M 1606	26	23	Perforated bottom 34.91 %, top 3.14 %, sides 3/5 perforated 3.14 % and 2/5 perforated 34.91 %, cavity filled with air, 20 mm SUND® on the frame, 900 mm x 2100 mm
M 1607	26	23	Perforated bottom 34.91 %, top 3.14 %, sides 3/5 perforated 3.14 % and 2/5 perforated 34.91 %, cavity filled with air, 40 mm SUND® on the frame, 900 mm x 2100 mm

7.5 Recapitulation

This part of the project has ben based on the previous construction of the ”supply air window”. The solution is built on the same format as previously. The idea for this work package was to enhance the reduction number by increasing the absorption, in the low frequency area. Initially, calculations for a resonator-based solution and a solution with perforated plates have been performed, as well as measurements with an open cavity wall to indicate whether this could increase the low frequency absorption. By opening up to the cavity wall, an improvement of the R_w+C_{tr} of 8 dB was found, as opposed to a solution with pure plaster board in the frame and 4 dB compared with measurements where 40 mm SUND® had been applied to the frame.

In the laboratory, a large number of measurements have been performed on the resonator based solution as well as the perforated solutions. For this resonator based solution, there was no benefit in inserting resonators in the frame. However, measurements with pure tones have shown that noise reduction of these could be achieved. Measurements performed for the perforated solutions display good results, and improvements are also seen in the frequency areas, where calculations had predicted the improvements. A difference is seen in the sound reduction index at low frequencies, while the reduction index at the higher frequencies is of the same size as in the solution, where the boxes have been closed by plastic boards. To increase the single-number quantity maximally, previously found conclusions are used and SUND® absorber is affixed to the outside of the perforated plates. An improvement of the R_w+C_{tr} of 2 dB is achieved, compared to a construction without perforated plates with 40 mm SUND®. By increasing the amount of absorber in the window by placing SUND® on the opener and the opposite glass on the opener and the glass opposite the opener, and improvement of the R_w+C_{tr} 8 dB is achieved compared to a frame mounted with plaster boards.
A number of measurements have been performed for various window dimensions. Just as in the first supply air window project, the results show that it is important to have a substantial height of the window and thus a long ”distance” for the traveling noise. There is a difference between a tall and a short window of R_w+C_{tr} 3-4 dB.

For the two types of tested constructions, only that with the perforated plates displays an improvement. For the resonator solution there was no improvement compared to the first supply air window project. For the perforated solution, there is a significant difference compared to that of the previous project. An R_w+C_{tr} of 22 dB has been achieved for the perforated solution with 20 mm SUND®. In the previous project the R_w+C_{tr}-value with 20 mm SUND® was 19 dB. This implies an increase of 3 dB. When comparing the two maximum measurements from the previous, and from this present project, an increase from an R_w+C_{tr} of 24 dB to 26 dB is seen. That results in an increase of 2 dB. Such increases in the reduction number are found entirely by inserting perforated plates.

8. Window type 2: ”Ordinary window” with internal solution

Illustration 8A. Prototype for ”ordinary window” with internal solution.

This chapter describes an ”ordinary window” with an internal solution, for which the main purpose is to improve a standard window's sound insulation, without adding anything to the window on the outside.

The construction principle focuses on opening windows (windows which can be opened) with moderate sound insulation in the open position, i.e. a window that may be used in areas, where the noise level is approximately 5 dB above the limit. As opposed to supply air windows, which often require a special window format and vents, placed top and bottom, respectively, and shutter solutions, which will influence the design and appearance of the inside facade, the idea is to be able to use ordinary windows with ordinary opening functions (e.g. side- or top-hung) combined with an inside sound barrier in the window.
Thus the aim is to work with a less expensive solution, (than the supply air window) which fits an ordinary size window (in this case width x height at 1250 mm x 1500 mm). The reference is therefore a single two-winged window, as shown in Illustration 8B.

Illustration 8B. Photos of reference window: Single two-winged window shown from both inside (left photo) and outside (right photo).

8.1 Developing the solution principle

The principle could be that in a traditional double window construction between the two layers of glass, sound barriers could be established, which will only appear, when the window is open. The sound barrier must ensure that there is a ”detour”, which will reduce the direct sound transmission, simultaneous with a certain amount of sound absorption occurring in the window cavity.

When the window is closed the “sound-shutter” is folded in and parked in the frame or rolled-up to the top of the window, so that there is a free view through this. The “sound shutter” will, when in function, partly shut-off the inflow of light/free view.

Focus has been on two solutions. One solution focuses on a two-winged side-hung window with two frames (hereinafter denominated “two-winged”), whereas the other focuses on a one-winged side-hung window with one frame (hereinafter denominated “side-hung”).

Illustration 8C. Photo of the closed double window seen from the inside.

A basis window structure has been constructed, to be used for both solutions, all according to which frames are opened. The structure consists of 2x2 frames, which have been put together as depicted in Illustration 8D (right hand side) – see other photos in Illustrations 8C and 8D (left hand side). In the case with the two-winged window, the set-up is as in the left photo in Illustration 8D.

Illustration 8D. Photos of the window when open. Left photo shows the window opened as a two-winged side hung window, while the right photo shows the window with all the sashes opened.

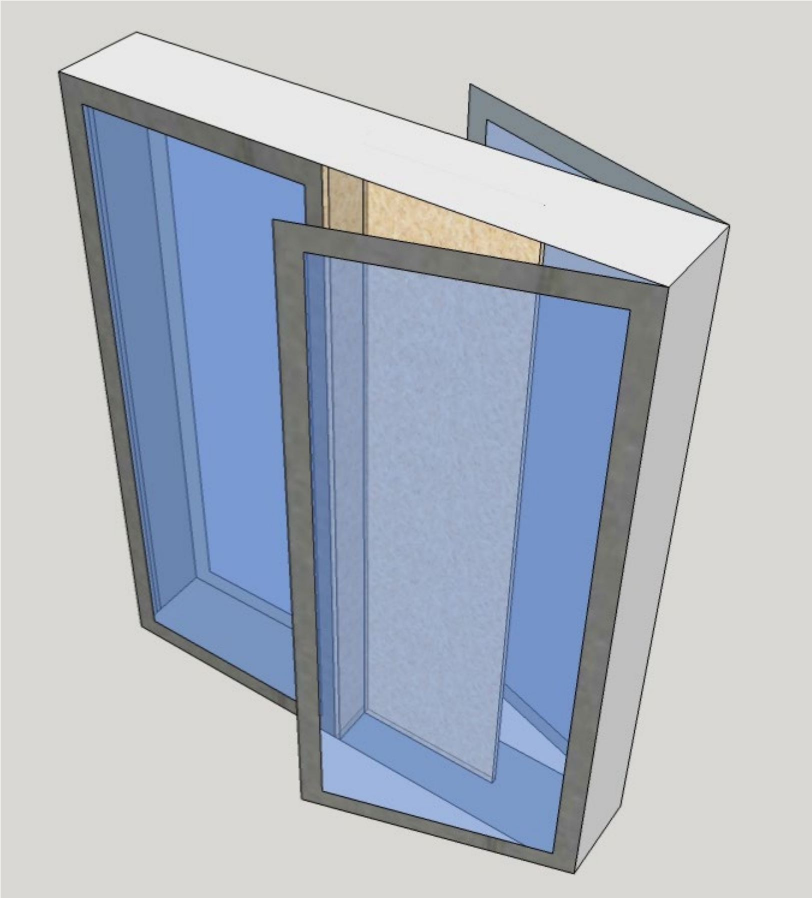


Illustration 8E. Sketch of the construction of the two-winged side hung window (see Illustration 8F for cross section through same sketch).

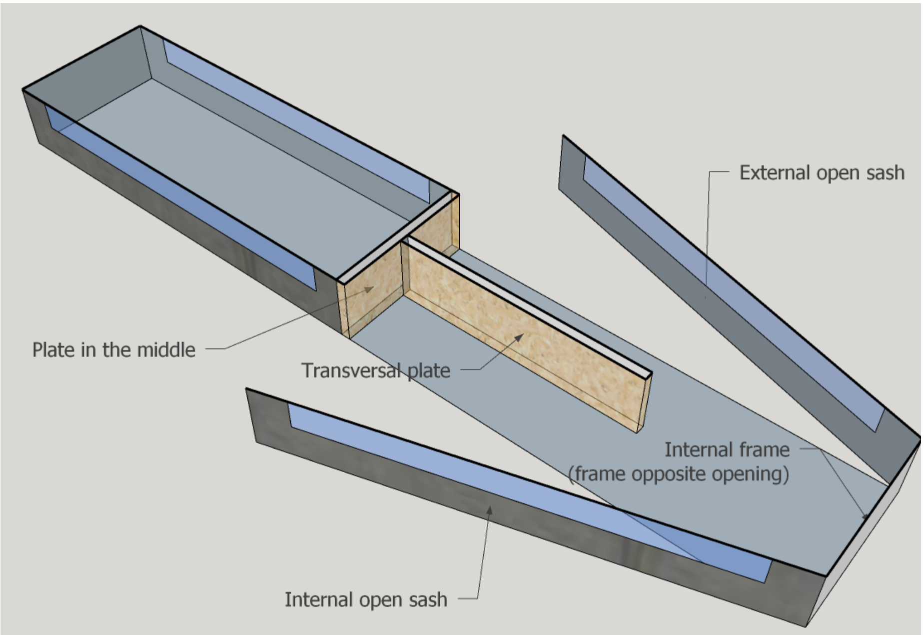


Illustration 8F. Horizontal cross section showing the two-winged side hung setup (see Illustration 8E).

In Illustrations 8E and 8F are shown a sketch of the two-winged setup. The two-winged window is parted in the middle by a plate, on which the transversal plate is mounted. Both the middleplate and the transversal plates are made of plywood for the mockup-measurements. During the measurements, absorbers are placed on the middle and transversal plates and in the frame (on the side, top and bottom).

In the same way, the sketches in iIllustrations 8G and 8H display how the side-hung window is constructed (It is not a ”real” one-winged side-hung window, but it is expected that the results, measured in this construction will be come very close to an actual one-winged side-hung window, since the more narrow angle, which would occur in a “correctly” side-hung solution, would be without significance as regards noise reduction issues). The Illustrations display, how a sound-absorbing element (in this case a transversal plate) is thought integrated in the cavity wall between the two window sections. Measurements will be performed with the transverse plate having alternating length and absorbing ability. Measurements will be made, which meet the requirement of a circulation area at 0.35 m^2 and measurements, for which the opening area is kept at 0.35 m^2, but the circulation area in the narrowest spot is smaller.

In the final version of the windows for the two-winged as well as the side-hung solutions, the aim is that the transversal plate(e.g. a foldable plate of absorbing material) will slide back, in order to still get the full inflow of light, when the window is closed. Another possibility is to make a plate from a transparent material, so as to avoid complicated solutions such as a foldable plate, and to ensure transparency.

For construction of the transversal plates and the “plate in the middle”, respectively, ordinary plywood have been applied. As absorbing material, SUND® Miljöundertak with a thickness of 20 mm has been applied. On a few occasions (on the inflow side of the frame for the two-winged construction) a thickness of 40 mm has been applied. As sheathing of the frames, the same absorber with a 20 mm thickness has been applied. In some cases, measurements have been performed with an inflow absorber (absorber applied at the side of the frame – as opposed to on the transversal plate) of a 40 mm thickness in the two-winged configuration.

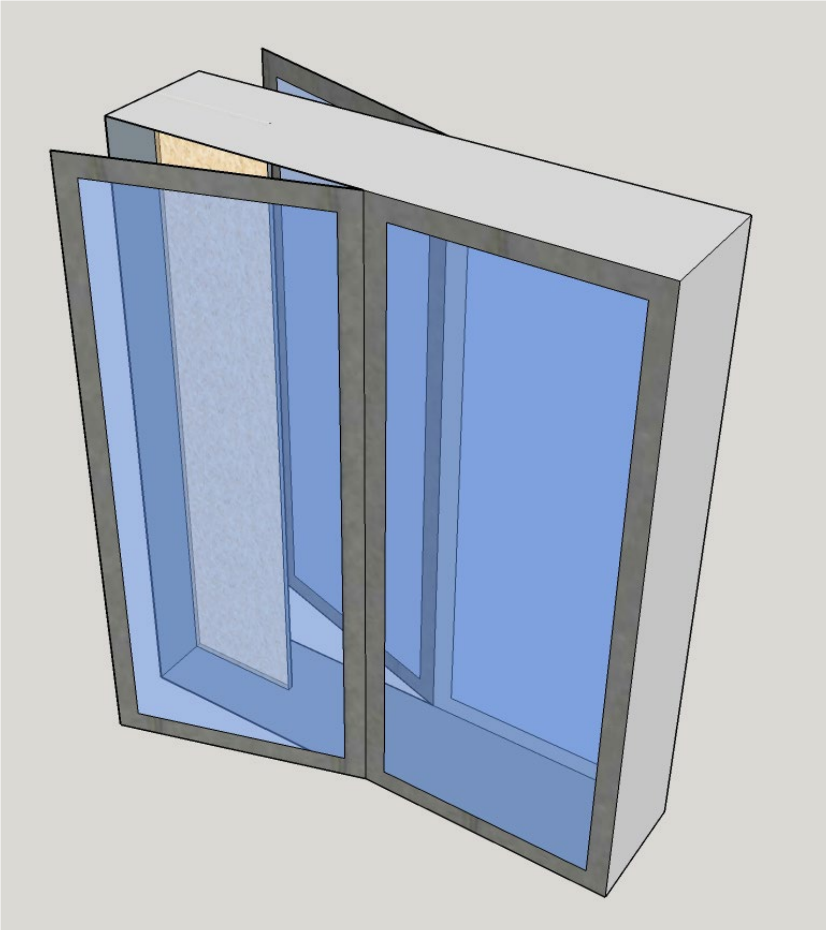


Illustration 8G. Sketch of the construction of the one-winged side hung window (see Illustration 8I for cross section through same sketch).

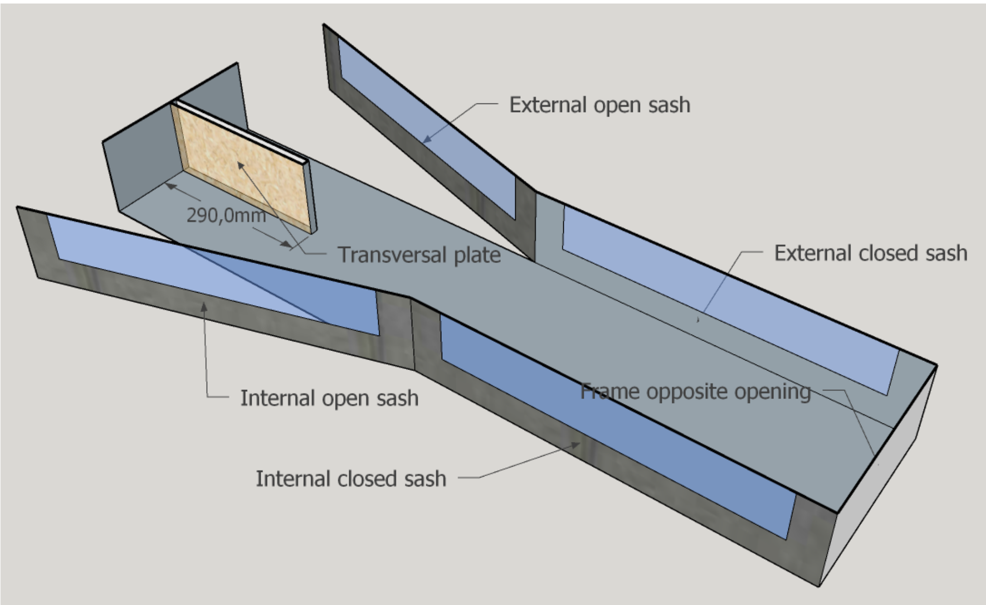


Illustration 8H. Horizontal cross section through same sketch, which shows the one-winged side hung test setup (see Illustration 8H).

8.2 Laboratory measurements on mockup-solution

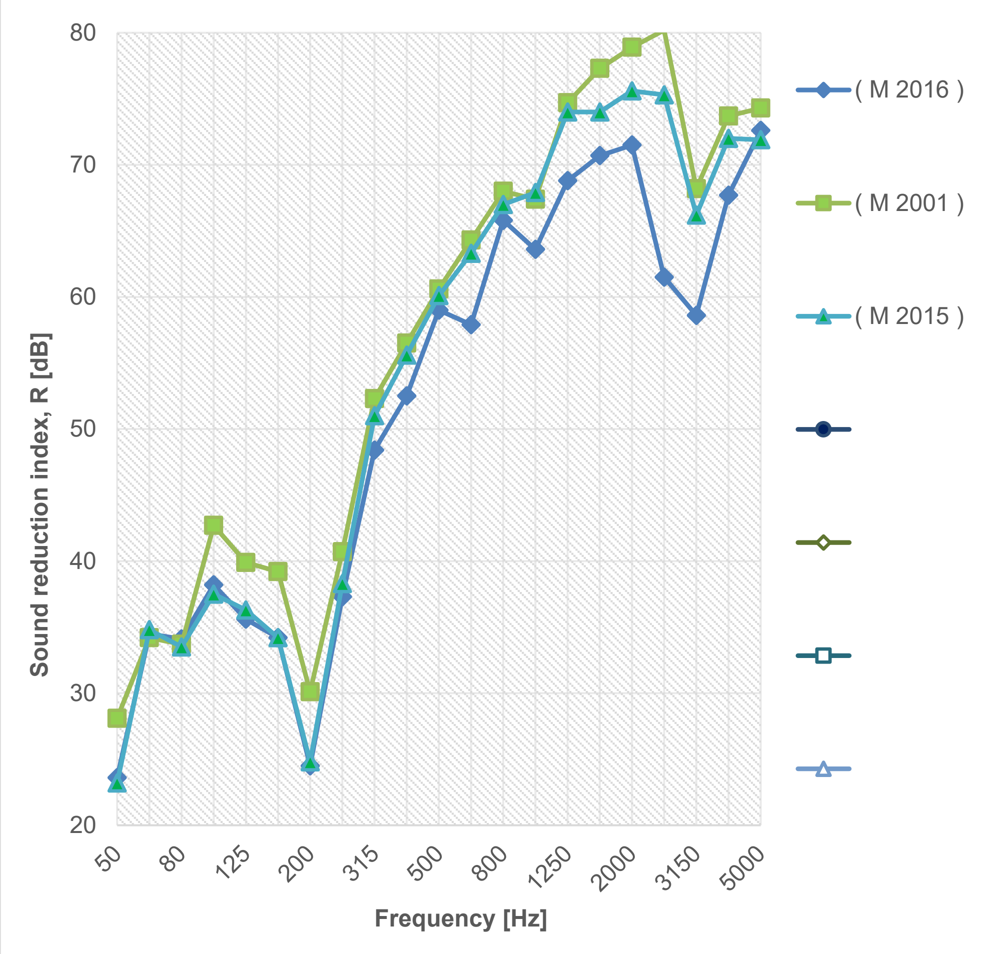
Subsequently, a number of laboratory measurements have been carried out on mockup-solutions.

8.2.1 Two-winged solution

Illustration 8I. Photo of two-winged solution during measurement. Absorbers can be seen on both the plate in the middle and in the frame (both in the side and in the bottom), but not on the transverse plate.

Firstly, the sound insulation of the closed double window and the effect of the middle plate and the addition of absorber are examined. It can be seen from FIGURE 15 that, in general, the closed configurations follow each other within the frequency area 100-1200 Hz. It is also seen that the configurations without a mounted plate at the sash bar are in line with each other at the lowest frequencies. Better reduction is obtained for the high frequencies, which is due to the 20 mm SUND®, mounted in the frame. The last configuration, on which the plate in the middle is mounted by the sash bar, in general has better sound insulation. This may be due to the amount of absorber being increased with the free surfaces at the now-mounted plate in the middle and the altered cavity wall.

FIGURE 15. Closed windows with different internal setup. Absorber thickness (when applied) 20 mm.

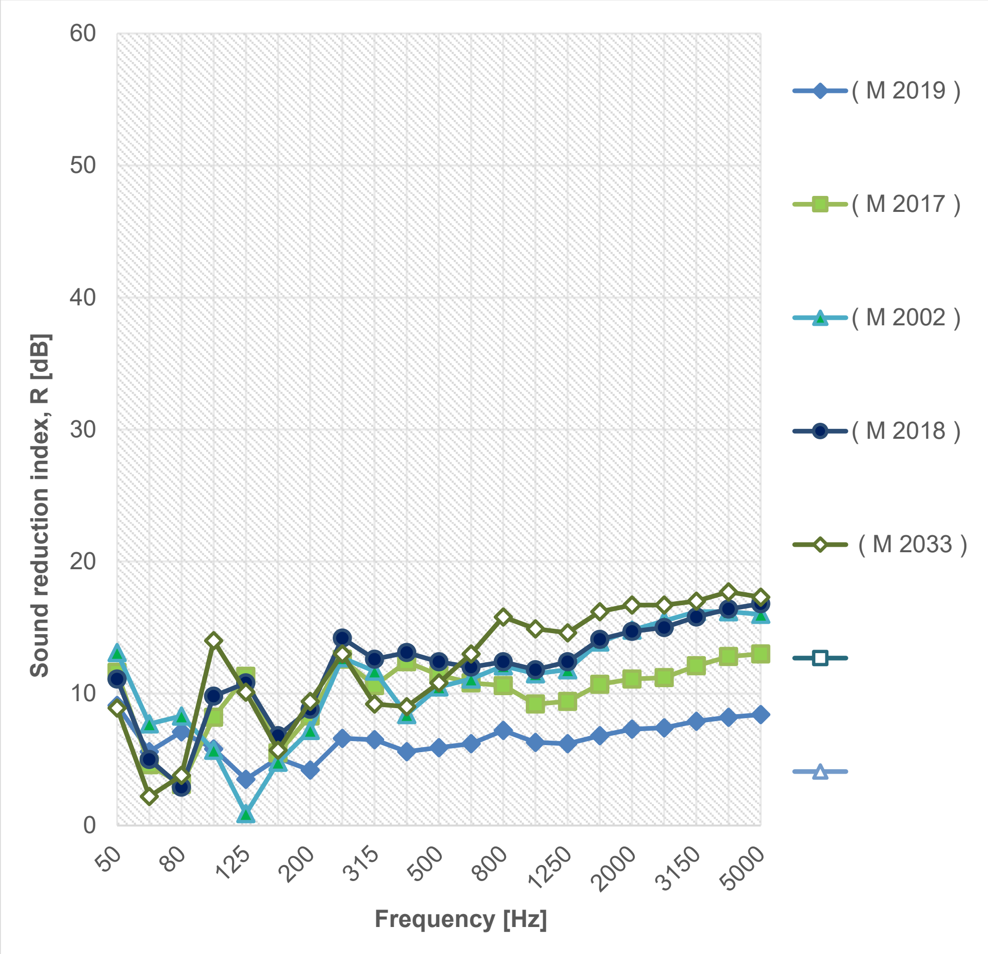


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2016	52	40	Without plate in the middle and without absorbers
M 2001	56	45	With plate in the middle. Absorber on the plate in the middle and at the frames
M 2015	52	40	Without plate in the middle. Absorber at the frames.

With open windows (opening area 0.35 m^2), see Illustration 8I, it is seen from FIGURE 16 that there is a significant improvement from the reference solution (one single window) to a double construction for an open window (0.35 m^2).The R_w+C_{tr} is increased by 4-7 dB as per the composition of the double construction and addition of absorption. However, it should be noted that there is also a significant difference between the various double constructions in the spectre. The difference appears, when a plate in the middle is to be mounted at the sash bar. There is a dip at approximately 125 Hz, when the plate in the middle is mounted. An explanation to this difference might be that the dimension of the cavity wall between the two windows has changed. The wavelength for 125 Hz is approximately 2.72 m, which results in a quarter length of 0.68 m. This length is very close to the distance between the plate in the middle and the frame. This means that certain frequencies go through the window without too much of a loss.

In constructions, where the plate in the middle has been removed, the significant dip is seen to disappear from approximately 125 Hz. In return, a new dip appears, however, not quite so remarkable, at approximately 70 Hz. The wavelength for 70 Hz is approximately 4.9 m, which results in a quarter length of 1.23 m. This distance concurs very well with the distance between the two frames. And this means that certain frequencies may pass through the window without major losses.

FIGURE 16. Significance of the plate in the middle plus comparison between reference window, two-winged double window and one-winged double window. The sashes are opened 0.35 m^2 and the thickness of the absorbers is 20 mm.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2019	7	6	Reference window / single window
M 2017	11	10	Two-winged. Without plate in the middle. Without absorbers.
M 2002	13	11	Two-winged. With plate in the middle. Absorbers on the plate in the middle and at the frames.
M 2018	14	12	Two-winged. Without plate in the middle. Absorbers at the frames.
M 2033	14	13	One-winged. Without plate in the middle. Absorbers at the frames.

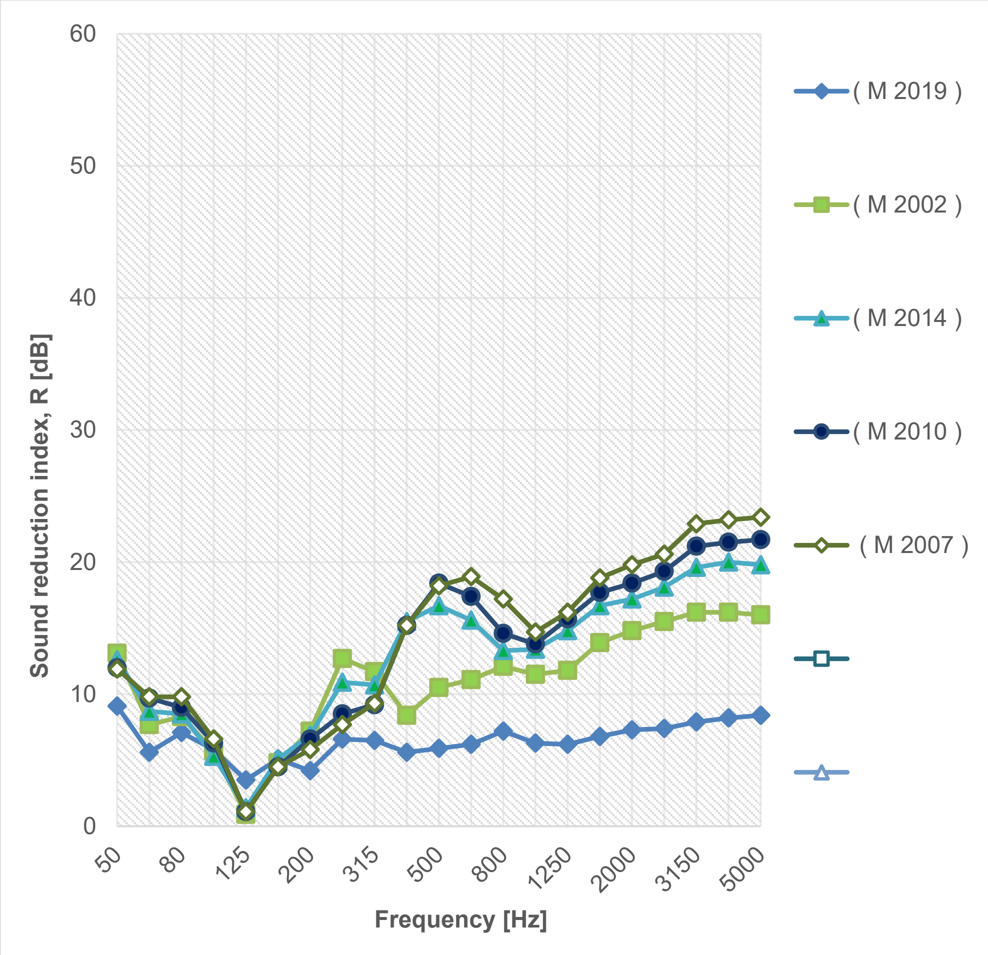
In this part of the project, focus has not been on removing the dip at 125 Hz. Thus, all measurements with the middle plate will include the dip more or less pronounced.

For the final construction with a plate in the middle mounted at the sashes, a perforated solution may be imagined. The solution must make use of the cavity in the closed part of the two-winged window. The degree of perforation must be adjusted to 125 Hz, so that this frequency is extraordinarily reduced/lowered. This construction will most likely entail that the transversal plate must be fixed. With a perforated plate in the middle, a folded plate or a blind is not an option.

FIGURE 17 to FIGURE 19 compare various constructions in the cavity for the two-winged window. The constructions include various lengths of the transversal plate from 20-35 cm counted from the plate in the middle, where the opening area is fixed at 0.35 m^2 and with various absorber setup in the cavity wall.

For the transversal plate with a length of 35 cm, the rule of 0.35 m^2 as the minimum cross sectional area is not kept. To obtain a satisfactory cross sectional area, the “outer” opening area at the actual window must be at least 0.64 m^2. Measurements have been made with both configurations, with and without compliance of the 0.35 m^2 for the circulation area. In FIGURE 17 to FIGURE 19 the determining opening area is defined as the area between the transversal plate.

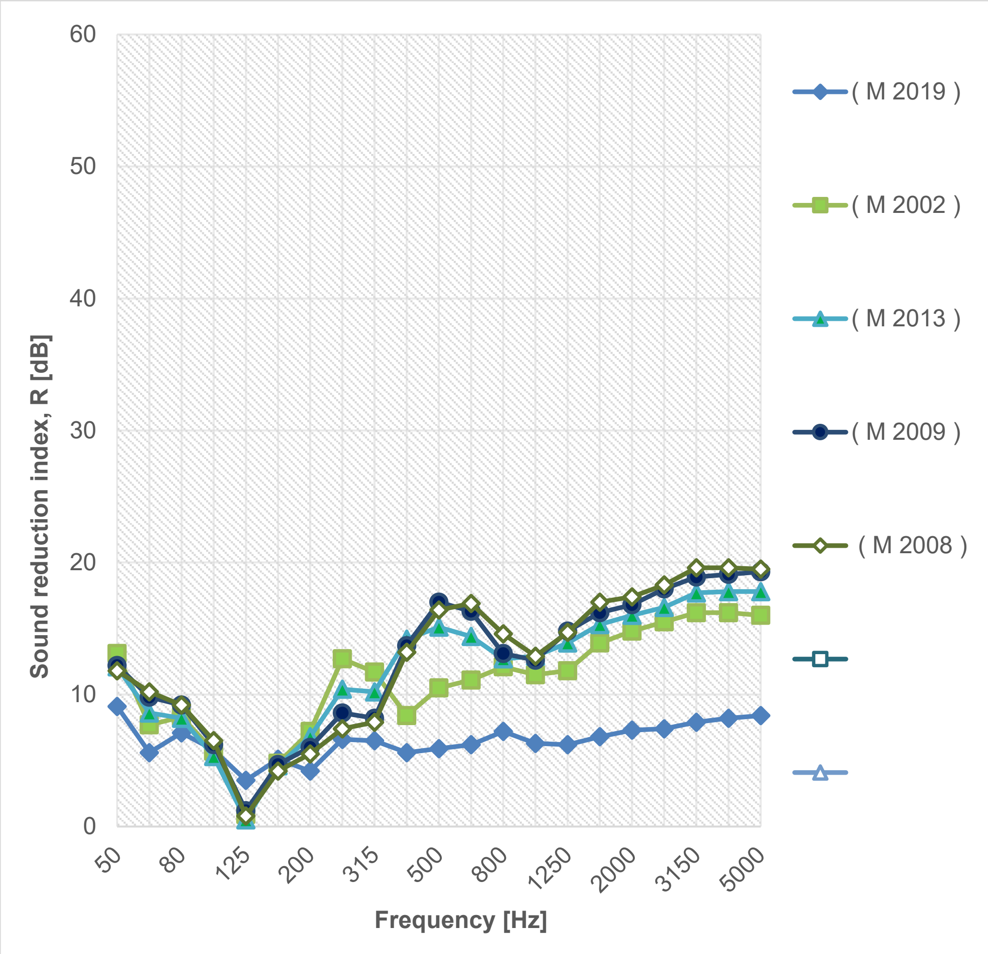
FIGURE 17. Influence of transversal plate with reference to a single window. The plate in the middle is applied (except for the reference setup), and 20 mm absorber line the middle plate, the transversal plate and the frames. The opening area is 0.35 m^2.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2019	7	6	Reference window (single window)
M 2002	13	11	Without transversal plate
M 2014	16	13	Transversal plate with a length of 20 cm
M 2010	17	13	Transversal plate with a length of 29 cm
M 2007	17	13	Transversal plate with a length of 35 cm

FIGURE 17 and FIGURE 18 depict the various plate lengths with and without absorber on the transverse plate, respectively. The value for the R_w+C_{tr} is 11 dB based on a double construction without a transversal plate (but with a plate in the middle) mounted. The variation in the length of the transversal plate is seen to influence the R_w-value a little in both cases, but in the R_w+C_{tr} there is no variation between the values, even though measurements have been performed with a long or short transversal plate. The values are stable for all 2x3 measurement (M 2014, M 2010, M 2007, M2013, M2009 and M2008) with varying lengths of the transversal plate. When comparing with the starting point of 11 dB for the R_w+C_{tr} there is a minor increase of 1 dB per step. This results in an R_w+C_{tr} of 12 dB with a mounted raw plywood and 13 dB with 20 mm SUND® on both sides of the plywood, respectively.

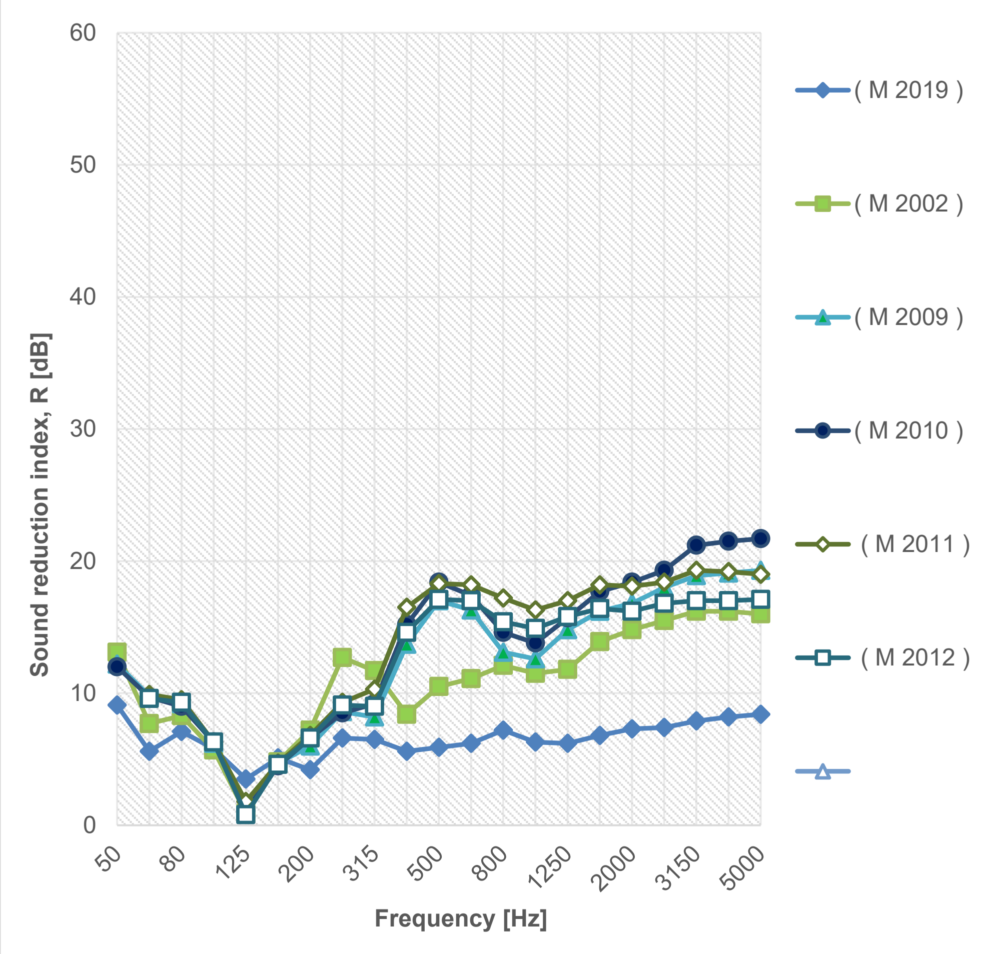
FIGURE 18. Influence of the transversal plate with reference to a single window. The plate in the middle is applied (except for the reference construction), and 20 mm absorber line the frame. The opening area is 0.35 m^2.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2019	7	6	Reference window (single window)
M 2002	13	11	Without transversal plate
M 2013	15	12	Transversal plate with a length of 20 cm
M 2009	15	12	Transversal plate with a length of 29 cm
M 2008	16	12	Transversal plate with a length of 35 cm

In FIGURE 19 the length of the transversal plate, while the absorbers' location and their thickness vary. The transversal plate has a fixed length of 29 cm, the opening area is 0.35 m^2, so that the circulation area is minimum 0.35 m^2 through the entire window. The 29 cm have been chosen since this length will keep the requirements, exactly. Comparison is made with and without absorber, respectively, on the transversal plate, and with varying thickness of the absorber at the inflow frame. As mentioned above, only limited changes will be obtained in the R_w+C_{tr}, by mounting a transversal plate (The R_w+C_{tr} is unaltered for 12 and 13 dB, respectively, without and with absorber on the plate). In case a thicker absorber mounted on the inflow frame, a limited increase is achieved, so that the R_w+C_{tr} is 13 and 14 dB, respectively, without and with absorber on the transversal plate.

FIGURE 19. Influence of different configurations of absorbers with a 29 cm long transversal plate. The opening area is 0.35 m^2.

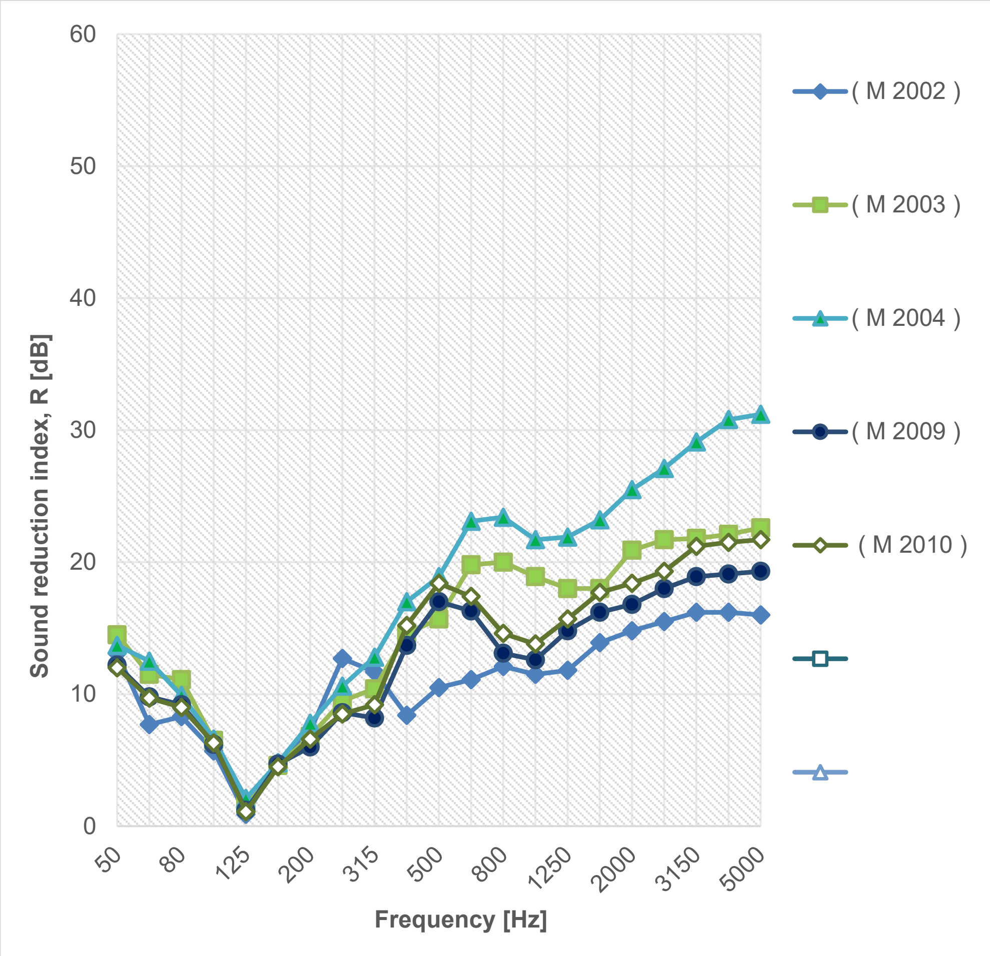


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2019	7	6	Reference window (single window)
M 2002	13	11	Without transversal plate
M 2009	15	12	Without absorber at the transversal plate and with 20 mm absorber at the frame opposite the opening
M 2010	17	13	With absorber at the transversal plate and with 20 mm absorber at the frame opposite the opening
M 2011	17	14	With absorber at the transversal plate and with 40 mm absorber at the frame opposite the opening
M 2012	16	13	Without absorber at transversal plate and with 40 mm absorber at the frame opposite the opening

FIGURE 20 depicts sound insulation for various opening areas and different lengths of the transversal plate. Tests have been made with a transversal plate of 46 cm, which results in an opening area of 0.20 m^2. This measurement is compared with the measurement performed on a plate of 29 cm, which is the largest allowable plate in order to comply with the circulation area of 0.35 m^2. It is seen that the length of the transversal plate combined with a smaller opening area has the effect that the single-number value for the R_w+C_{tr} increases by 2-3 dB compared to a similar measurement, so that the final value will become 14 and 16 dB without and with absorber, respectively.

The fact that the increase in sound insulation with absorber for the transversal plate of 46 cm is higher than for the short plates is due to the fact that the total area covered by absorber is somewhat larger.

FIGURE 20. Comparison of measurement with an opening area of 0.20 m² with and without absorber, and measurement with an opening area of 0.35 m² with and without absorber. As reference is used the configuration without transversal plate with an opening area of 0.35 m².



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2002	13	11	0.35 m². Without transveral plate
M 2003	18	14	0.20 m². Transversal plate 46 cm, without absorber on the plate
M 2004	21	16	0.20 m². Transversal plate 46 cm, with absorber on the plate
M 2009	15	12	0.35 m². Transversal plate 29 cm, without absorber on the plate
M 2010	17	13	0.35 m². Transversal plate 29 cm, with absorber on the plate

8.2.2 Two-winged solution in summary

Various constructions of a two-winged window have been examined. Relative to the reference window (one single window) significant improvement is seen for an open window with installation of an extra window section, so that a double construction with a cavity between the two window sections (improvement of the single figure values of approximately 4 dB for the R_w+C_{tr}).

The cavity wall (between the window sections) has furthermore been modified with transversal plates at various lengths with various configuration of absorbers. By keeping a circulation area of 0.35 m^2 is seen an improvement of up to 4 dB for the R_w+C_{tr} (relative to the double construction without a plate in the middle and absorption). Furthermore, it turns out that variation in the length of the transversal plate, (which maintains the circulation area at 0.35 m^2) does not result in changes to the sound insulation in the single number quantities.

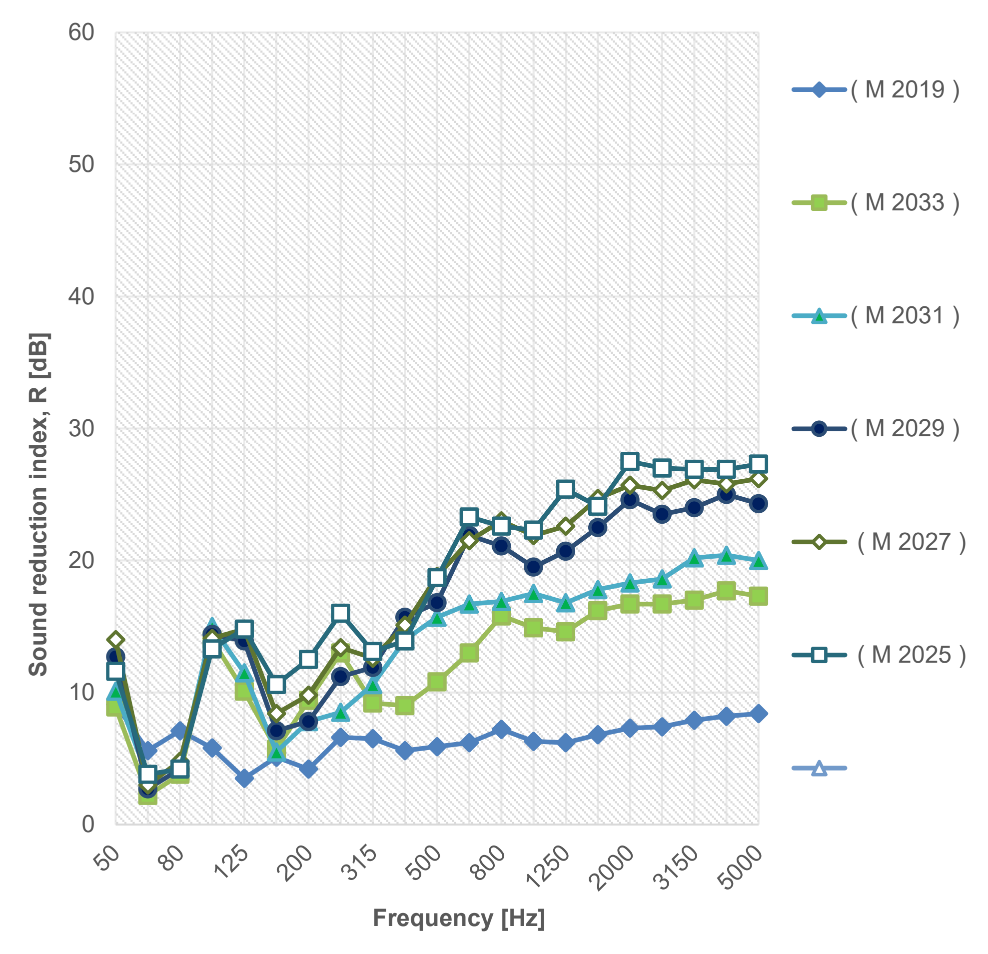
Addition of absorber on the transversal plates will provide improvement of the sound insulation of approximately 1 dB. Calculations have been conducted for which the dip at the 125 Hz is neutralised so that it follows the curve naturally. There is no change in the single number quantities for the measurements, even if the dip is removed. Thus it may be concluded that the results would not have been any different, if the dip was non-existent..

8.2.3 Side hung solution

Similarly, a measuring series has been performed for the simulated side-hung solution, see Illustration 8J. FIGURE 21 and FIGURE 22 show the significance of a varying length of the transversal plate, without and with 20 mm absorbers on the transversal plate, respectively. In summary, it may be concluded that a long transversal plate will result in higher sound insulation, especially for frequencies from 613 Hz and up, but as for the two-winged window, the biggest improvement is obtained when changing from a single window to a double glass window.
However, addition of the transversal plate holds one improvement – up to 2 dB for the solution without absorber on the transversal plate and 3 dB for the solution with absorber on the transversal plate (for R_w+C_{tr}) – for lengths of the transversal plate up to 29 cm. To obtain a cross section of 0.35 $m^{2,}$ the length of the transversal plate can be no longer than 29 cm. Measurements conducted on a plate of 51 cm, result in a circulation area of 0.20 m^2. For the plates with the lengths of 60 and 70 cm, the circulation area is 0.15 m^2. The sound insulation (R_w+C_{tr}) increases by 3 and 2 dB with and without absorber, when the opening area is cut down to 0.2 m^2 (51 cm plate). The sound insulation (R_w+C_{tr}) increases another 2 dB without absorber and 4 dB with absorber by extending the transversal plate from 51 cm to 70 cm.

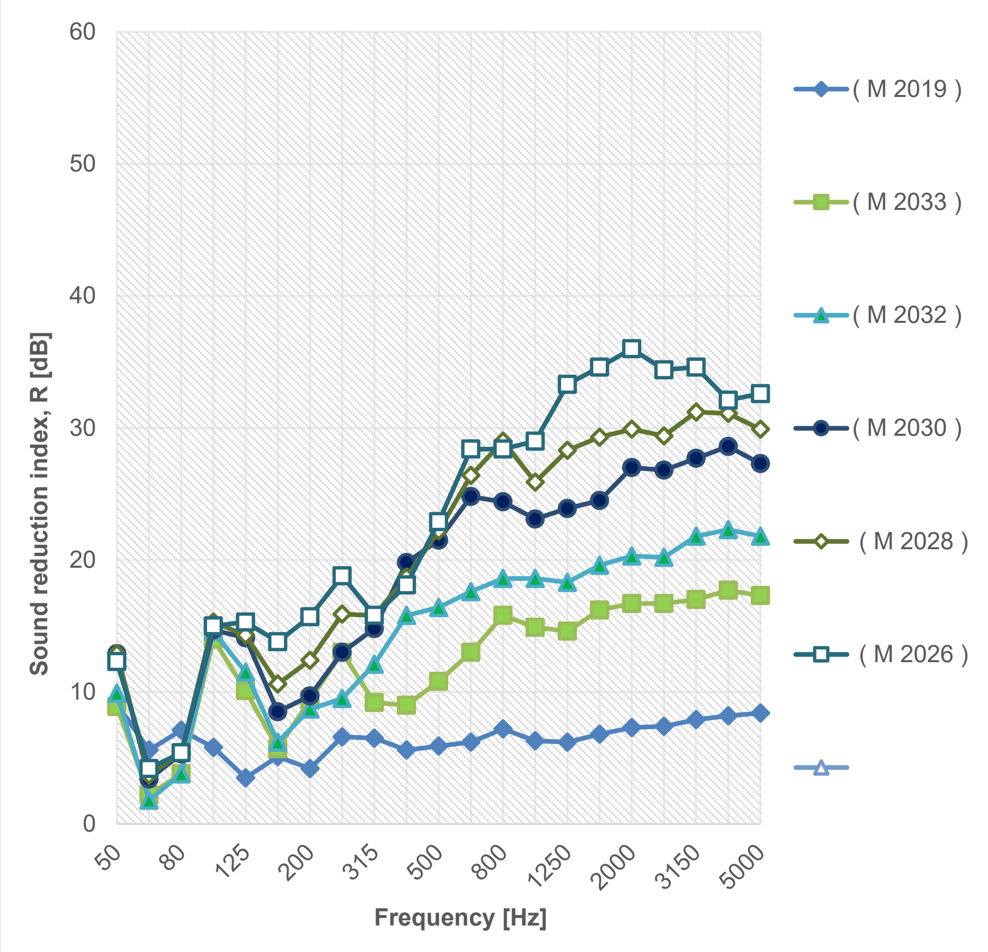
Illustration 8J. Photos of the simulated one-winged sidehung solution without absorbers on the transversal plate.

FIGURE 21. Comparison of different length of the transversal plate mounted in the one-winged side hung configuration without absorber on the transversal plate. The opening area is 0.35 m^2.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2019	7	6	Reference window (single window) – (configuration as two-winged)
M 2033	14	13	Double window, without transversal plate
M 2031	17	15	Double window, transversal plate, length 29 cm
M 2029	20	17	Double window, transversal plate, length 51 cm (0.2 m^2)
M 2027	22	18	Double window, transversal plate, length 60 cm (0.15 m^2)
M 2025	23	19	Double window, transversal plate, length 70 cm (0.15 m^2)

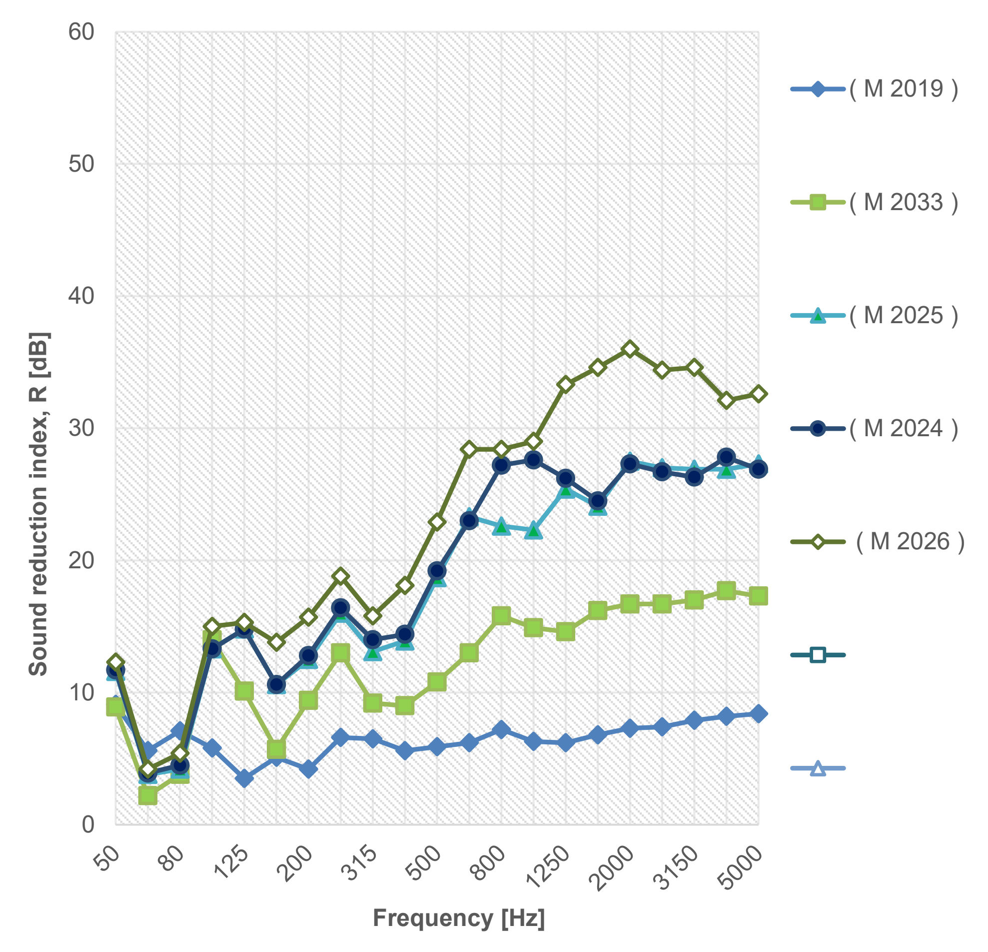
FIGURE 22. Comparison of different lengths of the transversal plate mounted in the one-winged side-hung configuration with 20 mm absorber on the transversal plate. The opening area is 0.35 m^2.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2019	7	6	Reference window (single window) – (configuration as two-winged)
M 2033	14	13	Double window, without transversal plate
M 2032	18	16	Double window, transversal plate, length 29 cm
M 2030	23	19	Double window, transversal plate, length 51 cm (0.2 m^2)
M 2028	25	21	Double window, transversal plate, length 60 cm (0.15 m^2)
M 2026	27	23	Double window, transversal plate, length 70 cm (0.15 m^2)

In supplement, the significance of the absorber's position has been examined at a length for the transversal plate of 70 cm (which provides a opening width of 53 cm). The results are shown in FIGURE 23. It may be seen that the thickness of the inflow absorber (absorber applied at the side of the frame – contrary to the transversal plate, see Illustration 8H) is significant in the frequency area 800-1000 Hz, for which a doubling of the absorber thickness results in a clear improvement of the sound insulation.
The addition of absorber on the entire transversal plate produces a very obvious improvement of the sound insulation in the entire frequency area from 100-5000 Hz. With a transversal plate at a length of 70 cm the increased area of the absorber is close to 2 m^2.

FIGURE 23. Comparison of different configurations of absorbers, all with 70 cm transversal plate (except the reference configuration). The opening area is 0.35 m^2.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2019	7	6	Reference window (single window) – (configuration as two-winged)
M 2033	14	13	Double window, without transversal plate
M 2025	23	19	70 cm transversal plate without absorber and 20 mm absorber at the frame opposite the opening
M 2024	23	20	70 cm transversal plate without absorber and 40 mm absorber at the frame opposite the opening
M 2026	27	23	70 cm transversal plate with absorber and 20 mm absorber at the frame opposite the opening

8.2.4 Side hung solution in summary

Various constructions of a side hung window have been examined. When comparing with the reference window, a significant improvement is seen, when mounting an extra window section, so that a double structure with a cavity wall between the two sections is obtained (improvement of the single number quantities of approximately 4 dB for the R_w+C_{tr}). The cavity wall (between the window sections) has also been modified by transversal plates of various lengths and with different configurations of absorbers.
By maintaining a circulation area of 0.35 m^2 an improvement of up to 3 dB for the R_w+C_{tr} is obtained (relative to a double structure with a plate in the middle and absorption). Contrary to the two-winged window, a clear insulation improvement is seen by extending the transversal plate (which maintains a circulation area of 0.35 m^2). Better improvement may be achieved by even further extension of the transversal plate (circulation area of 0.20 m^2/0.15 m^2). Addition of absorber on the transversal plates results in an improvement of the sound insulation of approximately 2-4 dB (for the R_w+C_{tr}).

8.3 Developing a prototype

Based on the measurements of the mockup-solutions, it was decided to continue with the two winged solution. For the prototype, the transversal plate is replaced by an internal sliding window, i.e. which provides the ability to slide the window to one of the sides entirely, to create a large airflow, and on the other hand, to close the window entirely. Drawings are depicted in Illustrations 8K and 8L.
However, the distance between the window panes is different than what is shown, so that the movable glass-panel is right between the two window panels, see the photos in Illustrations 8A, 8M and 8N. This is an aluminium construction. For practical reasons, for the measurements on the prototype, the window has been mounted in a double plasterboard wall (as opposed to the mockup-solutions, which were mounted in a double concrete wall), as it provides det possibility of working with a deeper frame absorber, see chapter 7. The distance between the window panels is the same as for the two winged mockup-solution.

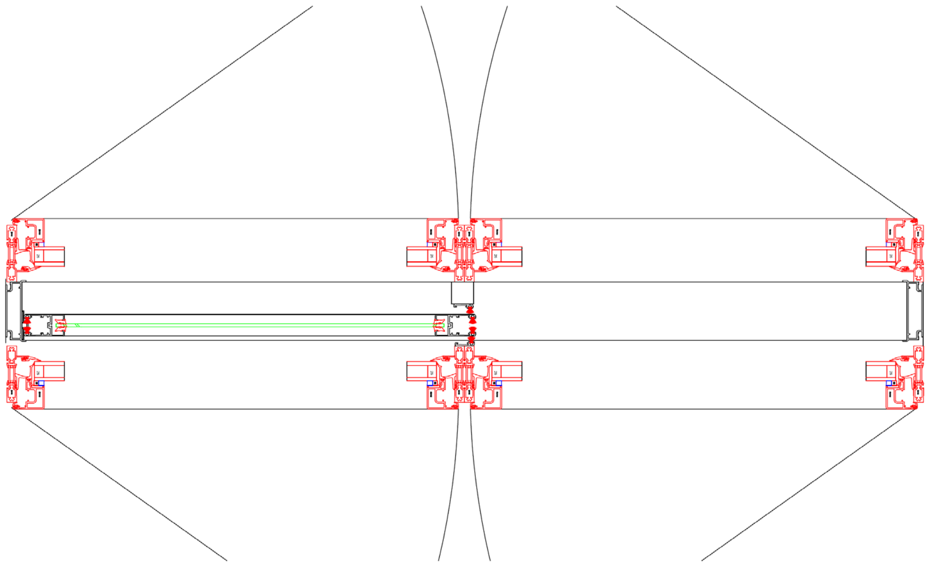


Illustration 8K. Horizontal cross section of the prototype solution.

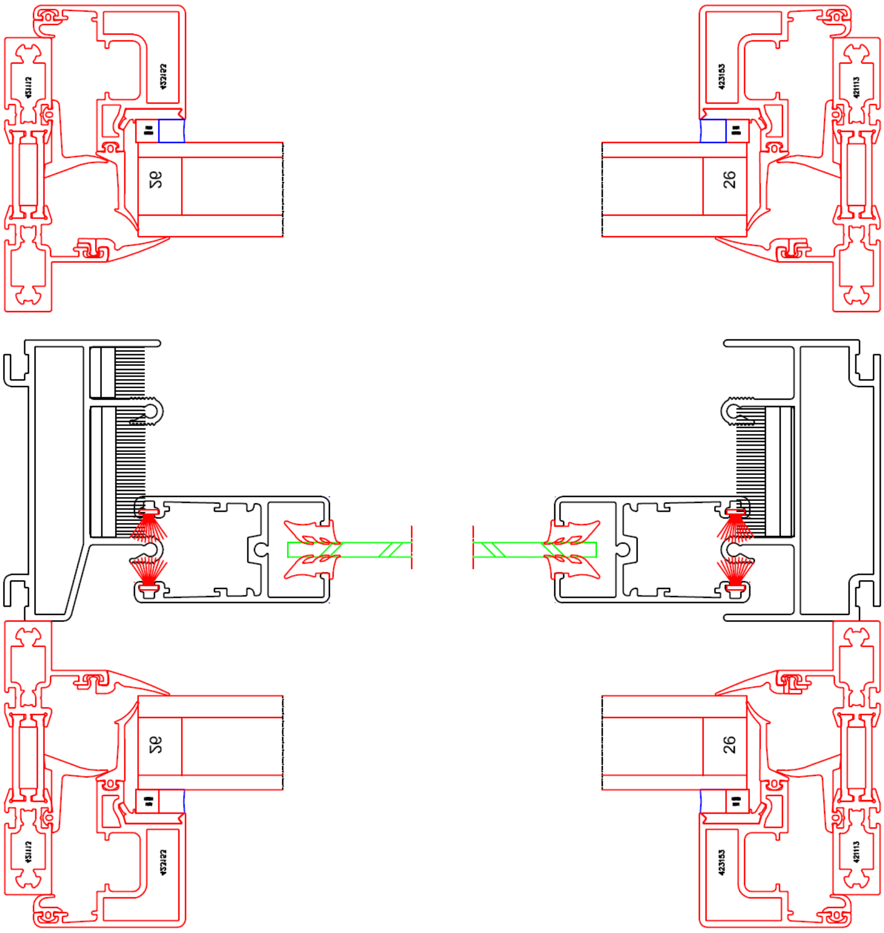


Illustration 8L. Vertical cross section of the prototype solution.

8.4 Laboratory measurements on the prototype

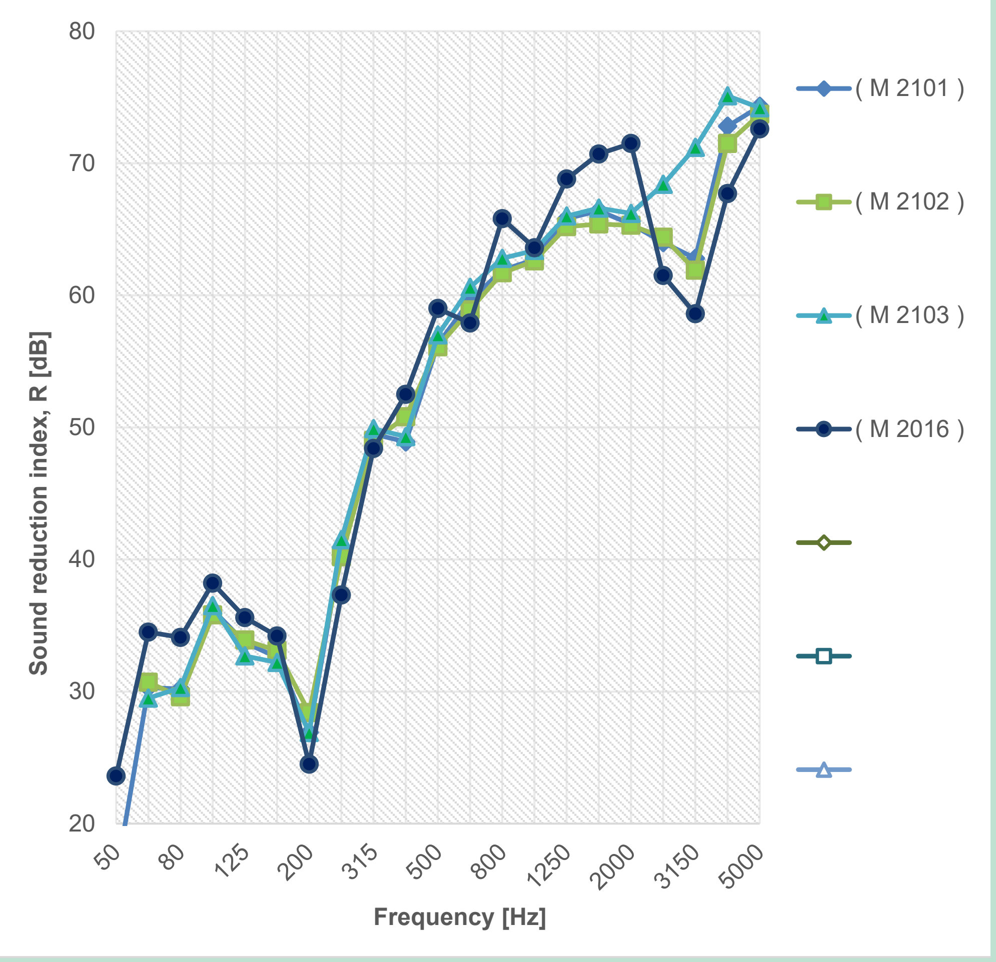
Subsequently, a number of measurements have been performed on the prototype model, which may be seen in the following:

Illustration 8M. Photos of the applied absorber. Left side: 20 mm SUND ®. Right side: Perforated plaster-board plate in front of mineral wool in the wall cavity.

Illustration 8N. Photos of the applied absorbers. Left side: No absorber (non-perforated plasterboard plate). Right side: Opened to the applied mineral wool in the cavity in the double plasterboard wall.

FIGURE 24 depicts the sound insulation for the prototype solution in the closed position (the outer windows in the double structure) with the internal sliding window in different positions with and without frame absorber (please note that any influence from flanking transmission has not been corrected), and compared with a similarly set-up mockup-construction. Overall, there is no huge difference in the results, except for those of the frequency area above 1200 Hz – the curves as well as the single number quantities are comparable.

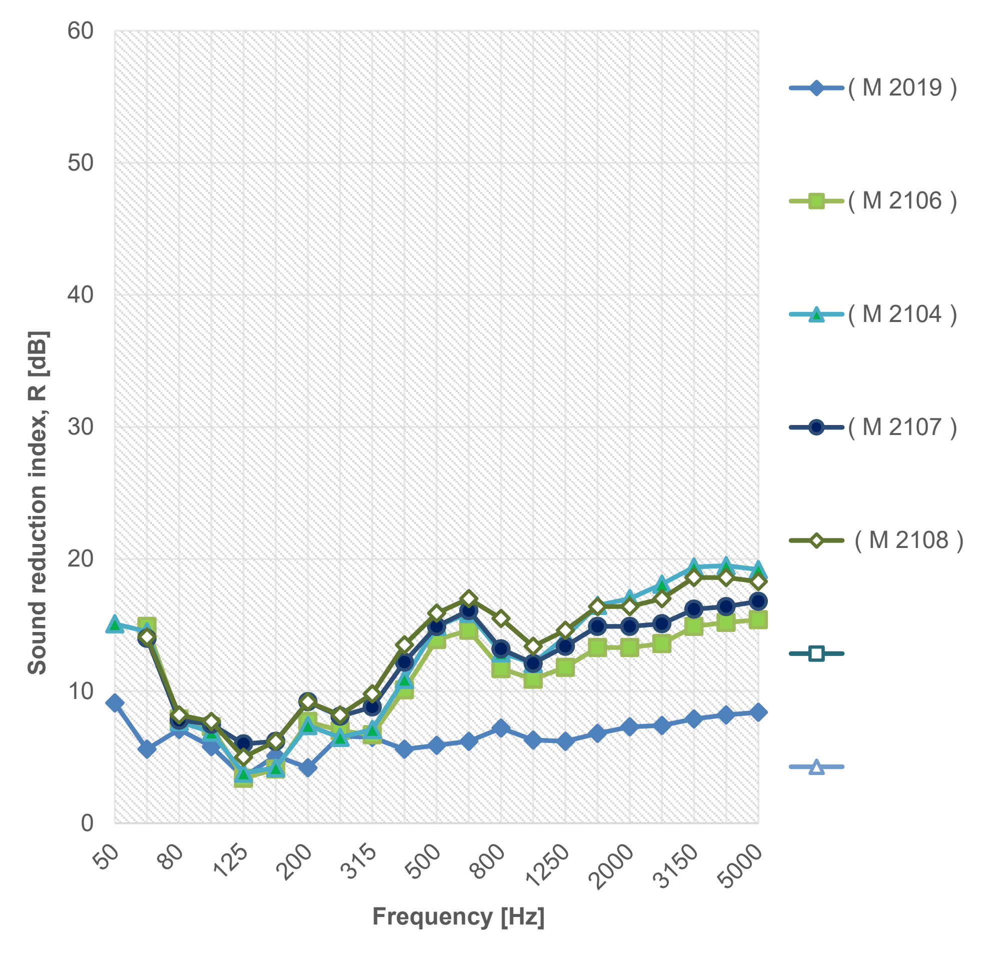
FIGURE 24. Influence of different positions of the internal sliding window for closed windows both with and without absorbers at the frame. Additionally compared with corresponding mockup-construction without absorber and plate in the middle.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2101	52	41	No absorber at frame. Sliding window set 29 cm from the middle
M 2102	53	43	No absorber at frame. Sliding window set 53 cm from the middle
M 2103	52	41	20 mm absorber at frame. Sliding window set 29 cm from the middle
M 2016	52	40	Two-winged mockup. No plate in the middle. No absorber

FIGURE 25 displays the sound insulation for the prototype solution in the open position with the internal sliding window placed so that the opening area and circulation area is just 0,35 m^2 and with different varieties of frame absorbers.
Compared with a single window panel (reference), the sound insulation improvement for frequencies below 300 Hz is limited, whereas the improvement above 300 Hz is much more obvious. For the single number quantities, the improvement is 6-9 for the R_w and 5-7 dB for the R_w+C_{tr}. Compared with the measurement without frame absorber (M 2106) the improvement in sound insulation is limited (Up to 3 dB for the R_w and up to 2 dB for the R_w+C_{tr}), and the best effect is achieved when there is opened to the insulation in the cavity of the double wall.

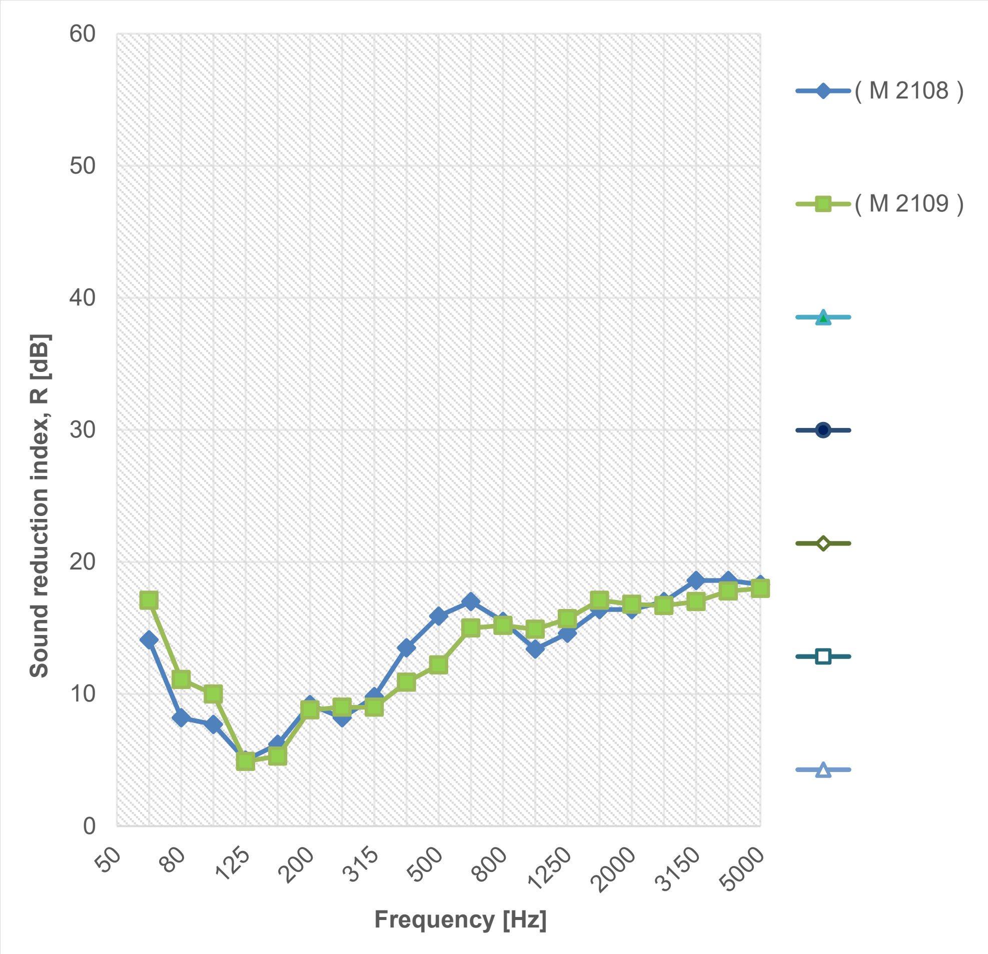
FIGURE 25. Comparison of different variations of absorber at the frame for an open window with the sliding window positioned, so that the opening area and the flow area is just 0.35 m^2.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2019	7	6	Reference window (single window) – (configuration as to-winged)
M 2106	13	11	Without absorber at the frame
M 2104	15	12	With 20 mm absorber at the frame
M 2107	14	12	Perforated plate (with mineral wool behind) at the frame opposite the opening
M 2108	16	13	Fully open, no cover of mineral wool in the cavity at the frame opposite the opening

For the mockup-solution of the same construction (see section 8.2.2) it turned out that the varying length of the transversal plate (which complies with the circulation area of 0,35 m^2) did not involve any significant change in the sound insulation of the single number quantities. The results of varying the internal sliding window is shown in FIGURE 26, and no particular change in the sound insulation is seen in the single number quantities.

FIGURE 26. Comparison of different positions of the sliding window, no cover of the mineral wool in the cavity in double plasterboard wall.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 2108	16	13	Sliding window, set 29 cm from the middle
M 2109	15	13	Sliding window, set 46 cm from the middle

8.5 Recapitulation

This chapter describes an ”ordinary” window with an internal solution, for which the main purpose is to improve the sound insulation of the standard window without adding anything to the window on the outside.
The construction principle focuses on opening windows with moderate sound insulation in the open position, i.e. a window which may be used in areas, where the noise level is approximately 5 dB above the limit value. As reference is used a single two winged window as depicted in Illustration 8B. Firstly, two different mockup solutions have been tested, a two-winged and a side hung window, and subsequently a prototype variant of the two-winged solution has been constructed. Compared with a single two-winged window, is seen a good improvement in the open as well as the closed positions, by adding an internal two-winged window so that a double construction is obtained, for which the improvement in the open position is of the size 5-7 dB for the R_w+C_{tr}. The addition of a transversal plate inside the double window is also significant (1 dB for the R_w+C_{tr}).
Variation in the length of the transversal plate does not seem to have a sound insulation effect on the two winged window. For the side hung solution the addition of a transversal plate has a sound insulating improving effect of up to 2 dB for the R_w+C_{tr}. The addition of absorbing material on the transversal plate has an improving effect of approximately 1 dB for the two-winged solution and approximately 1 dB for the R_w+C_{tr} for the sidehung solution. Addition of frame absorbers is also improving, as per the construction/location.

The purpose with the construction was to increase the sound insulation approximately 5 dB compared to that of an ordinary window. For the solution, has been obtained an R_w of 15 dB and an R_w+C_{tr} of 12 dB, which is a total improvement for the R_w of 8 dB and for the R_w+C_{tr} of 5 dB compared to that of an ordinary open window.

9. Window type 3: ”Ordinary window” with external solution

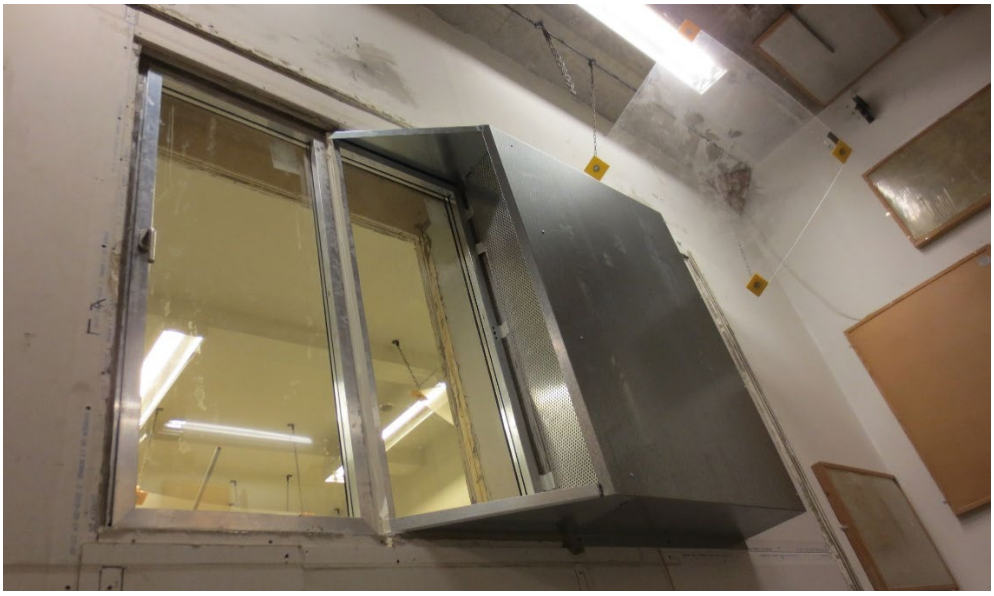


Illustration 9A. Photo of the prototype of ”Ordinary window” with external solution.

This chapter describes an ”ordinary window” with an added external solution. The aim is to work with a solution, which may be used in situations where more sound insulation is required by adding a construction to the existing window (e.g. by restoration) but which could also be used in new buildings by providing the opportunity to maintain the “usual” window dimensions. Just as previously, important parameters are:

- View
- Obtainable sound insulation
- Variation possibilities

9.1 Developing a solutions principle

The inspiration for the solution principle has roots in the literature search (see section 6.2.2) and from DELTA’s existing experience. To test the ideas, mockups are used. Based on a brainstorm, it was decided to work with three mockups – all made of plywood:

A. A solution that covers the window and has two openings
B. A solution that covers the window and has one opening
C. A solution, which is placed next to the window which has one opening

9.2 Laboratory measurements on mockup-solution

All the mockups were mounted on the outside of an "ordinary" window, which is subsequently denominated reference window. As in the previous chapter, an "ordinary window" is a two winged window (HSHansen a/s) in the standard format (width x height) 1230 mm x 1480 mm. For practical reasons, the window is mounted on a double plasterboard wall. Depending on the mockup, two different reference windows were used (both an "ordinary window"):

- A two-winged window opening inward, side frame hinged (see the left side of Illustation 9B)
- A two-winged window opening outward, hinged in the mullion (see the right side of Illustration 9B)

As absorbers are used SUND ®. Absorbers are included into the opening area, as it is assumed that the air can pass through these.

Illustration 9B. Photos of the applied "ordinary windows". Left photo shows a two-winged side hung window opening inward, with the hinges in the frame. Right photo shows a two-winged side hung window opening outward, with the hinges in the center.

Also see Appendix 2 for general details on the laboratory measurements.

9.2.1 Mockup-solution A

In principle, the mockup-solution A is a plywood box, open at both ends, so that the combined opened area for both ends meets the 0,35 m^2 requirement. Overall, the construction is the same as at Folehaven [16] [17], but with a changed geometry and with the possibility of investigating the possibility of the location of extra absorbers.
The mockup-solution is constructed as a solid plywood box for practical reasons, but a fully developed model is thought constructed partially (or completely) in glass, so that, as a minimum, the part that covers the reference window is transparent and will ensure the view and visibility. The principle is shown in Illustration 9C. Furthermore, the completed model may be constructed as that in the Folehaven, so that the entire external construction may be slided to the side, or parted in the middle and slided to the right and the left. Alternatively it may be created as a fixed construction.

If this solution is to become permanent, DELTA recommends that the solution will be designed so it also can be opened more than 0,35 m^2.

The reference for mockup-solution A is an ingoing two winged window opening inward in a standard format with one wing open 0,35 m^2 (with windows open towards the middle), see Illustration 9B.

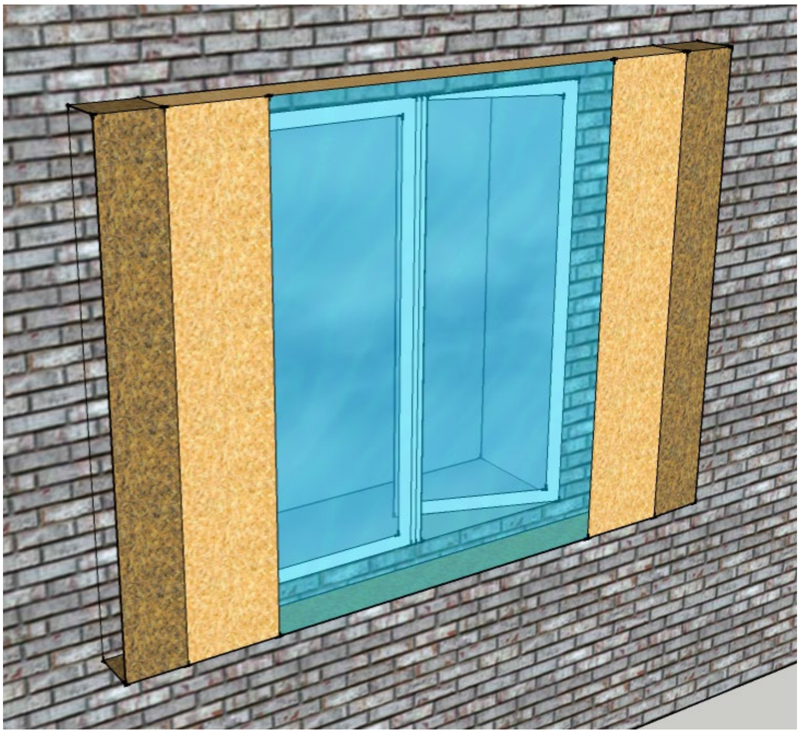


Illustration 9C. Sketch of mockup solution A. Both the blue surface and the surfaces marked with plywood in two nuances have been built by the same type of plywood for the measurements. The blue surface marks the part, which in a thought prototype is designed to be transparent (glass) and will therefore not be covered by absorbing material during the measurements. Both the light and dark part of the plywood (including the parallel wall) can be covered by absorbing material. The light part marks the default construction where the dark part marks the extension, which was also investigated.

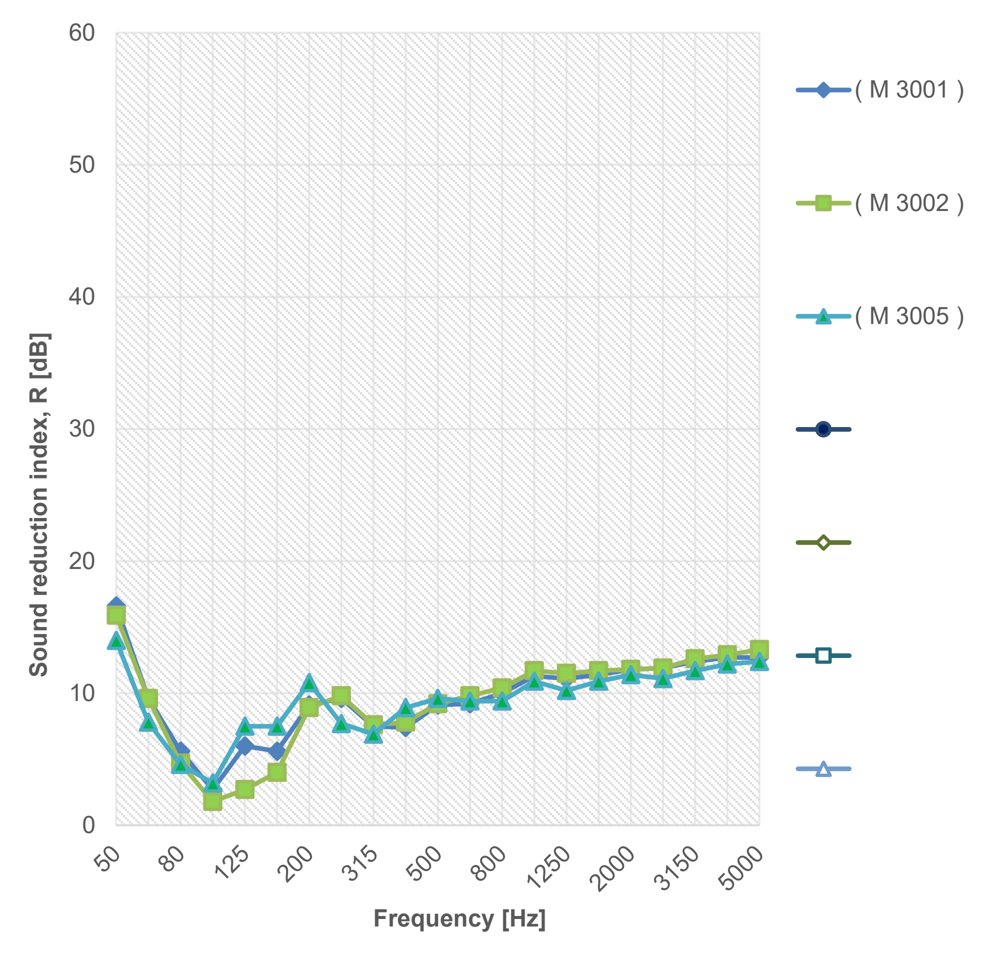
The actual solution is depicted in Illustration 9D, in which the construction may be seen from the outside as well as the inside and with and without added absorbing materials and with the two lengths of the solution that were investigated. The dimensions of the default mockup-solution are (width x height x depth) approximately 1850 mm x 1640 mm x 160 mm. The extended mockup-solution has been extended 20 cm at both ends, i.e. the total dimension is 2250 mm x 1640 mm x 160 mm.

Subsequently, a number of measurements have been carried out, where selected comparisons of the noise reduction in a 1/3-octave band has been displayed in a graph with the single number quantities R_w and R_w+C_{tr}. The individual 1/3-octave band values and all the relevant single number quantities can be found in Appendix 3.

Illustration 9D. Photos of the actual implementation of mockup solution A. Left photo shows the extended version mockup solution A from the outside without added fiber gypsum. The middle photo is taken from one end and shows the construction without added absorber. The right photo is also taken from one end and shows the construction with added 20 mm absorber in the sides and 40 mm in top and bottom.

The Mockup-solution is created totally symmetrically, and it should therefore be without significance which of the two windows in the two winged reference window that could be opened. Still comparative measurements and a measurement with both sash opened are carried out, so that the total opening area for all the measurements is kept at 0.35 m^2.
The results may be seen in FIGURE 27, where it can be seen that the curves are almost identical. The largest difference is seen at the measurement where both sashes are open. The single number quantities show the same result for all three measurements.

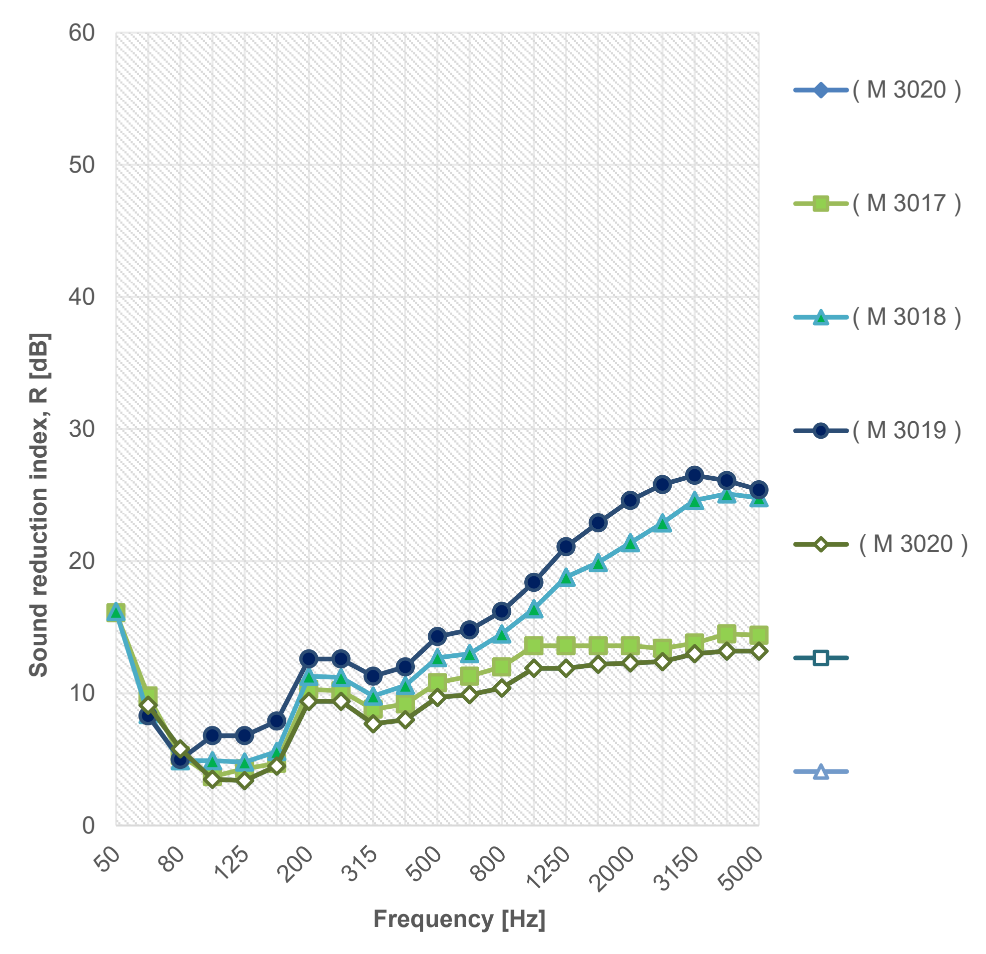
FIGURE 27. Mockup solution A – not extended. Investigation of influence of which sash to open (total opening area always 0.35 m^2 – absorption not added).



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3001	11	10	Right sash opened
M 3002	11	10	Left sash opened
M 3005	11	10	Both sash opened

Subsequently, the significance of added absorption is investigated, which may be seen in FIGURE 28. As expected, it is seen that the sound insulation increases as the absorption is added, especially for the highest frequencies. At the lowest frequencies, a significant effect is not seen until the 40 mm thick absorber is added to the sides. The single number quantities show an improvement of 5-8 dB (from 11 to 19 dB for the R_w and 10 to 15 dB for the R_w+C_{tr}).

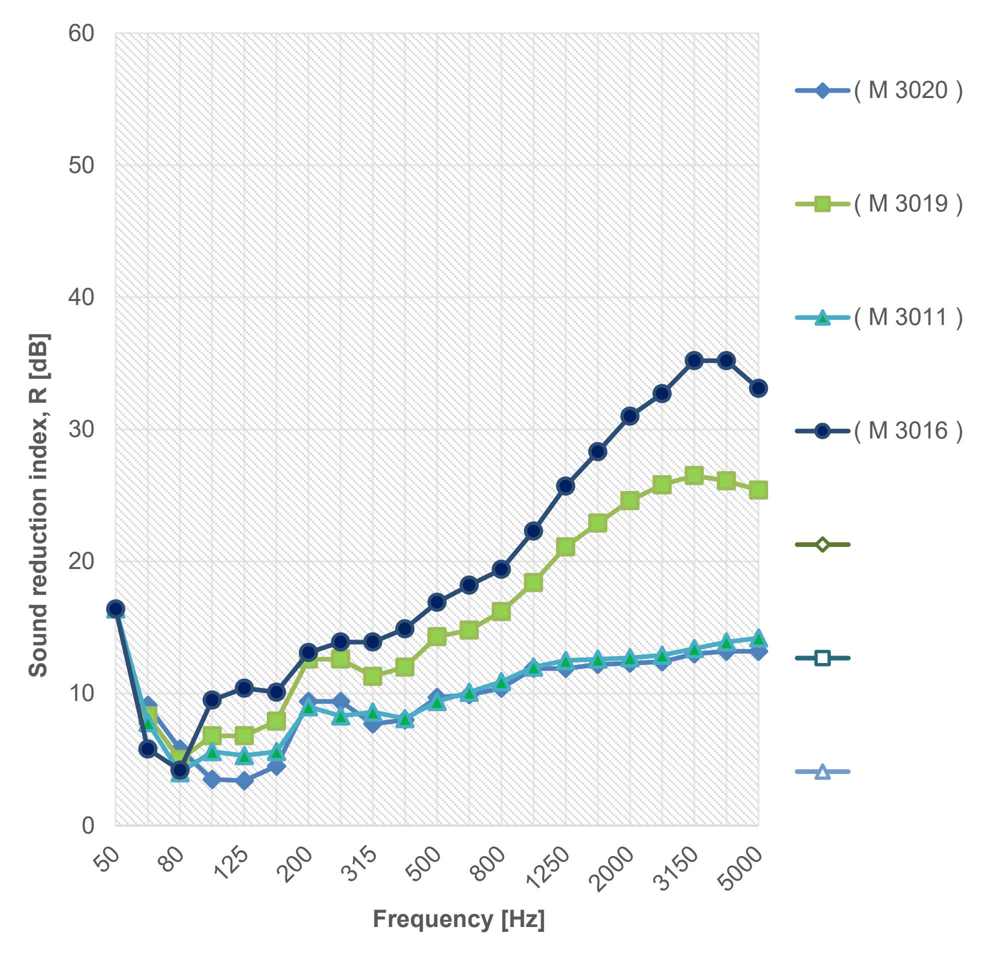
FIGURE 28. Mockup solution A – not extended. Significance of added absorption.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3020	11	10	Without absorber
M 3017	13	11	40 mm absorber in top and bottom
M 3018	17	14	40 mm absorber in top and bottom. 20 mm in sides
M 3019	19	15	40 mm absorber in top and bottom. 40 mm in sides

Furthermore it is interesting to see the significance of extending the "box", which may be seen in FIGURE 29. The box has been extended by 20 cm at both ends. It is seen that without absorber, the extension makes hardly any difference at all, the curves are almost identical, however there is a slight improvement in the low frequencies. With absorber there is an average improvement of approximately 3 dB in the curves as well as the single number quantities.

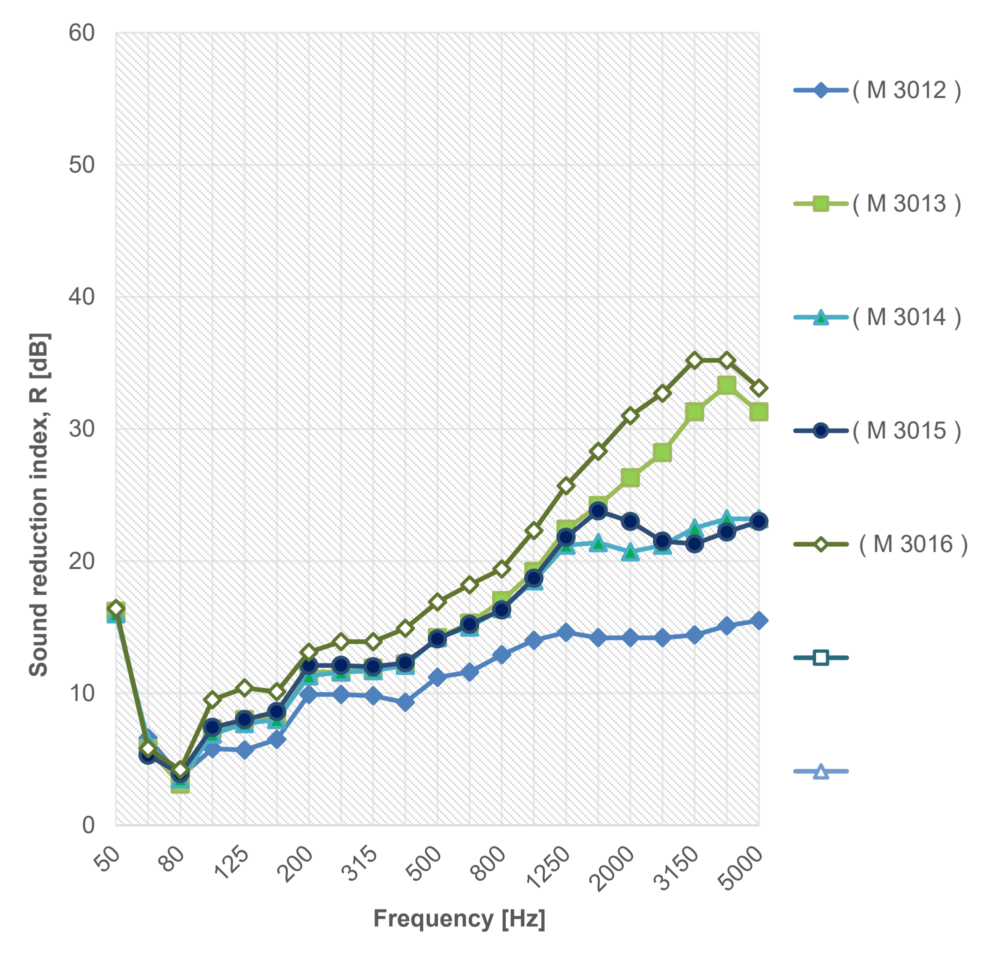
FIGURE 29. Mockup solution A. Significance of extended solution.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3020	11	10	Not extended. Without absorber
M 3019	19	15	Not extended. 40 mm absorber in top, bottom and sides
M 3011	12	11	Extended. Without absorber
M 3016	22	18	Extended. 40 mm absorbers in top, bottom and sides

With the extended "box" it has also been investigated whether the location of the absorbers is significant, see FIGURE 30. For three of the curves,the amount of absorption is identical (M 3013, M3014 and M 3015), but the location is very different. As can be seen, the curves are almost identical up to approximately 1250 Hz, after which the resemblance ceases to exist. Of these three, the absorber location which result in the lowest sound reduction is that on the wall next to the windows. The best solution is to distribute the absorbing material on both sides, in order to obtain a surface, as large as possible. However, this is of no significance to the single number quantities (supposedly as the difference is almost only seen above 2000 Hz). The very best result is obtained with 40 mm absorber at both sides, which provides an improvement of almost all frequencies, compared to those of the other configurations. For the single number quantities, is obtained an improvement of 3-4 dB for the R_w and 2-3 dB for the R_w+C_{tr}.

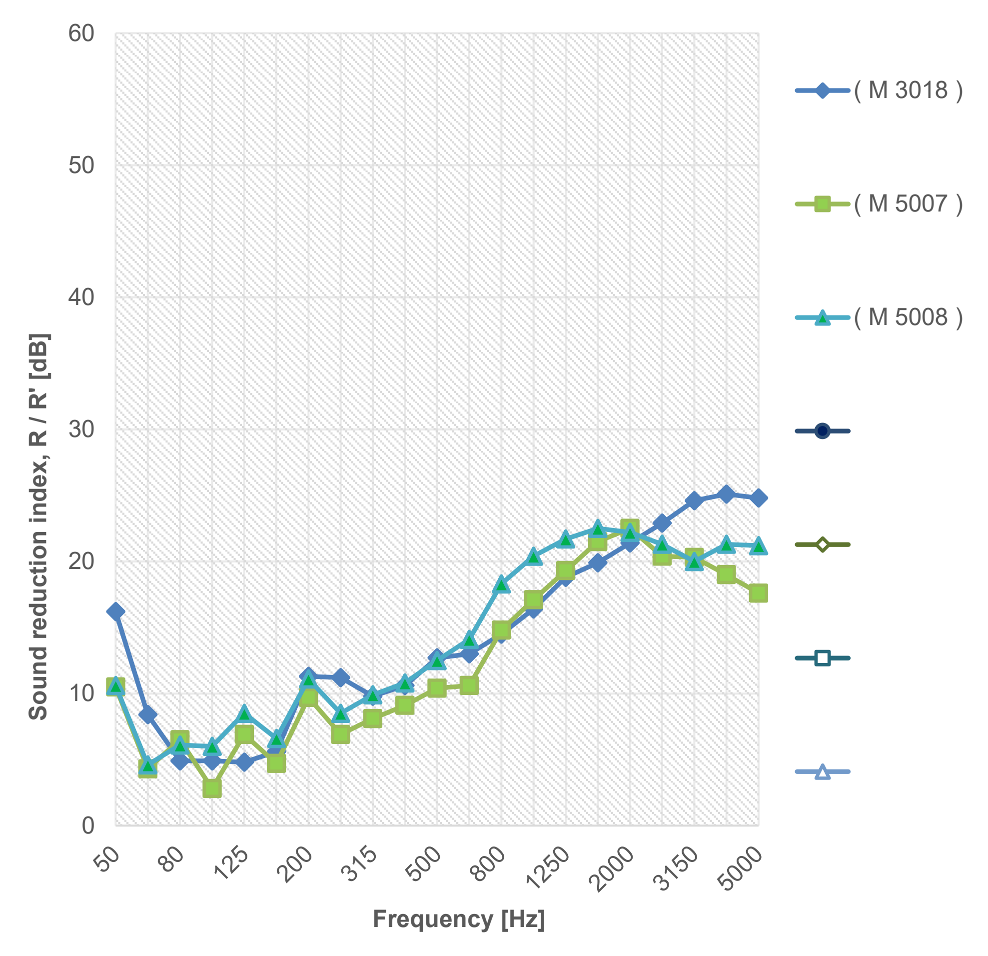
FIGURE 30. Mockup solution A - extended. Influence of position of absorption in the sides (40 mm absorber in top and bottom for all shown measurements).



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3012	13	12	Without absorber in the sides
M 3013	19	16	20 mm absorber in both sides
M 3014	18	15	40 mm absorber at internal side (against wall)
M 3015	19	16	40 mm absorber at external side (against plywood)
M 3016	22	18	40 mm absorber in both sides

Finally, the measurements have been compared with chosen measuring results from Folehaven [17], which are displayed in FIGURE 31 (denominated SBi-measurements 9 and 10). The prerequisites are not 100 % identical, but even so, a rather good agreement is obtained between the curves. SBi-measurement 9 was conducted with only the original absorber in the sound-lock, whereas the SBi-measurement 10 was added an extra 40 mm absorber, type SUND ® in the middle of the sound-lock. The opening area was adjusted to being 0.35 m^2.

FIGURE 31. Mockup solution A compared with sound shutter measurements – Folehaven.



M no	R_w / R'_w [dB]	R_w+C_{tr} / R'_w+C_{tr} [dB]	Description (position and absorbers)
M 3018	17	14	Mockup-løsning A. 40 mm top og bund. 20 mm i sider.
M 5007	16	12	SBi-measurement 9. No extra absorber.
M 5008	18	15	SBi-measurement 10. 40 mm extra absorber at the middle.

9.2.2 Mockup-solution B

In general, mockup-solution B resembles mockup-solution A with the important difference that the plywood ”box” is only open at one end – the end opposite the opening wing of the reference window. Since the ”box” is only open at one end, the box will have to be double as thick as mockup-solution A in order to have a sufficient opening area, see principle sketch in Illustration 9E. As with mockup-solution A, this has been constructed in plywood, see Illustration 9F, but the idea is to – as a minimum – make the area in front of the reference window transparent. Thus no measurements, with extra absorption material have been added to the part, which was planned transparent – a principle sketch of this is shown in Illustration 9E, from which the blue transparent part shows where the placing of the glass pane is thought to be in the final solution. Furthermore, a number of measurements have been performed with an extended box, which in Illustration 9E is indicated with a slightly darker colour. Only the opening end of the construction is extended. The ”non-extended” part of the mockup-solution was added plasterboard plates to ensure sufficient weight and sound insulation, see Illustration 9F.
It is chosen to have the opening in the side, even though similar results are expected if the opening is placed at the top or bottom (depending on the opening function for the internal window construction). The reference for mockup-solution B is the same as for mockup-solution A, an ingoing two-winged standard format window with one wing opened 0.35 m^2 and with side-hung ingoing frames, see Illustration 9B (left photo). The dimensions on the default mockup-solution are (width x height x depth) approximately 1850 mm x 1640 mm x 290 mm. The extended mockup-solution is further extended 20 cm at one end, i.e. the total dimensions are 2050 mm x 1640 mm x 160 mm.

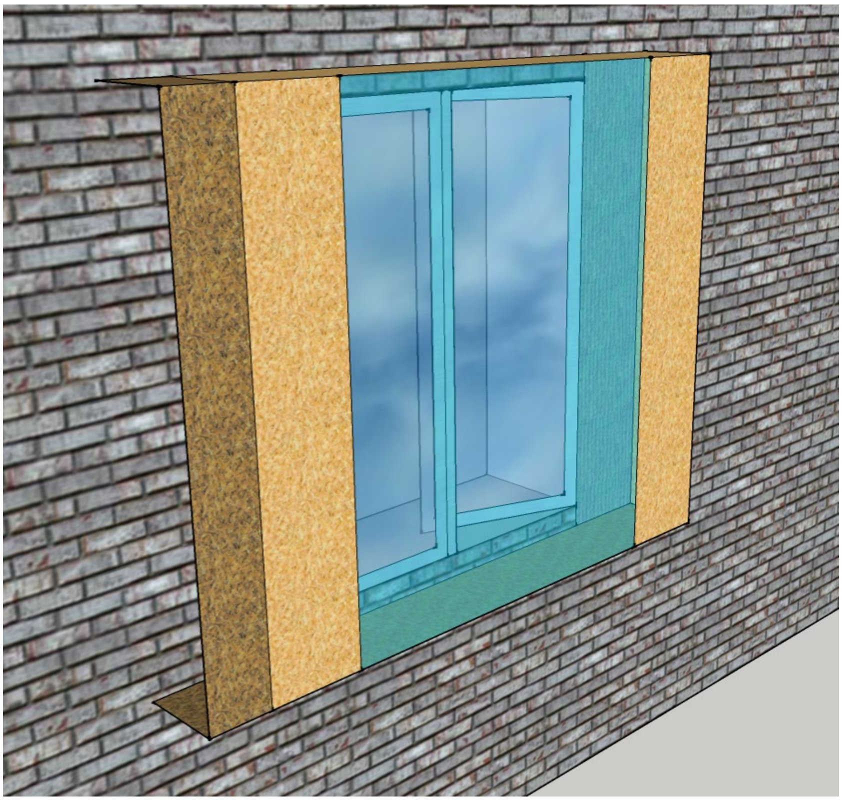


Illustration 9E. Sketch of mockup solution B. Both the blue surface and the surfaces marked with plywood in to nuances are constructed of the same type of plywood during the measurements. The blue surface marks the part, which in a final solution will be transparent (glass) and will therefore not be covered by absorbers during the measurement. Both the light and the dark park of the plywood (including the wall in parallel) can be covered by absorber during the measurements. The light part marks the default construction and the dark part marks the extended version which was also investigated.

Illustration 9F. Photo of the actual implementation of mockup solution B seen from the outside.

Illustration 9G. Two photos of mockup solution B, both taken from the open end of the construction. Left photo shows the construction without added absorber. Right photo shows the highest amount of added absorber investigated during the measurements, which is 40 mm in top, bottom and sides plus extra 20 mm in the middle.

Results of measurements of the non-extended version with various amount of added absorption are depicted in FIGURE 32. The location of the absorption is shown in Illustrations 9G and 9I. As expected, it is seen that an increased amount of absorption provides better sound insulation – however, effects are primarily seen at higher frequencies. It is an interesting result that the two measurements without absorption in the “end cavity” (M 3102 and M 3103) show remarkably different graphs than the measurements with absorption in the ”end cavity” – the primary differences in the graphs are seen for the lowest frequencies, however. The ”End cavity” is the closed completion of the construction opposite the opening, see Illustrations 9H and 9I. The displayed addition of absorption provides an improvement on the single number quantitites of up to 9 dB for the R_w and 6 dB for the R_w+C_{tr}.

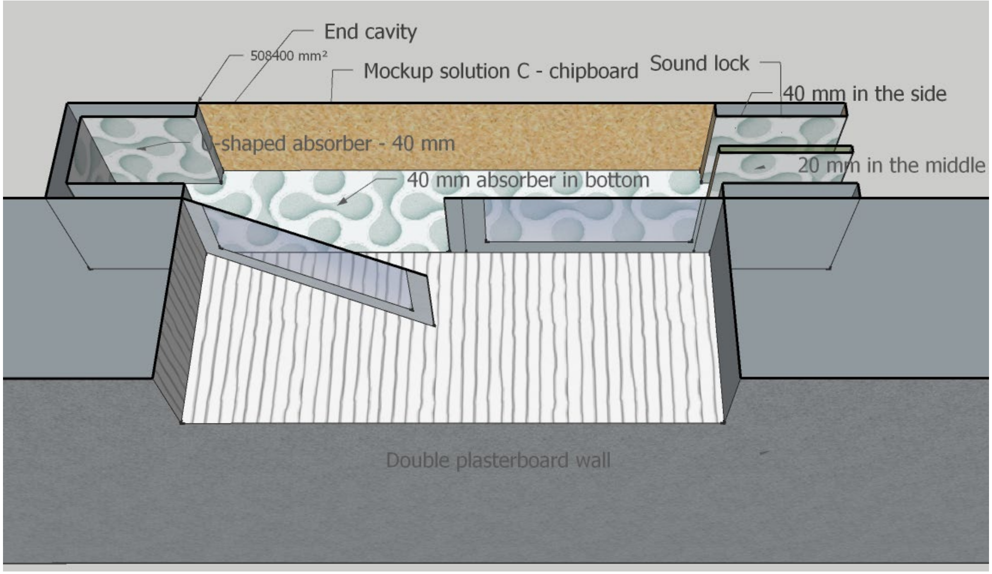


Illustration 9H. Horizontal cross section in sketch seen from above and from the inside. The sketch shows the solution with 40 mm U-shaped absorber in the end cavity, 40 mm absorber in the bottom, 40 mm absorber in the sides plus 20 mm absorber in the middle of the opening.

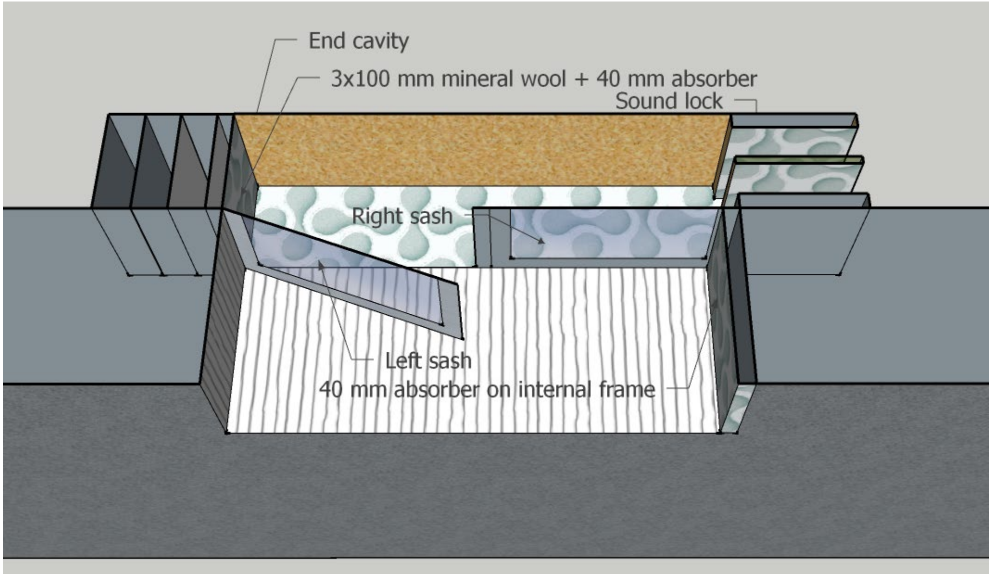
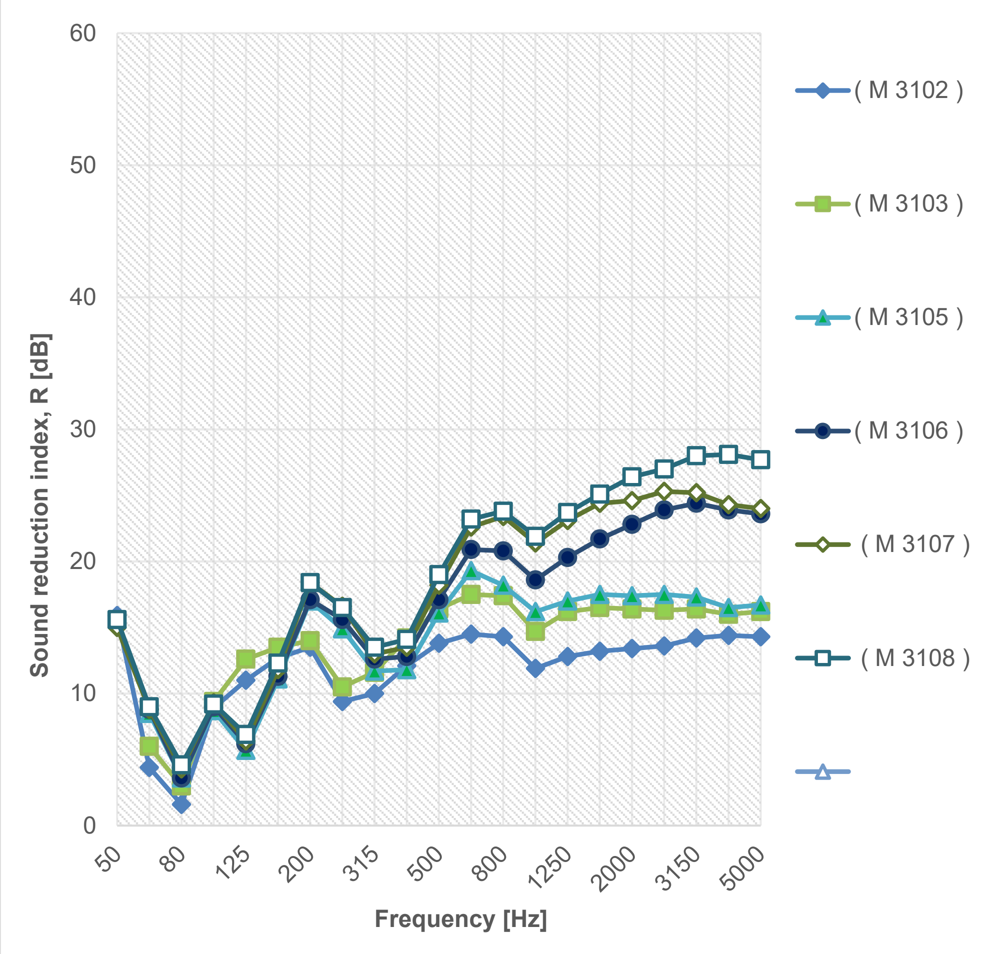


Illustration 9I. Horizontal cross section in sketch seen from above and from the inside. The sketch shows the solution with 40 mm on the inside of the original window frame, 3x100 mm + 40 mm absorber in the end cavity, 40 mm absorber in the bottom, 40 mm absorber at sides + 20 mmm absorber in the middle of the opening.

FIGURE 32. Mockup solution B. Investigation of influence of added absorber.

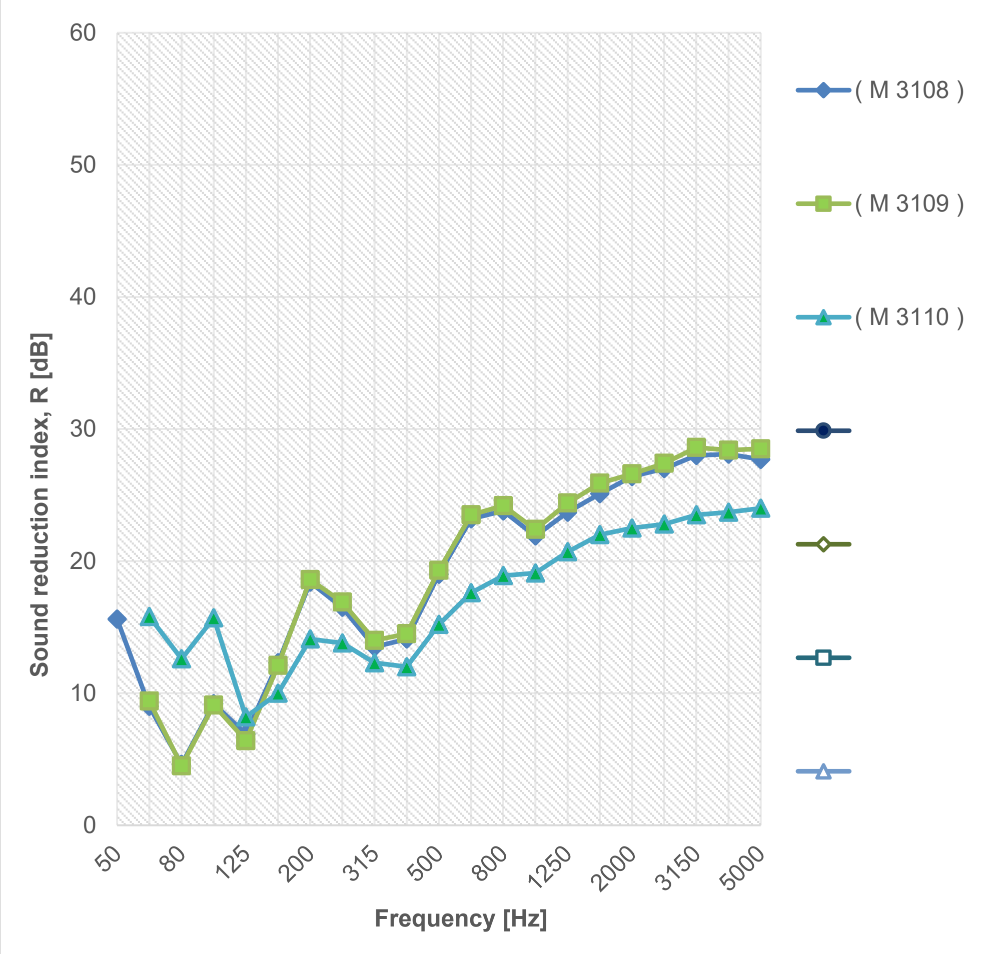


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3102	14	13	Without absorber
M 3103	16	15	40 mm absorber in top and bottom
M 3105	17	15	40 mm in top and bottom. 3x100 + 40 mm in end cavity
M 3106	20	17	40 mm in top and bottom. 3x100 + 40 mm in end cavity. 20 mm in sides
M 3107	22	18	40 mm in top and bottom. 3x100 + 40 mm in end cavity. 40 mm in sides
M 3108	23	19	40 mm in top and bottom. 3x100 + 40 mm in end cavity. 40 mm in sides. 20 mm in middle of the opening.

The importance of which of the sashes in the two winged reference window there is opened, is investigated in FIGURE 33. The displayed measurements are performed based on the added 40 mm absorption at the top and bottom as well as 40 mm on the sides by the opening of the mockup-solution – the sound-lock – and 20 mm in the middle of the sound-lock, see Illustration 9I.

If the right sash is opened instead of the left one, the sound insulation of the lowest frequencies, those below 125 Hz will be improved significantly. For frequencies above 125 Hz, the best sound insulation is obtained by keeping the left sash open. In the single number quantities, the left sash provides an improvement of 4 dB for the R_w and 2 dB for the R_w+C_{tr} compared to the single number quantitites for the right sash. The same figure also investigates the effect, if any, of adding 40 mm absorption inside the frame opposite the open sash in the reference window, see Illustration 9I. As can be seen, the difference is insignificant.

FIGURE 33. Mockup solution B. Influence of which sash to open. 40 mm absorber in top, bottom and sides, plus 20 mm absorber in the middle of the opening.



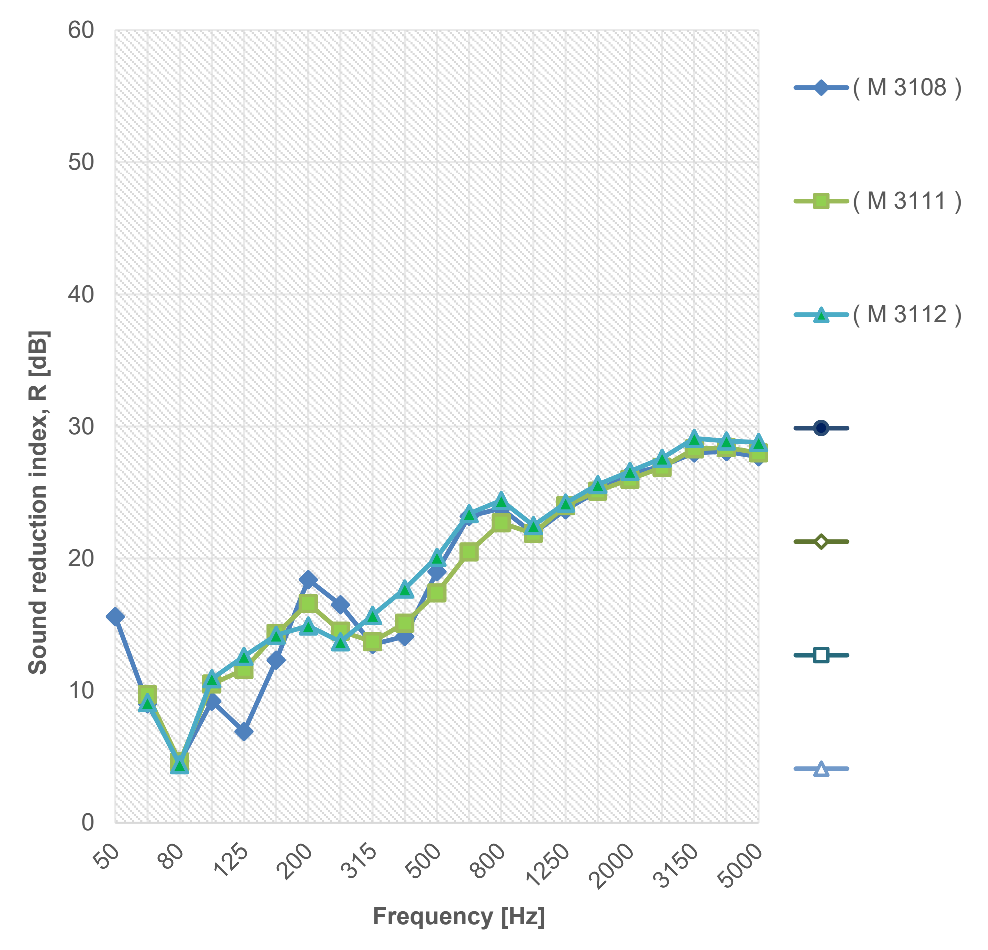
M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3108	23	19	3x100 mm + 40 mm in the end cavity. Left sash open.
M 3109	23	19	3x100 mm + 40 mm in the end cavity, plus 40 mm on internal frame. Left sash open.
M 3110	19	17	3x100 mm + 40 mm in the end cavity. Right sash open.

The significance of the ”end cavity” is then investigated, i.e. the amount and location of absorption in the closed part of the box, opposite the opening, see Illustrations 9G and 9I. Selected results are shown in FIGURE 34. The three depicted measurements provide relatively comparable results with the single number quantities of 22-23 dB for the R_w and 19-20 dB for the R_w+C_{tr}, even though the surface area, thickness and volume of the absorbers are rather different, see the table below.

	R_w [dB]	R_w+C_{tr} [dB]	Surface area [m^2]	Thickness [m]	Volume [m^3]
M 3108	23	19	0.40	0.34	0.14
M 3111	22	19	0.40	0.14	0.06
M 3112	23	20	1.22	0.04	0.05

The sound reduction index curves for the three solutions vary some, primarily in the frequency area 100-1000 Hz.

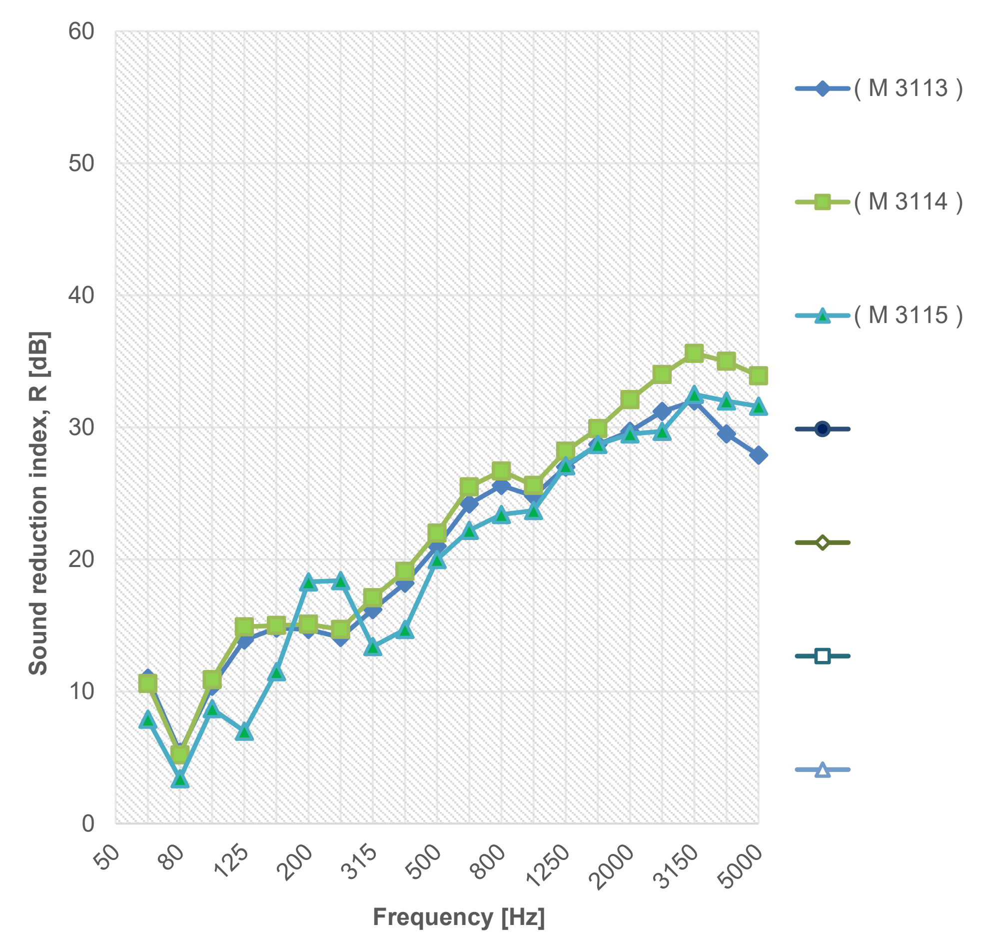
FIGURE 34. Mockup solution B. Investigation of type and position of absorber in the end cavity based on 40 mm absorber in top, bottom and sides plus 20 mm absorber in the middle of the opening.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3108	23	19	3x100 mm + 40 mm in the end cavity
M 3111	22	19	1x100 mm + 40 mm in the end cavity
M 3112	23	20	U-shape of 40 mm absorber

The mockup-solution has been extended finally. The results from these measurements are shown in FIGURE 35. The ”box” has been extended by 20 cm at the end where the opening is, see principle sketch in Illustration 9E. FIGURE 35 displays three measurements, of which measurement M 3115 is the result of placing a 13 mm plaster board at the front of the ”end cavity” (which is filled with absorption), which thus creates an illusion of a lesser total amount of absorption in the mockup-solution. The other two measurements displayed in the figure have U-shaped absorbers in the ”end cavity”. When the three measurements are compared it can be seen that addition of absorption results in higher sound insulation, for most frequencies but also for the single number quantities, which increase by 1-2 dB for the R_w and 2-3 dB for the R_w+C_{tr}.

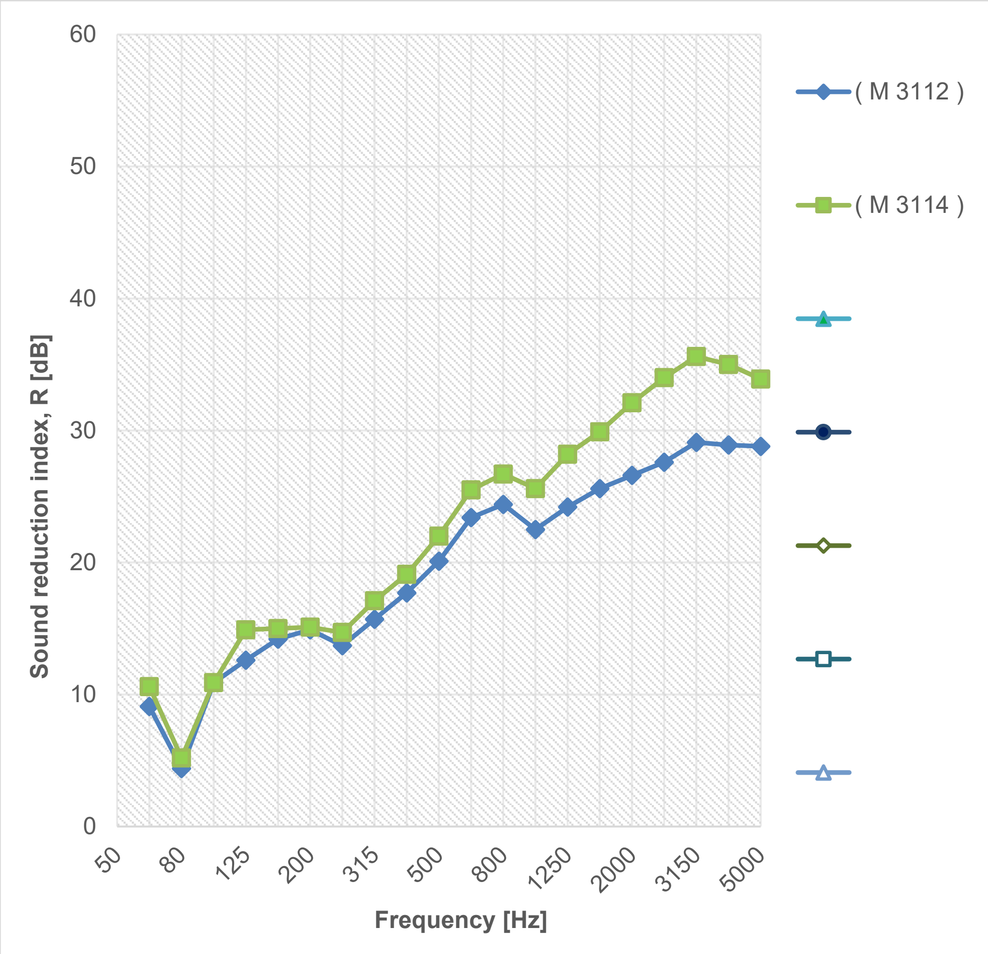
FIGURE 35. Mockup solution B – Box extended 20 cm.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3113	25	21	40 mm at the top, bottom and sides. U-shape of 40 mm absorber
M 3114	26	22	40 mm at the top, bottom and sides. 20 mm in the middle. U-shape of 40 mm absorber.
M 3115	24	19	40 mm at the top, bottom and sides. 20 mm in the middle. 3x100 mm + 40 mm in end cavity with 13 mm plasterboard plate in front.

Finally, the non-extended and extended versions are compared. The result of this comparison is shown in FIGURE 36. It can be seen that the extension has an entirely positive influence on the sound insulation, which has been improved in the entire frequency area. The single number quantities display improvements of 3 dB for the R_w and 2 dB for the R_w+C_{tr}.

FIGURE 36. Mockup solution B. Comparison between non-extended and extended box, both with 40 mm absorber in top, bottom and sides, plus 20 mm in the middle of the opening and plus U-shaped 40 mm absorber in the end cavity.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3112	23	20	Not extended
M 3114	26	22	Extended

9.2.3 Mockup-solution C

The reference for mockup-solution C is an outgoing two winged window in standard format with the frames hung in the mullion with one frame opened 0.35 m^2, see Illustration 9J. As the two previous mockup-models, this mockup-solution C is constructed of plywood, and also in this case the model is a box, which is open at both ends. However, the primary difference is that the box is not placed above the reference window, but on the side instead.
The model is constructed so that the sash is opened outward and is locked in a position so that a closed duct is created through the mockup-model and through the window. The principles are shown in Illustrations 9J, 9K and 9L. Measurements are performed with the ”box” at two lengths and with absorption material added to the sides.
As in the previous work packages, the primary investigation has been about the significance of adding the absorption and about extending the ”box”. The dimensions for that part of the default mockup-solution that is to the right of the window element, are (width x height x depth) approximately 470 mm x 1480 mm x 290 mm, see Illustrations 9K and 9L. The extended mockup-solution has been extended by 50 cm at one end, i.e. the total dimensions are 970 mm x 1480 mm x 290 mm.

Illustration 9J. Sketch of mockup solution C. The construction is here shown with two different brown patterns, where the light part marks the default construction, and the dark part marks the extension which was also investigated. Both parts (including the parallel wall) can be covered by absorber.

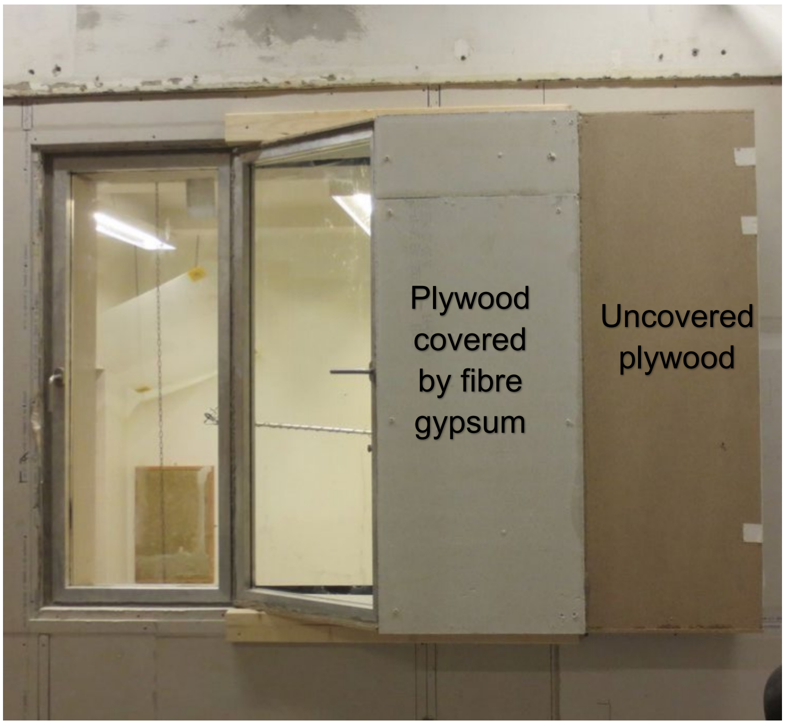


Illustration 9K. Two photos of mock-up solution C. Left photo shows the construction seen from the outside and shows the extended version (the default version equals the part covered by fibre gypsum (left side) and the extension equals where the plywood is visible (right side)). Right photo shows the construction seen from the open end with the maximum added absorber, meaning 40 mm in top, bottom and sides plus additional 20 mm in the middle of the opening.

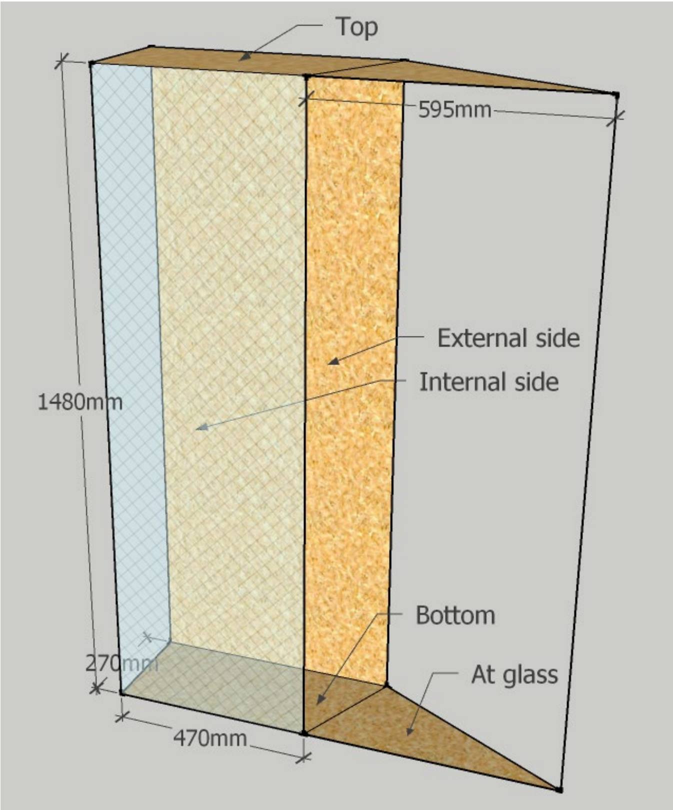
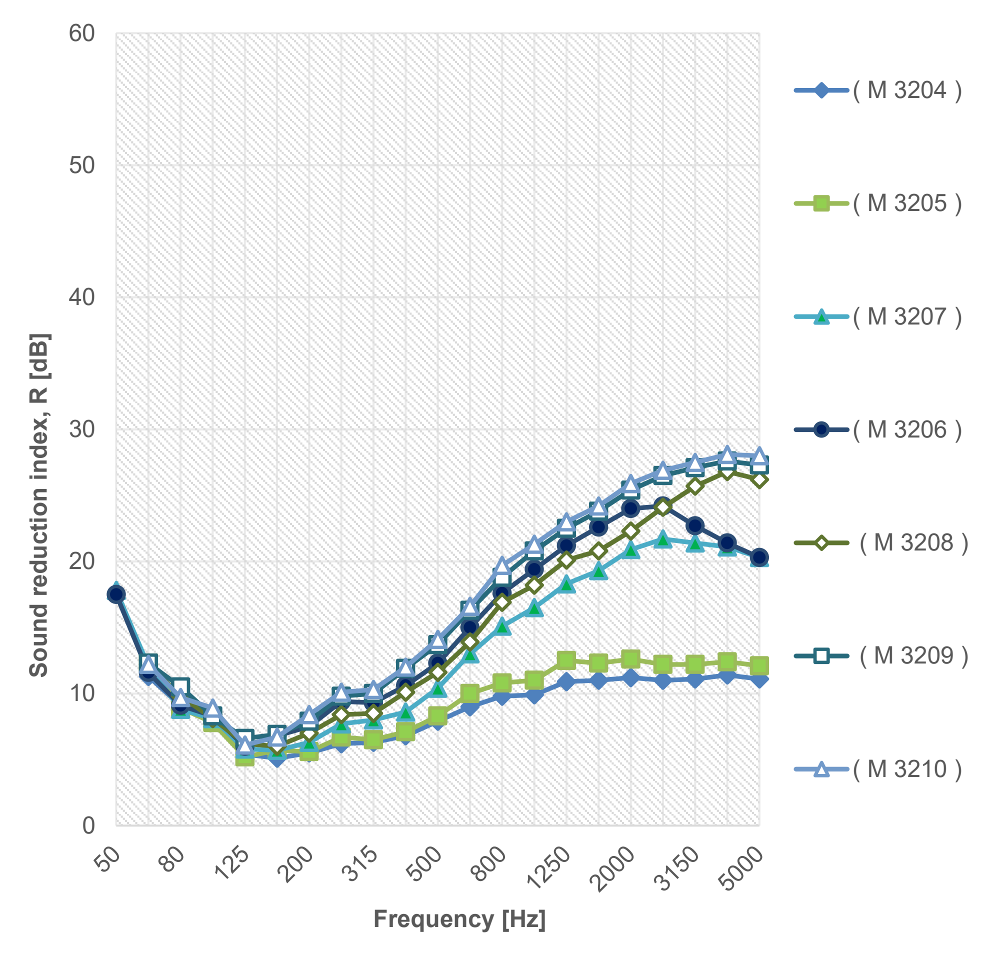


Illustration 9L. Sketch of mockup solution C seen from the inside. Absorber was added to all parts, which here is shown as plywood (brown color) and at the wall in parallel.

FIGURE 37. Mockup solution C. Not extended.

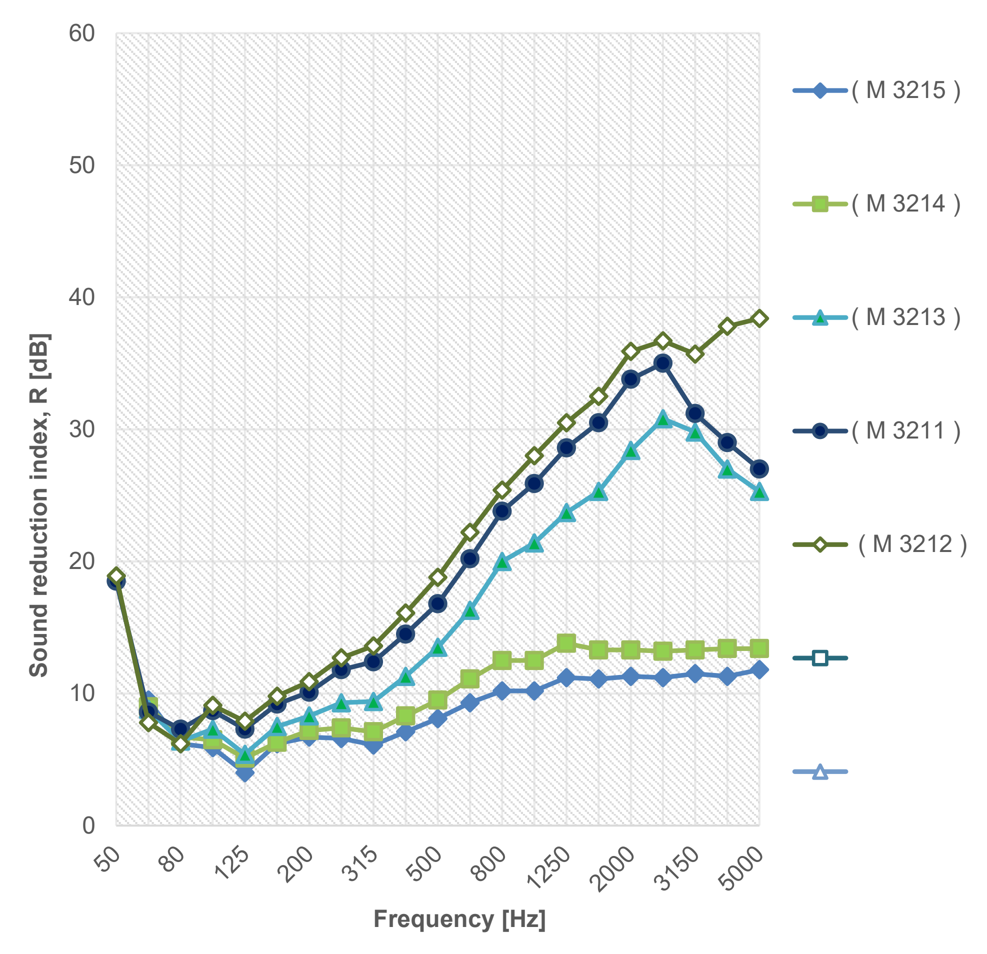


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and absorbers)
M 3204	10	9	Without absorber
M 3205	11	10	40 mm at top and bottom
M 3207	16	13	40 mm at top and bottom. 20 mm in the sides
M 3206	18	14	40 mm at top and bottom. 40 mm in the sides.
M 3208	17	14	40 mm at top and bottom. 20 mm in the sides. 20 mm in the middle.
M 3209	19	15	40 mm at top and bottom. 40 mm in the sides. 20 mm in the middle.
M 3210	19	15	40 mm at top and bottom. 40 mm in the sides. 20 mm in the middle. 20 mm at glass (see marking at Illustration 9L)

For mockup-solution C in the non-extended version, selected results are shown in FIGURE 37.
As was the case for the previous solutions, improved sound insulation is seen when more absorption is added. Especially absorption added to the sides has a good effect. The improved sound insulation is only observed for frequencies from 200 Hz and above, while the entire frequency area below 200 Hz is almost unaltered, despite the amount of absorption. Compared with the mockup-solution without absorber, the sound insulation is however improved for the single number quantities of 9 dB for the R_w and of 6 dB for the R_w+C_{tr} for the best solution.

Similarly, selected results have been displayed for mockup-solution C in the extended version in FIGURE 38. The same observations as for FIGURE 37 apply here, except that in this case, an improvement is observed in the sound insulation in the frequency area 80-200 Hz when adding absorption.
Compared to the mockup-solution without absorber the sound insulation as single number quantities is improved 14 dB for the R_w and 10 dB for the R_w+C_{tr} for the best solution.

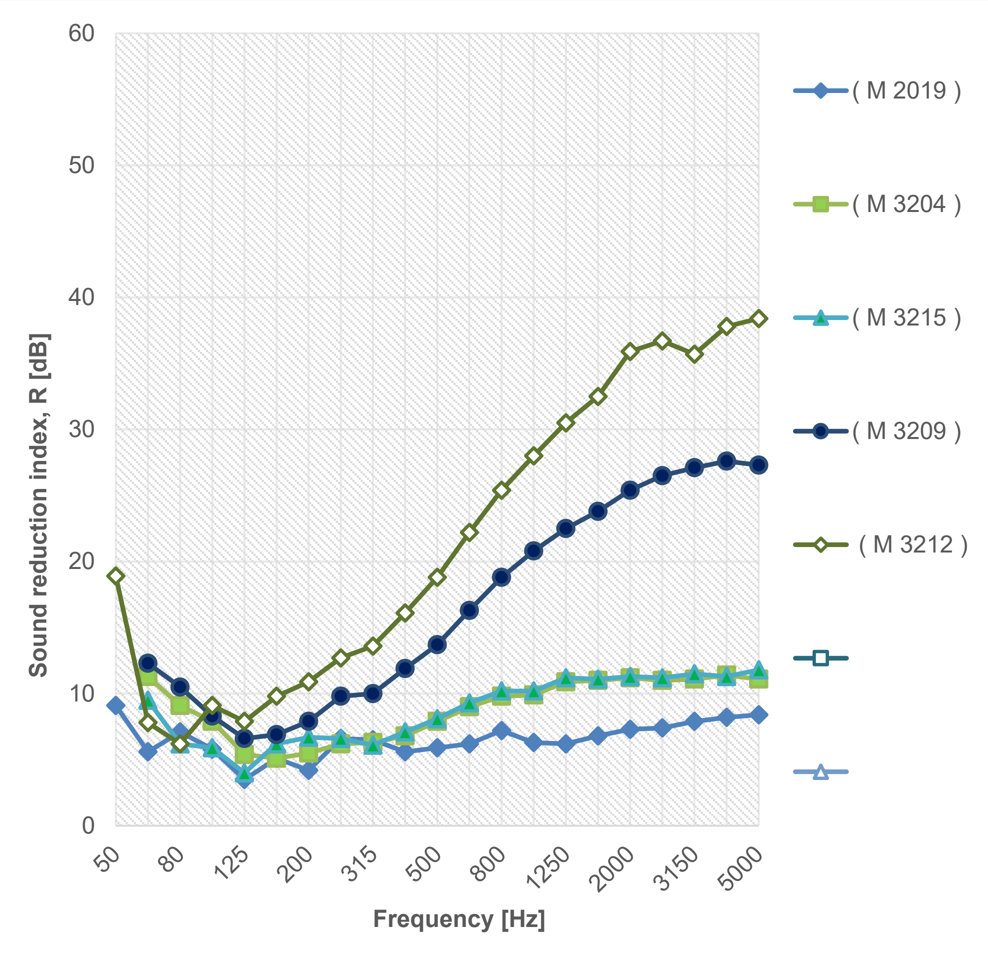
FIGURE 38. Mockup solution C. Extended.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and thickness of absorbers)
M 3215	10	9	Without absorber
M 3214	12	11	40 mm in top and bottom
M 3213	19	15	40 mm in top and bottom. 20 mm in sides. 20 mm at glass
M 3211	22	18	40 mm in top and bottom. 40 mm in sides. 20 mm at glass
M 3212	24	19	40 mm in top and bottom. 40 mm in sides. 20 mm at middle. 20 mm at glass

Mockup-solution C in the extended and non-extended versions are compared in FIGURE 39, from which it may be seen that the length is of no significance, when no absorption has been added (no difference in the single number quantities). However, the length has huge significance, when absorption has been added (an improvement in sound insulation for the single number quantities of 5 dB for the R_w and 4 dB for the R_w+C_{tr}).

FIGURE 39. Mockup solution C. Comparison with and without extension.

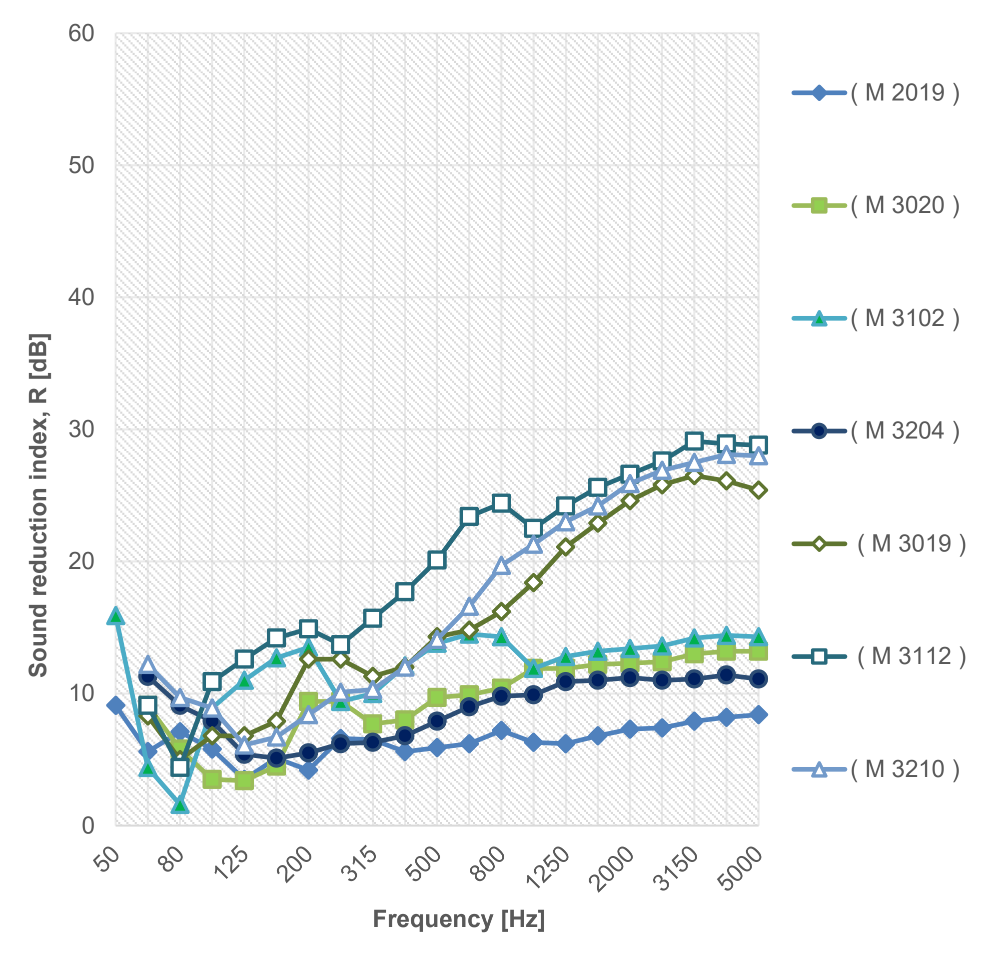


M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and thickness of absorbers)
M 2019	7	6	Reference (without mockup solution C)
M 3204	10	9	Without extension and without absorber
M 3215	10	9	With extension and without absorber
M 3209	19	15	Without extension and with ”max” absorption (40 mm in top, bottom and sides. 20 mm in middle. 20 mm at glass)
M 3212	24	19	With extension and with ”max” absorption (40 mm in top, bottom and sides. 20 mm in middle. 20 mm at glass)

9.2.4 Comparison of the three mockup-solutions

A number of tests have been carried out with each of the mockup-solutions, and selected results for the three mockup-solutions are displayed in FIGURE 40 and FIGURE 41. The first-mentioned figure shows results of the non-extended mockup-solution and the latter of the two shows the results of the extended mockup-solution. In each figure is also shown a measurement without added absorption and the measurement with the most added absorption. Furthermore, the measurement on the reference window has also been included in both figures.

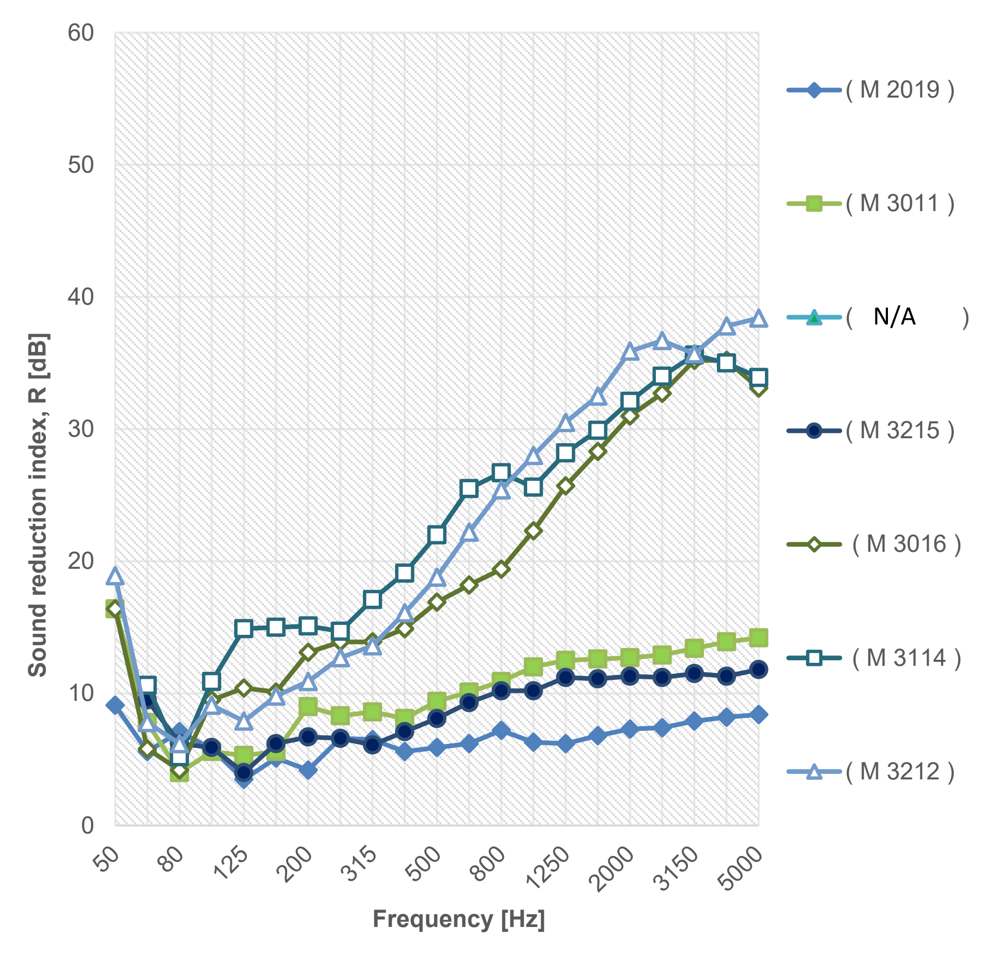
FIGURE 40. Comparison of mockup solutions in default length.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and thickness of absorbers)
M 2019	7	6	Reference (without mockup solution)
M 3020	11	10	Solution A. Without absorber
M 3102	14	13	Solution B. Without absorber
M 3204	10	9	Solution C. Without absorber
M 3019	19	15	Solution A. With absorber
M 3112	23	20	Solution B. With absorber
M 3210	19	15	Solution C. With absorber

For the non-extended mockup-solution in FIGURE 40 it may be seen that mockup-solution B, has the best sound insulation – especially in the low frequency area – both with and without absorber. Mockup-solutions A and C are approximately comparable. A similar picture may be seen for the extended mockup-solutions in FIGURE 41. Mockup-solution C also looks as if it has the lowest sound insulation without added absorber, whereas the solution with added absorber is slightly better than mockup-solution A. A summary of single number quantities is shown in Table 4.

FIGURE 41. Comparison of extended mockup solutions.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description (position and thickness of absorbers)
M 2019	7	6	Reference (without mockup solution)
M 3011	12	11	Solution A. Without absorber
N/A	-	-	Solution B. Without absorber
M 3215	10	9	Solution C. Without absorber
M 3016	22	18	Solution A. With absorber
M 3114	26	22	Solution B. With absorber
M 3212	24	19	Solution C. With absorber

Table 4 Summary of single figure values for the three mockup-solutions

	Without absorber				With absorber			
	Default	Long	Default	Long	Default	Long	Default	Long
	R_w	R_w	R_w+C_{tr}	R_w+C_{tr}	R_w	R_w	R_w+C_{tr}	R_w+C_{tr}
A	11	12	10	11	19	22	15	18
B	14	-	13	-	23	26	20	22
C	10	10	9	9	19	24	15	19

9.3 Developing a prototype

Based on the performed laboratory measurements, one construction is chosen for further development of a prototype. Different factors weigh the pros and cons for each of the three mockup-solutions. Solution A may be eliminated relatively fast, as a very similar construction already exists as a turnkey product [16], and thus it is more interesting to investigate less tested constructions. Primarily, the choice is between solutions B and C. It is decided to continue working with solution C, even though this construction has not provided the best sound insulation, but on the other hand, it is the most innovative and least tested solution. It is also a less comprehensive solution, it does not have to be transparent and it can be constructed in almost any material, however with a density that is no less than what is equal to 2 mm steel to ensure sufficient sound insulation through the sides of the box (less density might be sufficient, but that has not been tested in this project). The solution is also thought of interest to architects and designers as one with which to further develop. It is also the solution of the three, which makes it possible to entirely open up the window, with the possibility of ventilating a larger opening area than that of 0.35 m^2.

Therefore, a prototype edition of the extended version of the C-model, was built (with the overall same dimensions). The model was constructed in 2 mm steel, and with birds' grates at both ends. When comparing with the mockup-measurements, the panels have been replaced to 3/0.38/3-16-4 mm argonfilled insulating glass units in the window.

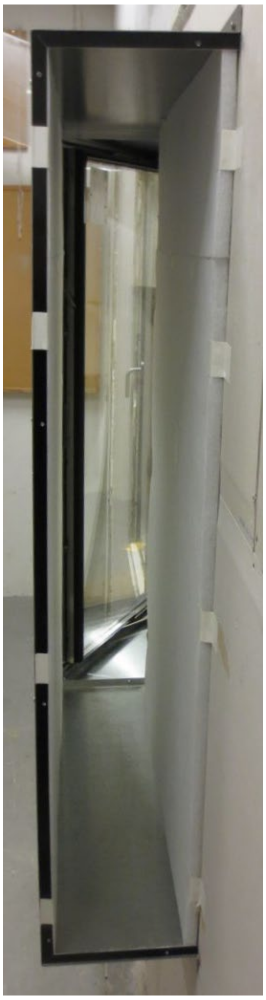
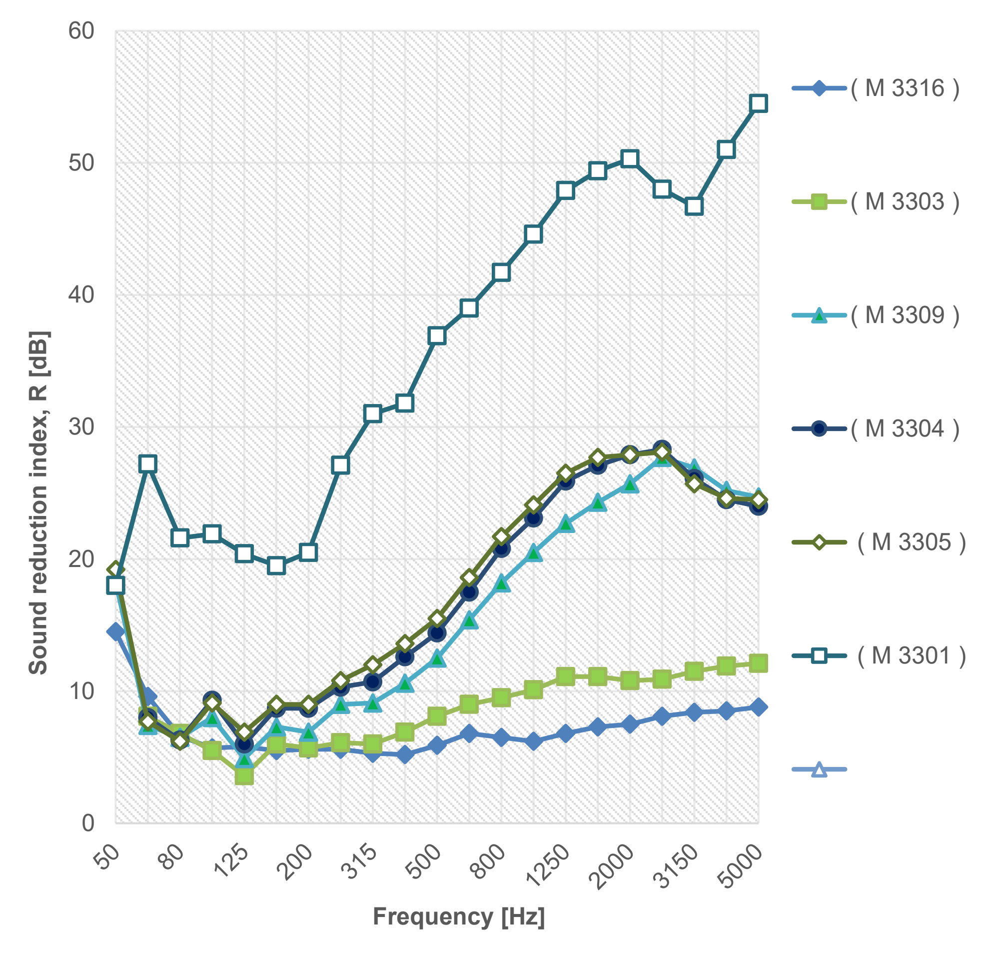


Illustration 9M Photo from the outside of the prototype. Left photo shows the construction from below, where the bird grate can be seen. Right photo shows the construction from the opening in the prototype, where 20 mm absorber is added to the top, bottom and sides. See additionally Illustration 9A.

9.4 Laboratory measurements on prototype

The prototype edition of mockup-solution C has subsequently been installed in the laboratory in the same way as mockup-solution C, and a number of laboratory measurements have been carried out.

FIGURE 42. Investigation of influence of addition of absorber for the prototype. Additionally, compared with the reference window and with the window closed.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description
M 3316	7	7	Open “ordinary window” without prototype mounted.
M 3303	10	9	Open, with prototype, without absorbers.
M 3309	18	14	Open, with prototype and absorbers (40 mm in top and bottom. 20 mm in sides).
M 3304	20	16	Open, with prototype and absorbers (40 mm in sides).
M 3305	21	17	Open, with prototype and absorbers (40 mm in top, bottom and sides)
M 3301	38	31	Closed, with prototype, but without absorbers.

Selected results from the prototype are shown in FIGURE 42, on which also the significance of addition of absorbing material is investigated. Compared with the reference window, the sound insulation is not improved significantly when installing the prototype without also adding absorbing material (for single number quantities in the range 3 dB for the R_w and 2 dB for the R_w+C_{tr}). When adding absorbers, the sound insulation is improved, however, primarily for frequencies above 250 Hz. The improvement with absorbers for single number quantities is in the range 8-11 dB for the R_w and 5-8 dB for the R_w+C_{tr} compared to the measurement without absorbers.

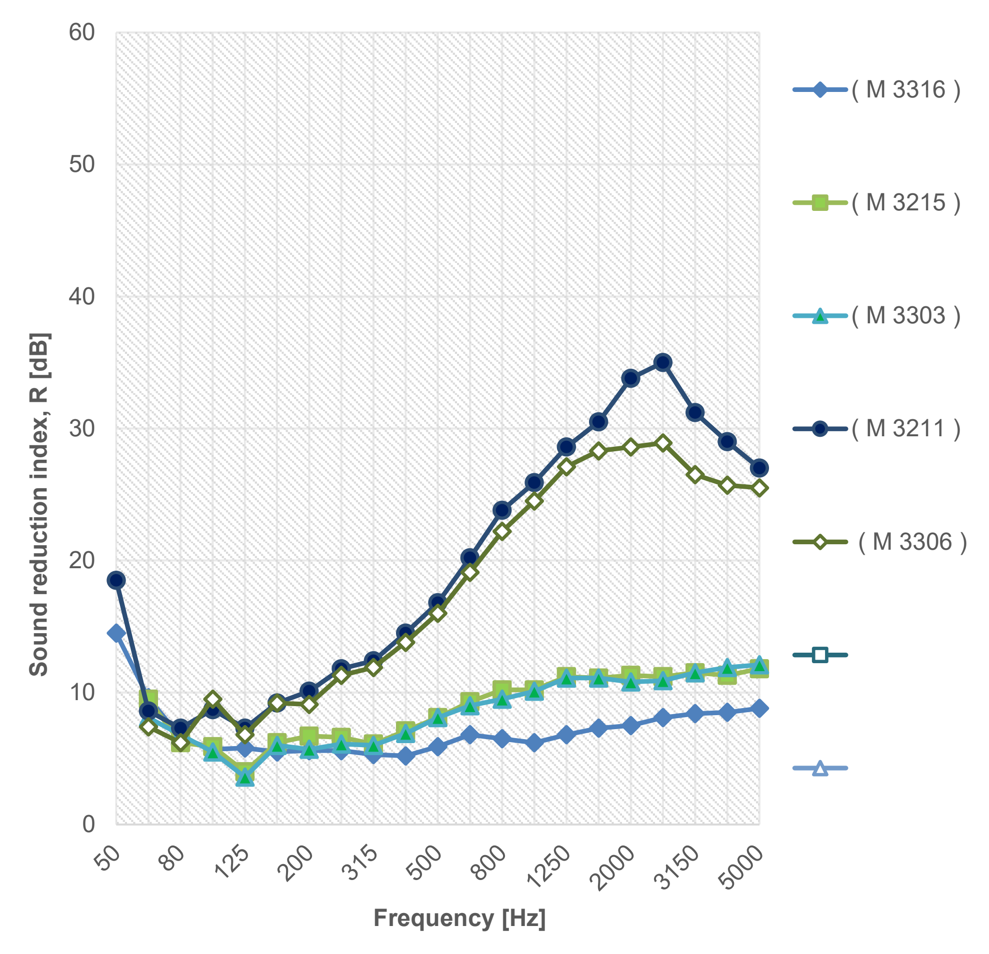
FIGURE 43 shows comparison between:

- The reference window only
- Mockup-solution C in the extended version (i.e. the same dimensions as the prototype-solution) – with and without absorption
- The prototype solution - with and without absorption

Mockup-solution C and the prototype solution, both, without added absorption give almost identical results, there is only very little difference in the curves, and no difference in the single number quantities. When comparing these with the measurement on the reference window, it can be seen that the sound insulation for mockup-solution C and the prototype is somewhat higher than that of the reference window. The difference is seen primarily for frequencies above 300 Hz and is in the size ranging from 3 dB for the R_w and 2 dB for the R_w+C_{tr}.

Mockup-solution C and the prototype solution added the same amount of absorption will result in approximately the same single number quantities (22 and 21 respectively for the R_w and 18 and 17 for the R_w+C_{tr}) – however, the curves are slightly different, as the sound insulation at approximately 2500 Hz is higher for mockup-solution C than for the prototype. Mockup-solution C and the prototype solution added absorption have significantly better and higher sound insulation than the reference window, especially for frequencies above 500 Hz. When comparing the single number quantities, the difference is seen in two digit figures (from 7 to 21-22 dB for the R_w and from 7 to 17-18 dB for the R_w+C_{tr}).

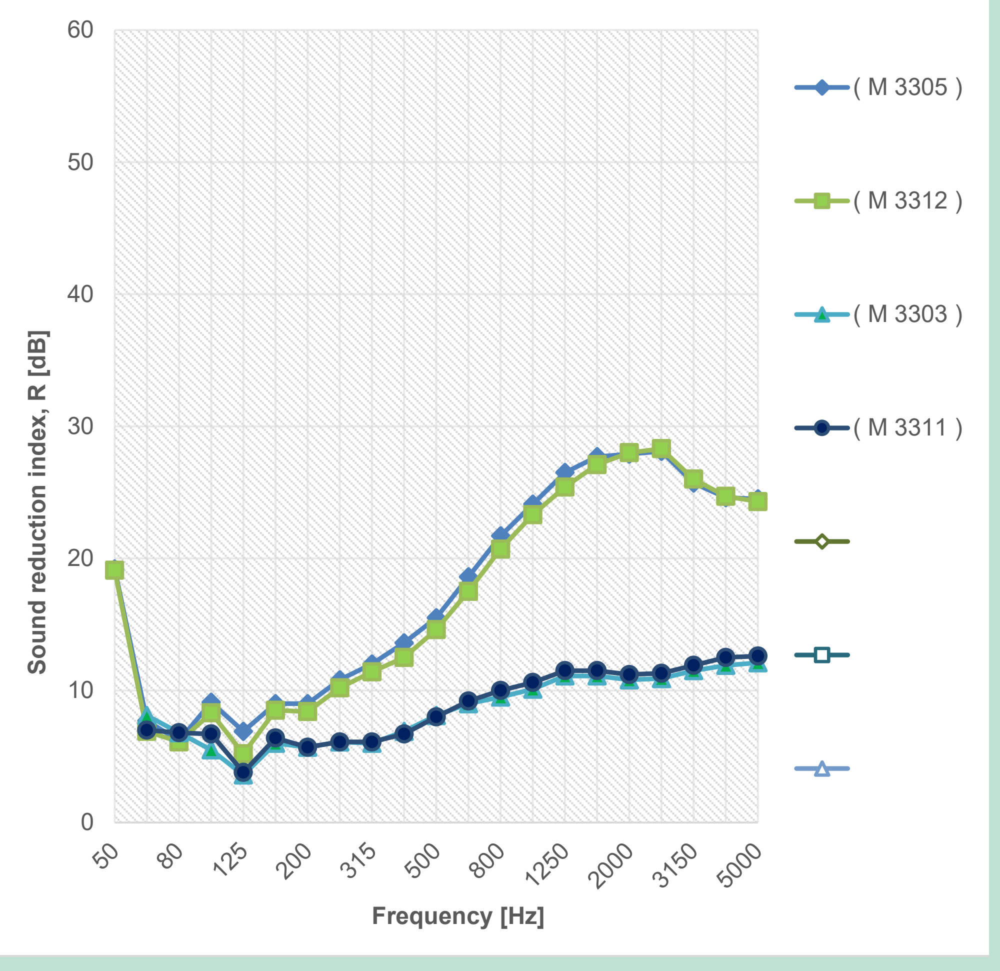
FIGURE 43. Comparison between mockup solution C in extended version and the prototype – both added to an ”ordinary window” (two-winged, outward opening, with one sash open and with an opening area of 0.35 m²).



M no	R_w [dB]	R_w+C_{tr} [dB]	Description
M 3316	7	7	“Open ordinary window” without added mockup or prototype
M 3215	10	9	Mockup solution C, extended, without absorbers
M 3303	10	9	Prototype, without absorbers
M 3211	22	18	Mockup solution C, extended, with absorbers (40 mm in top, bottom and sides. 20 mm at glass)
M 3306	21	17	Prototype, with absorbers (40 mm in top, bottom and sides. 20 mm at glass)

Subsequently it was investigated whether the sound insulation of the prototype plate material is of any significance. This was determined by mounting 3 mm bitumen plates inside the prototype construction. The results of this are displayed in FIGURE 44, from which it can be seen that the difference in sound insulation with and without bitumen is insignificant.

FIGURE 44. Investigation of significance of adding of bitumen on the sides, bottom and top to the prototype.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description
M 3305	21	17	Without bitumen. 40 mm absorber in top, bottom and sides
M 3312	20	16	With bitumen. 40 mm absorber in top, bottom and sides
M 3303	10	9	Without bitumen. Without absorbers
M 3311	10	9	With bitumen. Without absorbers

9.5 Recapitulation

In this chapter, a two winged ”ordinary window” was examined with mounted outside noise reducing constructions to find a solution that could be applied in situations when better sound insulation is required by mounting a construction to the existing window (e.g.e at restoration) but also in newbuilding by maintaining the ”usual” window dimensions.

Three types of an ”ordinary window” with outside solutions have been investigated in mockup-varieties, and subsequently, one type was selected, from which a prototype was developed:

A. A solution that covers the window and has two openings (Mockup)
B. A solution that covers the window and has one opening (Mockup)
C. A solution which is on the side of the window and which has one opening (Mockup and prototype)

For all the solutions apply that it provides full visibility straight ahead through the entire construction, whereas visibility slanting to the side is somewhat limited. The mockup-solutions have all been investigated at two different lengths to provide knowledge on the possibility of varying the lengths.

A number of laboratory measurements have been performed on the 4 different constructions (three mockup-solutions and a prototype solution), for which increased sound insulation of 4-15 dB was obtained for the mockup-solutions (described as the single number quantities R_w+C_{tr}), as per whether absorption was added or not.
For the prototype was obtained an improvement for the R_w+C_{tr} of 2-11 dB depending on, whether absorption was added (by comparing with a single open window for the mockup-solution as well as the prototype solution).

10. Field measurements

Illustration 10A. Photo from the field measurements.

Originally, the plan was to perform field measurements on each of the end constructions from work packages 1, 2 and 3 with the purpose of assessing the construction's noise insulation realistically, and ensuring that no significant systematic differences between the laboratory- and field results will occur.
To do this, it was necessary to find a location with the correct opening area (or possibility of adjustment) a high level of traffic noise and road, more or less parallel to a building. This turned out to be more difficult than expected. Thus it was decided to find a building with already installed supply air windows, perform field measurements on the windows (preferably on several floors) and subsequently perform laboratory measurements on identical windows. The purpose is to determine whether significant systematic differences will occur between the laboratory- and field results, and to get an idea whether the entrance angle of the noise is of any importance.

Illustration 10B. Photo from the field measurements, where the measurements at the third floor are being performed (the window is ”fully open”). 3 microphones can be seen positioned on the window.

Therefore the task was to find a building, which meets the following requirements, as best possible:

- The measurement can be performed as per ISO 16283-3:2016
- High level of noise from traffic
- A roadway almost parallel with the building
- A free view to the roadway from the window
- 1-winged supply air windows (i. e. not a combined window, which holds a supply air window as well as a fixed part)
- Finished residences (i.e. doors installed and a closed room behind the window)
- One window per room
- Supply air windows with vents that open 0.35 m^2
- A supply air window, manufactured by HSHansen a/s
- Supply air windows mounted in several floors’ height

Østergade 43-45 in Odense was selected, as it meets the most important criteria. However, the supply air windows could not open all of 0.35 m^2, and the view to the roadway was not totally without obstacles, since there are a few large trees (an avenue, see Illustration 10D). However, such criteria are not that important to the primary purpose.
The buildings at Østergade 43-45 are all occupied, so the next step was to gain access to performing the field measurements. Access was not allowed at the ground floor, and thus the measurements where only performed for the second and third floors.

Illustration 10C. Photo from the field measurements, where the vents are opened as much as possible. The three microphones are mounted on the glass.

10.1 Performing the field measurements

The measurements were performed a day in August 2016, with little wind only. The road surface was dry during the measurements. For each measurement, at least 50 motor vehicles passed by.
5 measurements were performed:

1. 3rd floor with a window that was opened as much as possible
2. 3rd floor with a closed window
3. 2nd floor with a window that was opened as much as possible
4. 2nd floor with a closed window
5. 2nd floor with a window that was open approximately 4 cm

When the windows are opened as much as possible, the outside window (the vent) has an opening area of approximately 0.21 m^2, while the similar inside window (the vent) has an opening area of approximately 0.24 m^2.
It was also desired that measurements with a lesser degree of opening area were carried out. Inspired by Hamburg (see section 6.2.1.4) it was opted to open the windows 4 cm. Opening and closing of the windows is motorized with pushbuttons, and therefore it is not possible to control closing of the outside and opening of the inside windows seperately. Hence, the outside window is opened approximately ca. 4 cm, and the inside window is opened approximately 6 cm. This results in outside and inside opening areas of approximately 0.03 m^2 and 0.07 m^2, respectively.

Illustration 10D. Photo from the field measurements, during the measurements at the second floor. The vents are open “4 cm”.

The measurements were performed as synchronous measurements with one indoor rotating microphone and three outdoor microphones placed on the pane, see Illustration 10C. the measurements were performed as per ISO 16283-3:2016 [24].

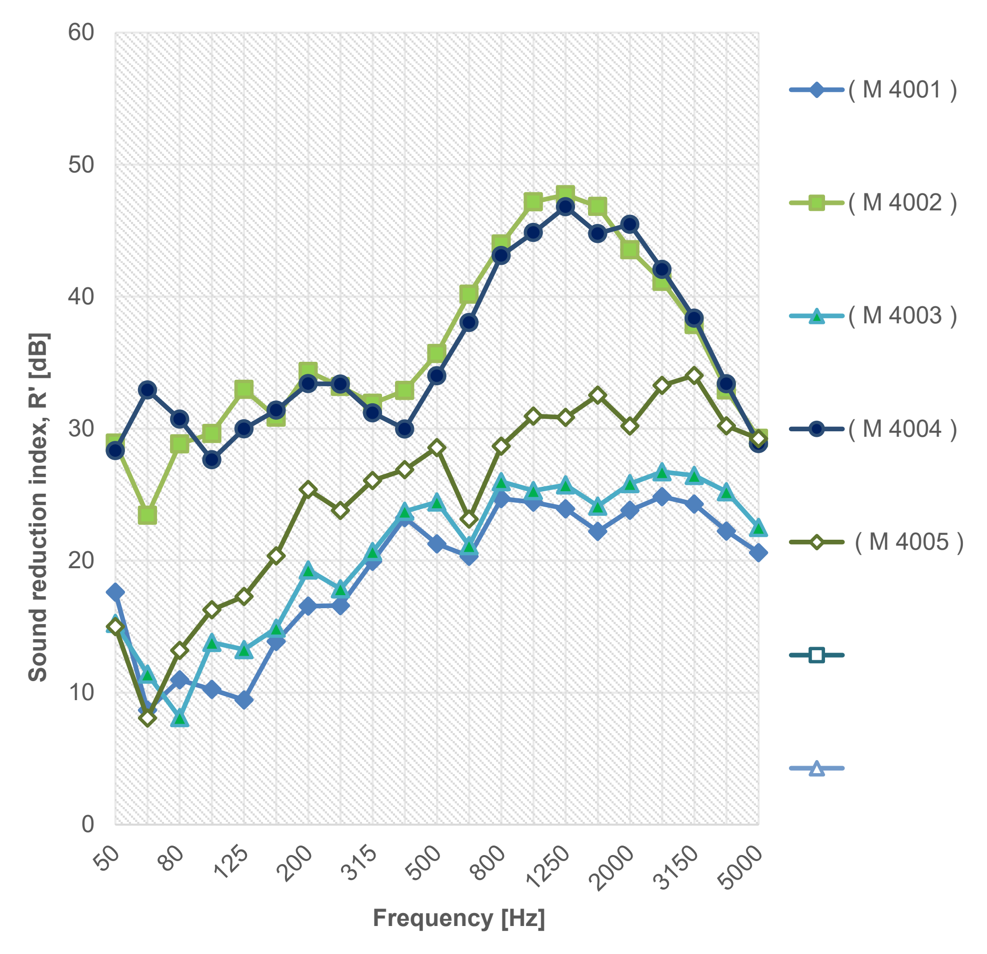
The outdoor level of noise, which was measured directly on the pane (primarily from traffic at Østergade) was approximately L_{Aeq} = 75-77 dB during the measurements. The level of traffic noise was thus not high enough for the measurements with closed windows to be performed correctly (too small difference to the background noise) and these measurements should only be used to verify the validity of the measurements with an open window.

The horizontal distance from the kerb to the facade of the building was 6.7 m by the window to the 3rd Floor and 7.3 m by the window to the 2nd floor (the two windows are located in different stairways). The road width was 10 m. There is a distance of approximately 16.5 m between the trees.
The window on the 2nd floor (the bottom) was 3.3 m above the ground, whereas the window on the 3rd floor (the bottom) was 6.3 m above the ground, see Illustration 10C. The window dimensions are (width x height): 910 mm x 2155 mm. There are 32 cm between the panes of the inside and outside parts. The space behind the window has a volume of approximately 15 m^3 and in both cases was furnished – the reverberation time was measured and corrected accordingly. Absorbing material has been applied to the frame inside the window frame at the top and bottom, whereas the bottom was non-absorbing (20 mm SUND®).

10.1.1 Results

The result of field measurements is shown in FIGURE 45. At the measurements of “completely open” windows, the level difference to background noise is satisfactory, whereas for the measurement with ”4 cm” open windows, the distance to the background noise is not sufficient for the frequency areas 315-500 Hz and 3150-5000 Hz, and the values for these frequency areas must be seen as minimum values.

FIGURE 45. Performed field measurements. The background noise level influenced the measurements with closed vents, and these measurements are only shown here to give an idea of the significance of the background noise level.



M no	R_w	R_w+C_{tr}	Description
M 4001	23	21	3. floor. Opened external 0.21 m^2 and internal 0.24 m^2.
M 4002	40	38	3. floor. Closed.
M 4003	25	23	2. floor. Opened external 0.21 m^2 and internal 0.24 m^2.
M 4004	40	37	2. floor. Closed.
M 4005	30	27	2. floor. Opened external 0.03 m^2 and internal 0.07 m^2.

For the measurements with ”completely open” vents, it can be seen that the curves at the upper most frequencies (from 800 Hz) are somewhat parallel for the measurements at the 2nd and 3rd floors, respectively. For the middle frequencies (250-800 Hz) the curves are more or less comparable, whereas the curves for the lowest frquencies (below 250 Hz) vary somewhat. In general, the sound insulation is highest for the measurements recorded at first floor, which may be seen from the single number quantities, for which are found differences of 2 dB for the R_w as well as the R_w+C_{tr}.

As expected it is also seen that the sound insulation is higher (4-5 dB for the R_w or the R_w+C_{tr}, respectively) for the measurement, for which the vents are more closed (the opening areas are smaller). This applies in general to the entire curve (except for the lowest frequencies), but is most pronounced for the highest frequencies.

10.2 Performance of laboratory measurements

In principle, the purpose with the laboratory measurements is to imitate the field measurements in the laboratory. A copy of the windows from the field measurements was therefore produced and a test wall has been built as a double plasterboard wall with the same thickness as the front wall from the field measurements, in which the window copy is mounted. Subsequently, a number of laboratory measurements have been performed, cf. Appendix 2.

Illustration 10E. Photo from the laboratory measurements taken from the inside. The vents are "fully open".

Apart from the differences of the situation (diffuse field versus free field) a number of things are not identical:

- Distance between the outside vent and the ground/floor
- Distance between inside vent and ceiling
- Sizes of the rooms, in which the measurements were carried out
- Reverberation time in the rooms

In the laboratory, the distance on the outside is 38 cm between the bottom of the window and the concrete floor (6.7-7.3 m at the fields measurements). On the inside of the laboratory, the built-up wall is placed in a slightly offset opening, i.e. the distance to a 17 cm deep concrete frame is 21.5 cm, while the totalt distance to the ceiling from the top of the window is 49 cm, see Illustration 10E (at the field measurements there was approximately 47 cm between the top of the window and the ceiling). The inside volume in the laboratory is 50.7 m^3 (the volume where the field measurements were made, was 15 m^3). For field measurements as well as laboratory measurements, corrections were made for the reverberation time. The reverberation time at the field measurements is approximately 0.5 s, and the reverberation time at the laboratory measurements is approximately 1.6 s.

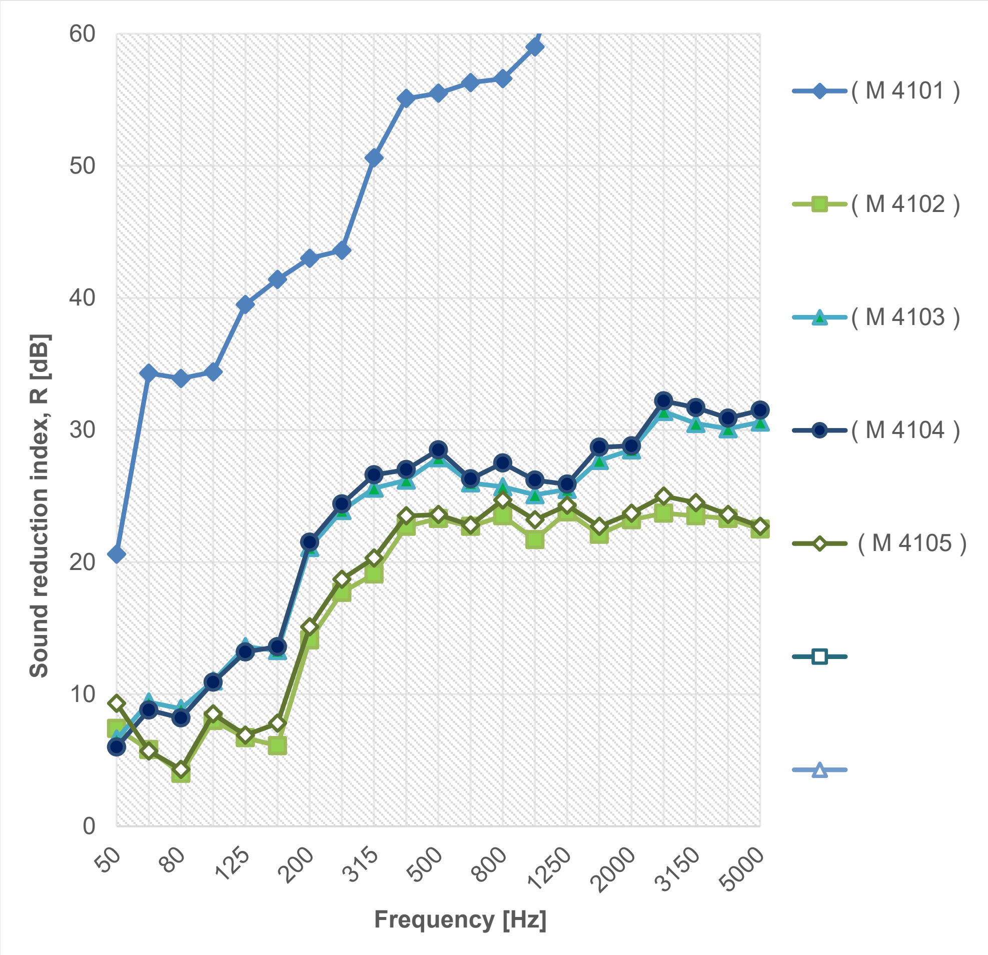
Illustration 10F. Photo from the laboratory measurements taken from the outside. Left photo shows the vents "fully open", while the right photo shows the vents "4 cm" open.

10.2.1 Results of laboratory measurements for comparison with the field measurements

The results of the laboratory measurements are depicted in **Error! Reference source not found.**, which also displays the results with closed vents as additional information. Flanking transmission has not been measured for the wall. The surrounding wall is designed as a double structure with three layers of plasterboard and one layer of fibregypsom on each side. Subjective evaluated there is a contribution from the wall. Thus the results with closed vents should be regarded as minimum values.

For open vents, 2x2 measurements have been performed, i.e. measurements for both applied opening positions and with and without the 20 mm frame absorber placed uppermost in the cavity between the external and internal window constructions.

FIGURE 46. Performed laboratory measurements to be compared with the field measurements.



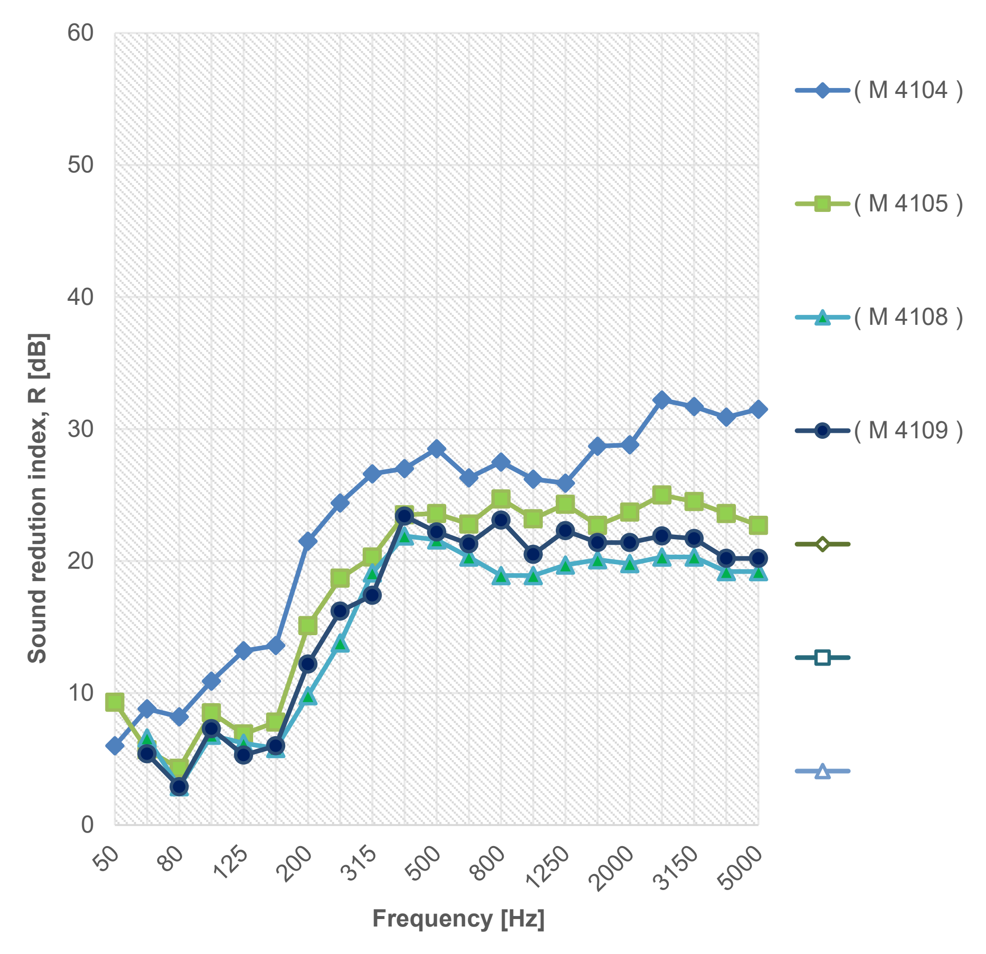
M no	R_w	R_w+C_{tr}	Description
M 4101	57	50	Closed. Without 20 mm absorber in top.
M 4102	23	19	Opened external 0.21 m^2 and internal 0.24 m^2. With 20 mm absorber in the sides. Without 20 mm absorber in the top.
M 4103	27	24	Opened external 0.03 m^2 and internal 0.07 m^2. With 20 mm absorber in sides. Without 20 mm absorber in top
M 4104	28	24	Opened external 0.03 m^2 and internal 0.07 m^2. With 20 mm absorber in sides and top
M 4105	24	19	Opened external 0.21 m^2 and internal 0.24 m^2. With 20 mm absorber in sides and top

The effect of adding absorber at the top is very minor, only, primarily in the frequency area above 200 Hz. For the single number quantities, the addition of absorber to the top is an improvement of 1 dB for the R_w, whereas the R_w+C_{tr} remains unaltered.

As expected, it is seen that the smaller the opening area, the higher the sound insulation, which applies to almost all frequencies. For the single number quantities, the limitation of the opening area means an improvement of 4 dB for the R_w, while the R_w+C_{tr} is increased by 5 dB.

10.2.2 Results of further laboratory measurements

FIGURE 47. Comparison of opening areas. All measurements with 20 mm absorber in top.



M no	R_w	R_w+C_{tr}	Description
M 4104	28	24	Opened external 0.03 m^2 and internal 0.07 m^2.
M 4105	24	19	Opened external 0.21 m^2 and internal 0.24 m^2.
M 4108	20	17	Opened external 0.35 m^2 and internal 0.37 m^2. (opened as much as possible)
M 4109	21	18	Opened external 0.35 m^2 and internal 0.35 m^2 ("diagonal position").

Apart from measurements comparable to the field measurements, measurements with an opening area of 0.35 m^2 were also performed. When the vents are opened as much as physically possible, i.e. photos in Illustrations 10G and 10H, the opening area is approximately 0.35 m^2. An opening area of 0.35 m^2 may also be found with the vents in the "diagonal position", also see llustrations 10G and 10H. Both configurations have been measured and shown in FIGURE 47 together with the two smaller previous opening areas. It can be seen that there is a clear difference between the two positions for 0.35 m^2 (approximately 1 dB difference), and it may be concluded that the opening angle for the vents is just as important as the opening area.

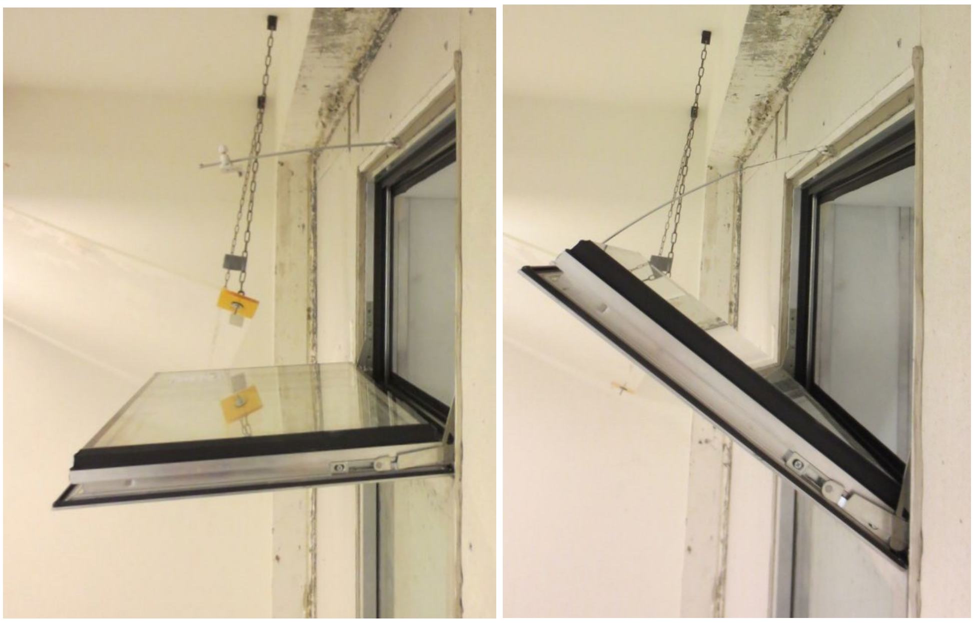
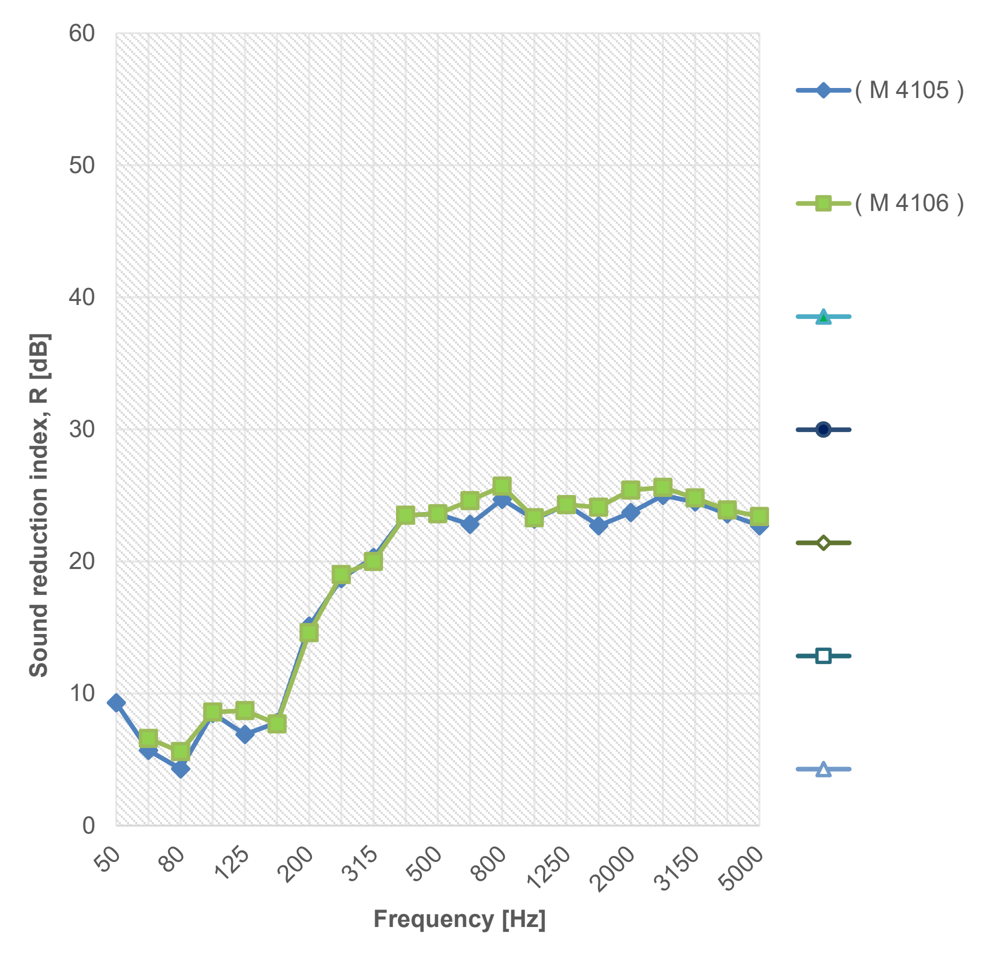


Illustration 10G. Photo from the laboratory measurements taken from the internal side. Left photo shows the vent opened as much as possible, while the right photo shows the vent in a “diagonal position”. In both situations the opening area is approximately 0.35 m^2.

Illustration 10H. Photo from the laboratory measurements taken from the external side. Left photo shows the vent opened as much as possible, while the right photo shows the vent in a “diagonal position”. In both situations the opening area is approximately 0.35 m^2.

FIGURE 48. Investigation of influence of the slit at the hinges.



M no	R_w	R_w+C_{tr}	Description
M 4105	24	19	Slit with a width of approximately 6 mm at the outer side and approximately 3 mm at the internal side.
M 4106	24	20	Slit closed with mineral wool and covered by tape

At the top of the external vent and at the bottom of the internal bottom-hung vent there is a small air-slit, which grows with the opening of the vent, see Illustration 10I. The sound insulation effect is desired known and therefore the slits were covered and the sound insulation measured. This was done by filling the cavity behind the slit with mineral wool and then covering the slit with thick tape. FIGURE 48 shows the result of this comparison. As can be seen, the slit only has minor significance in terms of sound insulation.

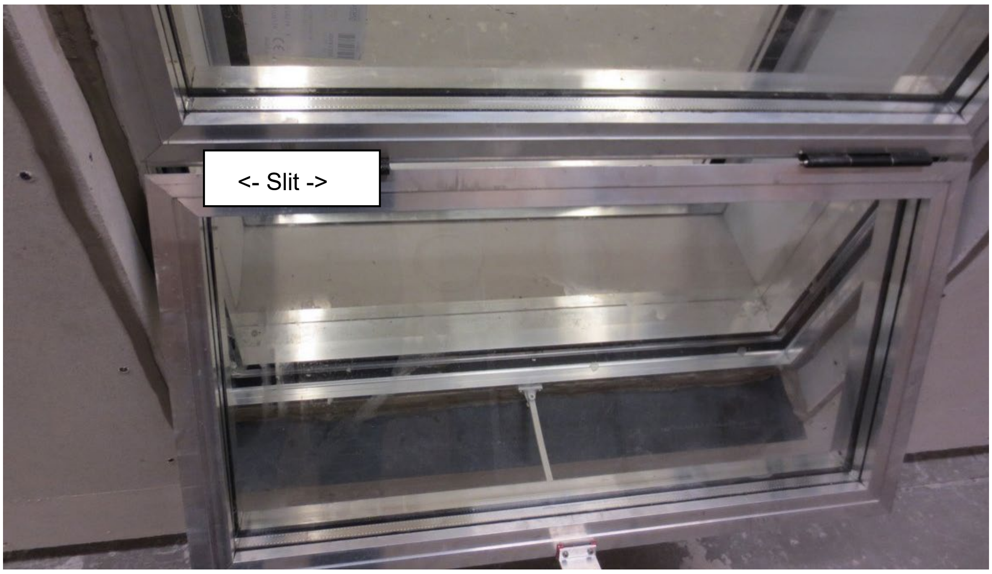
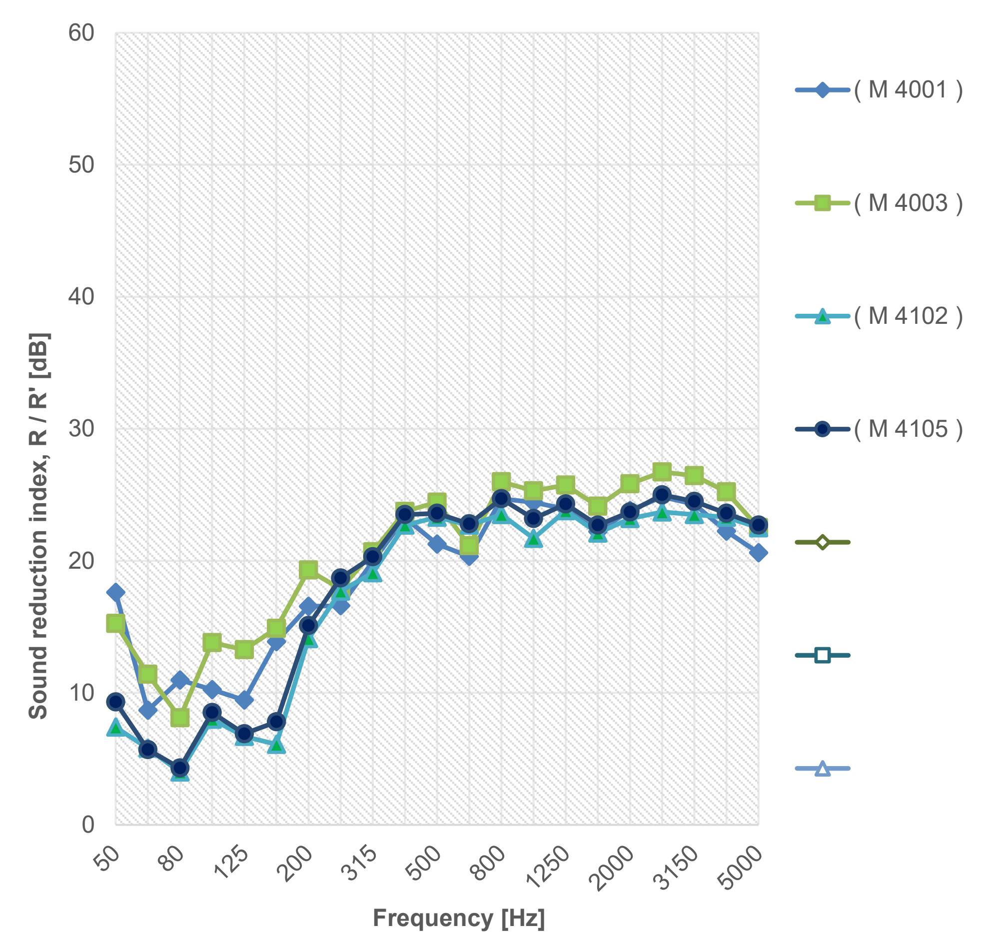


Illustration 10I. Photo from the laboratory measurements taken from the outer side. The photo shows a slit at the top of the vent, when the vent is opened.

10.3 Comparison of field measurements and laboratory measurements

FIGURE 49 depicts a comparison of field measurements and laboratory measurements, for which the vents were opened as much as possible during the field measurements. It can be seen that the sound insulation is highest in the field measurements for frequencies below 250 Hz. In the rest of the frequency area, the sound insulation is roughly comparable with a tendency to higher sound insulation for the field measurements for frequencies above 800 Hz. For the single number quantities, the R_w-values are also roughly comparable (23-25 dB for the field measurements and 23-24 dB for the laboratory measurements), whereas there is a more pronounced difference for the R_w+C_{tr}-values (21-23 dB for the field measurements and 19 dB for the laboratory measurements).

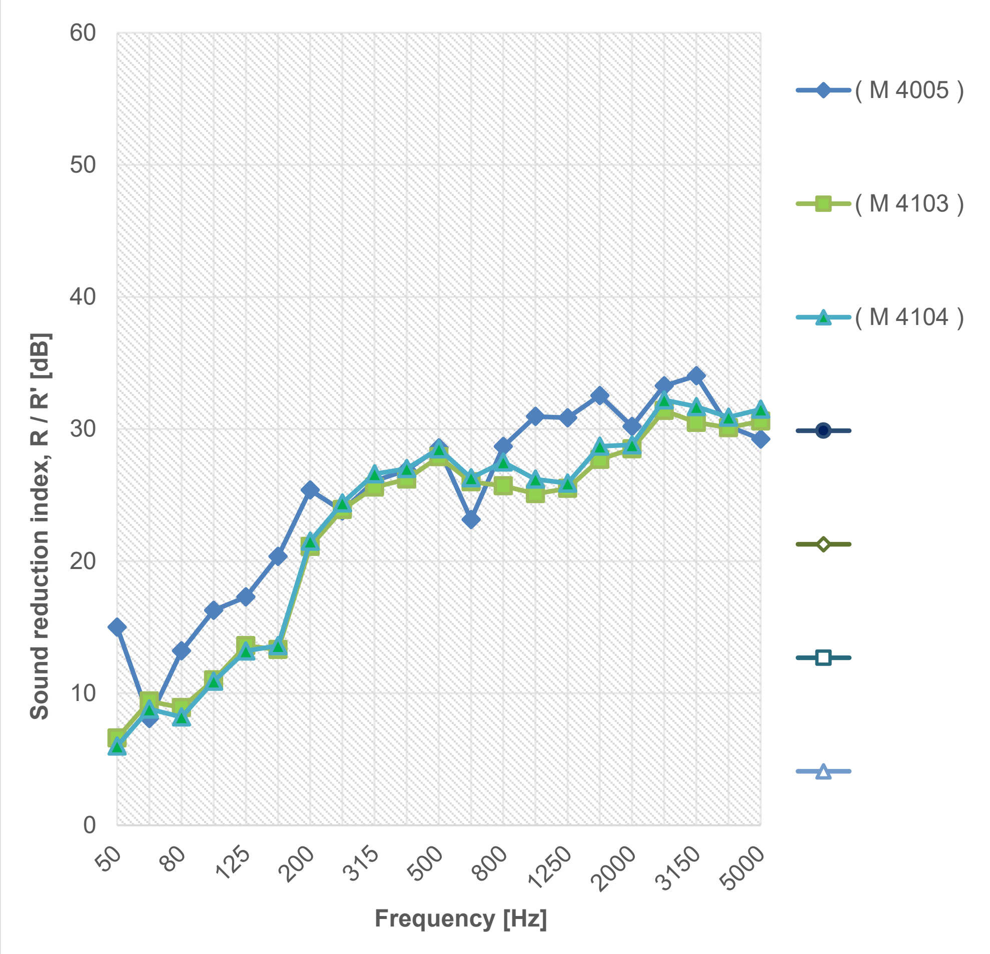
FIGURE 49. Comparison of field measurements and laboratory measurements. The vents are “fully open” (outer opening area 0.21 m^2 and inner opening area 0.24 m^2).



M no	R_w / R'_w	R_w+C_{tr} / R'_w+C_{tr}	Description
M 4001	23	21	Field measurement. 3rd floor.
M 4003	25	23	Field measurement. 2nd floor.
M 4102	23	19	Laboratory measurement. Without 20 mm absorber in top.
M 4105	24	19	Laboratory measurement. With 20 mm absorber in top

FIGURE 50 depicts a comparison of field- and laboratory measurements with vents approximately 4 cm open. It is seen that the sound insulation is best for the field measurements for frequencies below 250 Hz and in the frequency range 800 Hz to 2000 Hz. In the remaining frequency area, the sound insulation is roughly comparable. For the single number quantities, the sound insulation is a couple of dB higher for the field- than the laboratory measurements, applying to the R_w-values as well as the R_w+C_{tr}-values (R_w = 30 dB for field measurements and R_w = 27-28 dB for laboratory measurements and R_w+C_{tr} = 27 dB for field measurements and R_w+C_{tr} = 24 dB for laboratory measurements).

FIGURE 50. Comparison of field measurements and laboratory measurements. The vents are opened ”4 cm” (Outer opening area 0.03 m^2 and inner opening area 0.07 m^2).



M no	R_w / R'_w	R_w+C_{tr} / R'_w+C_{tr}	Description
M 4005	30	27	Field measurement. 2nd floor.
M 4103	27	24	Laboratory measurement. Without 20 mm absorber in top.
M 4104	28	24	Laboratory measurement. With 20 mm absorber in top.

10.4 Recapitulation

It looks as though, in general, the sound insulation increases for field measurements rather than for laboratory measurements – especially in the low frequency area (in this case up to 200 Hz). One explanation for this could be the difference in sound-inflow. In the laboratory, the sound field is diffuse, which means that the sound comes from all directions, (top, bottom, the side, etc.), whereas the sound in the field primarily flows diagonally from below (noise from tyres and engines).

The difference between field and laboratory measurements stated as R_w+C_{tr} is 3-4 dB, for which the field measurements show higher sound insulation than the laboratory measurements. It cannot be ruled out that the difference could be bigger for other types of windows, e.g. for the window types applied in work packages 2 and 3, as the openings are on the side and not at the bottom.

When comparing the two field measurements at the second and third floors, respectively, with fully open vents, there is a difference of 2 dB at the R_w as well as the R_w+C_{tr}, since the result on the second floor displays the lowest sound insulation.

It would seem that the higher the sound inflow (defined by the angle between the horizontal and the line between the road and the window) the lower the sound insulation. The difference in sound insulation for the window, depending on the noise inflow angle has, in another project, been attempted simulated by the room-acoustic simulation tool ODEON. The simulations partly confirm the results found by the field measurements, i.e. that especially the high frequency sound insulation decreases when the noise inflow angle increases. The results have been published in a paper presented at INTERNOISE in San Francisco, 2015 [33].

11. Measurement of traditional open windows and selected main results from the project

Illustration 11A. The window used for the laboratory part of chapter 10.

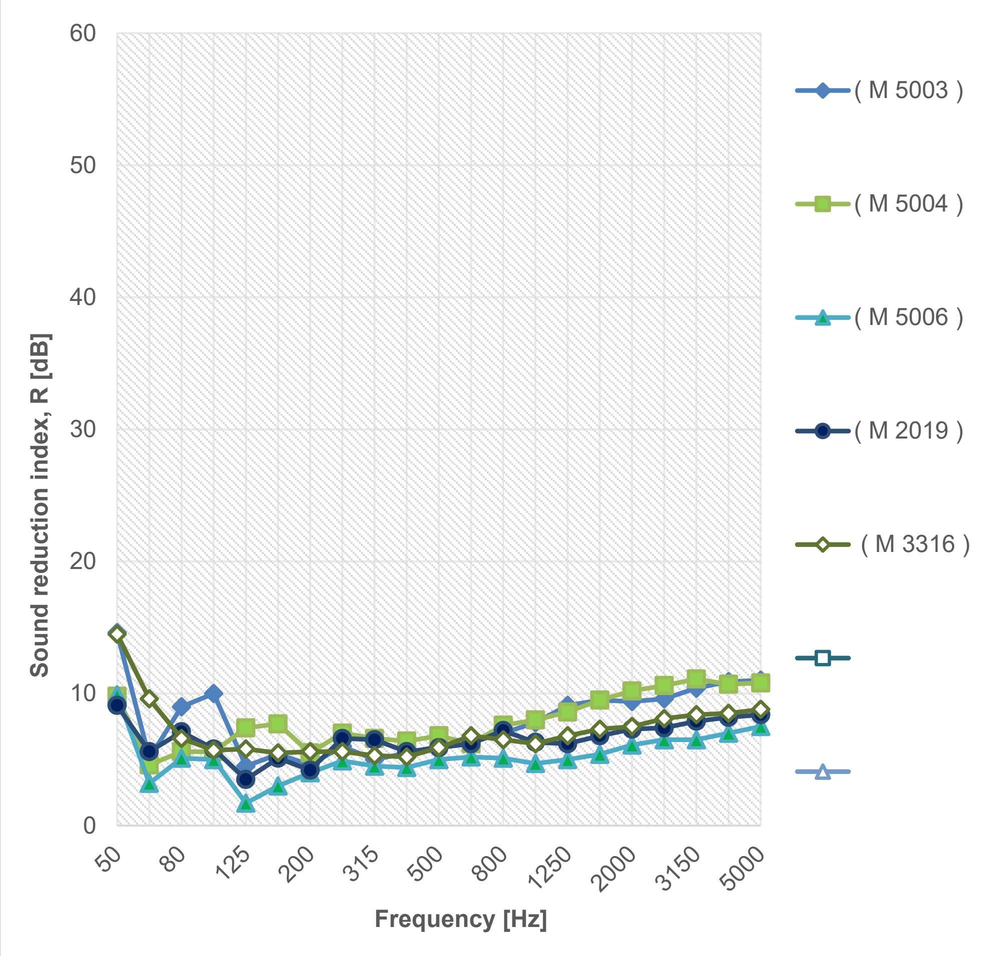
The purpose of this chapter is to compare various laboratory measured sound insulation values for traditional open windows with different design and selected results from the project.

11.1 Traditional open windows

The sound insulation for various traditional windows in standard format (1230 mm x 1480 mm) has been measured in the laboratory. Photos of the windows are depicted in Illustration 11B, and the result of the measurements are shown in FIGUR 51. All windows were opened so the total opening area was 0.35 m^2. The sound insulation is between 6-9 dB for the R_w and 5-8 dB for the R_w+C_{tr}.

Illustration 11B. Photos of the traditionally open windows measured in FIGUR 51. All photos except M 5006 are taken from the inside, while the photo of M 5006 is taken from the outside.

FIGUR 51. ”Ordinary, open windows”, see Illustration 11A.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description
M 5003	8	7	Opening inwards, side hung
M 5004	9	8	Opening outwards, top guided
M 5006	6	5	Dannebrog window, opening outward, side hung
M 2019	7	6	Two-winged, opening outwards, sash hinged in ”center”
M 3316	7	7	Two-winged, opening outwards, sash hinged in frame

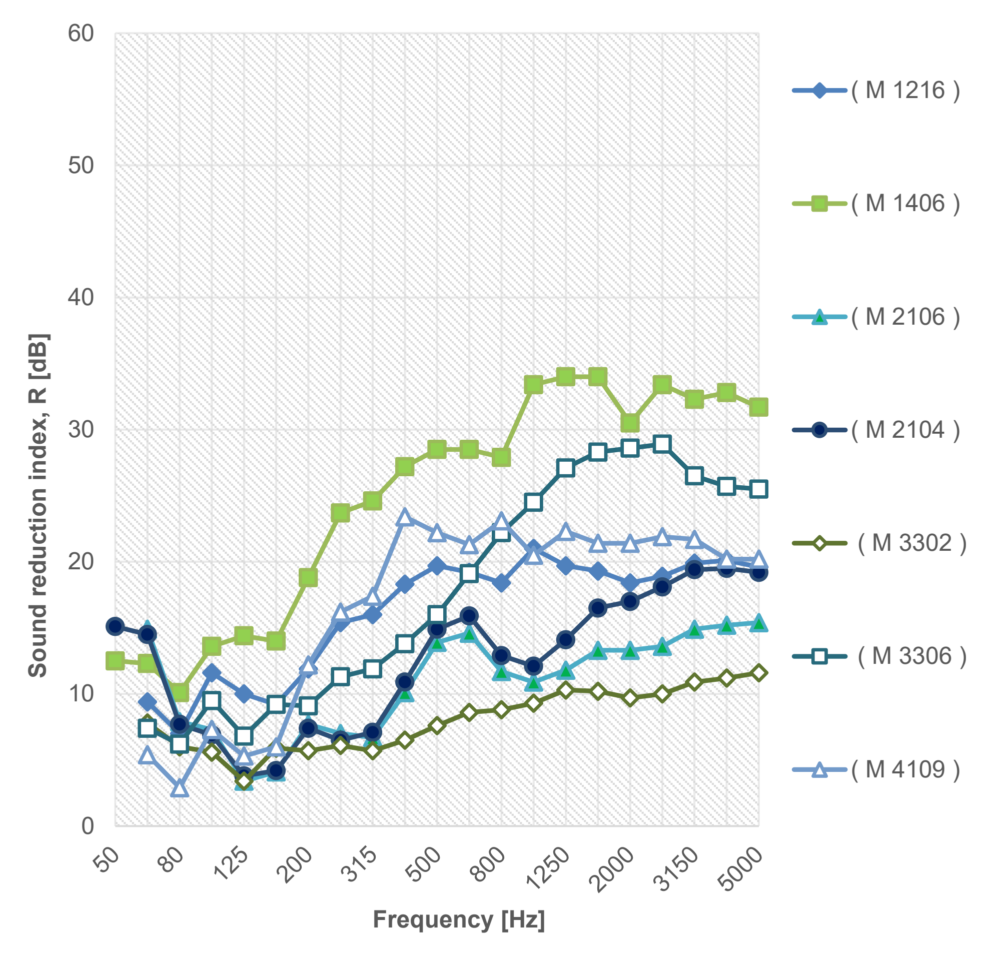
11.2 Selected results from the project

FIGURE 52 displays compiled selected results from the project (all with an opening area of 0.35 m^2) to provide an overall overview of found solutions and adhering sound insulation..
The applied window types were:

1. Further development of the ”Supply air window”
2. ”Ordinary window” with an internal solution
3. ”Ordinary window” with an external solution

Window type 1 has the dimensions (width X height) 1250 mm x 2100 mm. Window types 2 and 3 have the dimensions 1230 mm x 1480 mm (standard format), while the field measurement element (Supply air window) has the dimensions 910 mm x 2155 mm. The displayed measuring results are for constructions with and without absorber. For work packages 2 and 3 the displayed results are for the prototype solutions. It applies to all solutions that the displayed measurements are the best obtained, while still meeting the requirement of the 0.35 m^2 opening area, and the glass surfaces have not been covered by absorber.

FIGURE 52. Selected results from the project.



M no	R_w [dB]	R_w+C_{tr} [dB]	Description
M 1216	19	18	Window type 1 without frame absorber, see chapter 7
M 1406	30	26	Window type 1 with frame absorber, see chapter 7
M 2106	13	11	Window type 2 without frame absorber, see chapter 8
M 2104	15	12	Window type 2 with frame absorber, see chapter 8
M 3302	9	8	Window type 3 without frame absorber, see chapter 9
M 3306	21	17	Window type 3 with frame absorber, see chapter 9
M 4109	21	18	Field measurement, see chapter 10

It can be seen from the measurements that there is a large gap between the obtainable values, which is expected as seen from the purpose of the project. Solutions have been found which provide three different reduction indexes, but they are evenly divided from an R_w+C_{tr} of 12 dB (window type 2) to one at 26 dB (window type 1) with a solution in the middle of 17 dB (window type 3).

12. Conclusion

Based on a former project on ”Supply air windows” (”Optimizing the sound insulation of supply air windows”) [1] and an increasing demand for knowledge on sound insulation for open windows, a project titled ” Development of windows with good sound insulation in the open position” has been executed”. In general, three different window types have been investigated I) Further development of the “supply air window” II) ”Ordinary window” with an internal solution and III) ”Ordinary window” with an external solution.

Preliminary literature studies have been carried out for all three types of windows. For further development of the supply air window, focus has been on studies/methods based on low frequency sound insulation. Various methods have been found, some of which are based on resonators.

These are all based on completely closed double constructions. Other similar windows have been found, such as the Hafencity Fenster [22] and Plenum Window [14]. For the first mentioned reference applies that the opening area is significantly smaller than usually indicated in Denmark. The latter reference is a study of the significance of the noise’s entrance angle, performed on a scaled model.
For the two other window types (”Ordinary window” with internal solution and ”Ordinary window” with external solution) literature studies have been found that describe various sound shutter solutions, including those at Margretheholm [15] and Folehaven [16].

A significant number of laboratory tests have been performed with the various window types, as mockup-solutions as well as more complete prototype-solutions and a few field measurements. This report accounts for the performed measurements and derived conclusions.

As in previous studies, sound insulation seems to depend on dimensions, opening area and placing of the absorber.
The purpose of examining three different window types is to find alternatives to an ordinary open window, which cover both a wide range of sound insulation and a wide range of dimensions, position of absorbers/absorption and added constructions such as a external solution.

An optimised version of the supply air window has been developed, with special focus on sound insulation the low frequency area. As opposed to previously, perforated frames have been developed, which are tuned to specifically handling the low frequency part of the spectrum.

It can be concluded that with the perforated plates, improved sound insulation has been achieved at the lower frequencies as well as higher single number quantities, with the best result being R_w at 30 dB and R_w+C_{tr} at 26 dB.

A window which fits an ordinary window opening with an internal solution has been developed. With reference to a single window, improvements are seen in several steps: Firstly, when adding an extra window (i.e. an assembled double structure), secondly by adding a sliding window in the cavity and finally by adding absorber to the frame construction. The most significant improvement was seen in the change from single construction to double construction. Addition of a movable element within the double construction also contributes to the total increase in the reduction index, especially if absorption is also added to the double construction. The purpose with the construction was to increase the sound insulation by approximately 5 dB compared to that of an ordinary open window.

By this solution an R_w of 15 dB and an R_w+C_{tr} of 12 dB, have been achieved which is a total improvement for the R_w of 8 dB and for the R_w+C_{tr} of 5 dB when compared with an ordinary open window.

A window has been created which fits an ordinary window opening with an external solution, which does not necessarily require that changes be made to the window opening or the window.
The solution is based on an external construction in the shape of a mounted sound-lock with connection to the window frame, opening into the sound-lock. With the optimum set-up of absorbers in the sound-lock, sound insulation is achieved for the R_w at 21 dB and the R_w+C_{tr} at 17 dB, which is an improvement for the R_w at 14 dB and for the R_w+C_{tr} at 11 dB compared to that of an ordinary open window.

Comparative field- and laboratory measurements have been performed on an supply air window to investigate the differences, if any. Better sound insulation is seen for the field measurements than for the laboratory measurements, especially for frequencies below 250 Hz. The difference in the R_w+C_{tr} is 2-4 dB. One explanation could be the difference in sound inflow and thus is cannot be ruled out that the difference could be higher for window types, where the opening in the construction is not directed towards the noise source.

For the entire project it can be concluded that three window types ranging widely in sound insulation, dimensions and construction/solution principle, have been investigated. For the three window types, a laboratory measured sound insulation for the R_w+C_{tr} of 26, 12 and 17 dB, respectively, where an ordinary open window has a the sound insulation as R_w+C_{tr} at 5-8 dB.

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Appendix 2. About the laboratory measurements

Measuring room

All laboratory measurements have been carried out in DELTA's building acoustic laboratory at the premises of Teknologisk Institut, Aarhus. The facilities include three rooms in a row, a source room in the middle and a receiver room on each side of the source room. Illustration B1 depicts a horizontal cross section of the rooms where room 1 is the source room and rooms 2 and 3 are the receiver rooms. In Illustration B2 is displayed a vertical cross section of the rooms. The opening between rooms 1 and 2 has the dimensions 2120 mm x 1250 mm, whereas the opening between rooms 1 and 3 have the dimensions 4210 mm x 2600 mm. Rooms 1, 2 and 3 hold the volumes as 117.7 m^2, 64.8 m^2 and 50.7 m^2, respectively. The rooms meet all the requirements of ISO 10140-5, reference [28].

The large opening between rooms 1 and 3 is adjusted to the window dimensions by establishing light wall constructions with high sound insulation, in which the window opening has been established. The thickness of the two structures is approximately 220 mm and 320 mm, respectively.

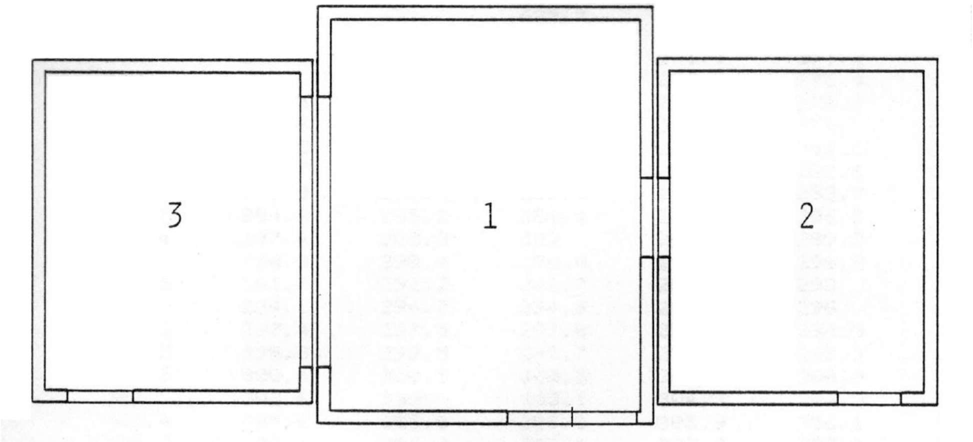

Illustration B1. Horizontal cross section in the laboratory.

Quantities

Measuring of the windows' sound insulation in the laboratory is performed as per the "ISO 10140-series "Acoustics -- Laboratory measurement of sound insulation of building elements", reference [25] to [28].

The measurements are usually performed as 1/3-octave bands in the frequency range from 100 Hz-5000 Hz, perhaps in the extended frequency range from 50 Hz-5000 Hz. The result consists of a reduction index curve determined by the 18, alternatively 21 1/3-octave values.

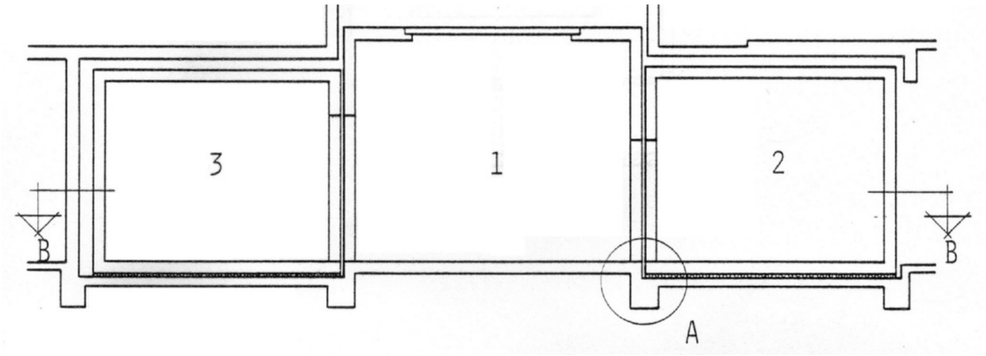

Illustration B2. Vertical cross section in the laboratory.

When determining the reduction index for traditional windows, compensation is made for the window area. This means that when measuring on the same window construction but with alternate dimensions/spaces (within certain limits) almost the same measuring result will be obtained.

E.g. when comparing products or for project engineering, to be able to operate with a more flexible quantity, the 1/3 octave values are recalculated to a single number quantity, the R_w, with two adhering spectral adaptation terms C and C_{tr} as per ”ISO 717-1”, reference [29].

The main results of a sound insulation measurement in the laboratory, expressed as a single figure value would look as follows:

R_w (C; C_{tr}) = 38 (-2; -5) dB

The spectral adaptation terms C and C_{tr} are added to the R_w-quantity and hence it is adapted the following types of noise:

Type of noise source	Relevant spectrum adaptation term
- Living activities(talking, music, radio, TV) - Children playing - Railway traffic at medium and high speed - Highway road traffic at more than 80 km/h - Jet aircraft, short distance - Factories emitting mainly medium- and high-frequency noise	C
- Urban road traffic - Railway traffic at low speeds - Aircraft, propeller driven - Jet aircraft, large distance - Disco music - Factories emitting mainly low and medium frequency noise	C_{tr}

As mentioned above, the window area is part of determining the reduction index. As regards closed windows (and the supply air window with closed vents) these should be regarded as a traditional window, which should be measured as per the ISO 10140-method, references [25] to [28].
If the vents are opened, the construction changes from a traditional window to a construction, which should be regarded as a simple opening or a duct, through which the sound is transmitted.

Sound transmission directly through the panes of a supply air window becomes less and less significant, the more the vents are opened. Hence, the abovementioned correction of the window area when measuring traditional windows will not be optimal. This means that the R_w (C; C_{tr}) for an open window only applies to the window in question and not to similarly constructed windows of other dimensions.

Therefore it might be considered to apply another quantity for open windows, the element normalised level difference, which similar to the reduction index is measured as per the ISO 10140-series. The quantity is denominated $D_{n,e}$ and the single number quantity $D_{n,e,w}$ (C; C_{tr}). This method is meant for measuring small building elements, often with a non-welldefined area, such as e.g. outside air valves and cable wall ducts. When measuring as per this method, the sound insulation properties for open window constructions, but with various dimensions, would be comparable.

As can be seen from the above, none of the two measuring methods are spot-on when it comes to describing open windows' sound insulation. It has been decided in this project to regard the constructions as a traditional window, i.e. that the sound insulation is stated as reduction index and the single number quantity R_w (C; C_{tr}).

R_w (C; C_{tr}) and $D_{n,e,w}$ (C; C_{tr}) for all measurements included in this report, are stated in Appendix 3.

If the $D_{n,e,w}$ (C; C_{tr}) is needed, this can be done based on the reduction indexes by simple recalculation.

Measuring results are presented as curves/graphs which state the reduction index per 1/3-octave, and as the single number quantity R_w and R_w+C_{tr}. In each figure is a number, which precisely identifies the measurement (e.g. M 2019). This number refers to Appendix 3, which list the 1/3-octave reduction indexes.

Appendix 3. Measuring results in tables

The denominations M xxxx in the uppermost row of each of the following tables represent the number of the measurement, which has been linked with the report figures in chapters 7-11.

Frequency	M 1001 [dB]	M 1004 [dB]	M 1005 [dB]	M 1007 [dB]	M 1008 [dB]	M 1108 [dB]	M 1109 [dB]	M 1110 [dB]	M 1111 [dB]
50	10.3	22.9	13.9	13.5	13.0	-	-	-	-
63	12.8	34.7	5.8	6.2	6.9	10.6	10.2	10.3	9.7
80	11.4	35.9	5.4	5.5	6.8	7.6	7.6	8.1	7.7
100	13.5	37.2	9.5	9.8	10.2	11.5	11.1	11.6	11.5
125	16.2	39.4	7.1	8.5	8.7	10.8	10.7	10.1	9.9
160	16.6	37.5	7.5	8.2	8.7	9.3	9.5	9.3	9.2
200	20.9	41.4	10.0	10.7	11.7	11.8	11.6	11.7	12.2
250	26.2	43.8	13.7	14.9	17.1	15.0	14.7	15.3	15.4
315	25.7	49.8	14.9	17.5	20.5	16.1	15.7	16.2	16.3
400	28.9	53.1	17.8	22.2	25.7	18.6	18.1	18.7	18.9
500	31.1	58.9	18.4	23.6	27.7	19.9	19.6	20.3	20.1
630	25.5	63.5	17.6	22.5	26.2	18.7	18.6	19.1	19.2
800	23.5	65.9	17.1	22.1	24.7	17.8	17.7	18.5	18.3
1000	27.3	70.4	19.6	27.5	29.4	20.7	20.6	21.0	20.9
1250	24.4	73.5	18.4	26.0	26.1	19.6	19.4	19.7	19.6
1600	23.4	72.7	18.3	25.0	24.5	18.8	18.7	19.1	19.1
2000	21.9	65.9	17.4	23.4	22.2	17.8	17.9	17.8	17.9
2500	23.7	64.4	18.1	25.2	23.0	18.7	18.8	18.8	18.8
3150	23.2	66.0	19.0	24.2	22.8	19.5	19.5	19.4	19.5
4000	22.5	75.4	19.2	24.4	22.9	19.1	19.0	19.0	19.1
5000	23.1	76.4	18.9	23.9	23.2	19.3	19.2	19.3	19.3
R_w / R'_w	24	57	18	23	24	19	19	19	19
C	0	-2	-1	-1	-1	-1	-1	0	0
C_{tr}	0	-7	-2	-4	-4	-2	-2	-1	-1
$D_{n,e,w}$ / $D'_{n,e,w}$	30	63	24	29	30	25	25	25	25
C	-1	-2	-1	-1	-2	-1	-1	-1	-1
C_{tr}	-1	-7	-2	-4	-4	-2	-2	-2	-2

Frequency	M 1208 [dB]	M 1210 [dB]	M 1213 [dB]	M 1214 [dB]	M 1216 [dB]	M 1304 [dB]	M 1306 [dB]	M 1307 [dB]	M 1310 [dB]
50	-	-	-	-	-	-	-	-	-
63	10.1	10.2	10.5	10.3	9.4	12.4	11.3	12.5	13.2
80	8.0	7.9	8.3	7.9	7.0	10.7	9.7	10.8	10.9
100	11.9	11.3	11.5	11.6	11.6	14.8	12.7	13.0	15.4
125	10.0	10.8	10.4	10.4	10.0	11.7	10.5	11.3	13.7
160	8.9	9.0	8.8	9.2	9.2	10.9	10.5	9.9	13.0
200	11.8	11.6	11.5	11.8	11.9	14.6	14.0	14.0	15.2
250	16.0	16.5	15.6	15.8	15.4	16.9	18.6	17.3	17.0
315	16.5	16.3	16.9	16.9	16.0	17.8	20.8	18.8	17.5
400	18.8	18.7	18.6	19.0	18.3	19.6	24.2	22.4	18.7
500	19.9	20.2	20.1	20.1	19.7	21.7	27.5	25.3	21.1
630	19.2	18.9	19.4	19.1	19.2	19.7	25.9	22.5	19.1
800	18.6	18.7	18.8	18.6	18.4	18.4	24.2	21.8	17.8
1000	21.5	21.3	21.4	21.2	21.0	21.2	28.9	26.7	20.9
1250	20.2	20.5	20.7	20.5	19.7	20.2	26.5	25.9	20.2
1600	19.6	19.9	20.1	19.7	19.3	19.6	25.2	25.1	19.7
2000	18.9	18.9	19.1	18.8	18.4	18.7	22.7	23.2	18.7
2500	19.5	19.6	19.7	19.5	18.9	19.4	23.5	24.4	19.9
3150	20.0	20.2	20.3	20.2	19.9	20.1	23.7	24.5	20.2
4000	20.3	20.5	20.5	20.5	20.1	20.1	23.7	24.4	20.2
5000	20.0	20.2	20.3	20.2	19.6	20.3	23.5	24.2	19.9
R_w / R'_w	20	20	20	20	19	20	25	24	20
C	-1	-1	-1	-1	0	-1	-2	-1	-1
C_{tr}	-2	-2	-2	-2	-1	-1	-4	-3	-1
$D_{n,e,w}$ / $D'_{n,e,w}$	25	26	26	26	25	26	30	30	25
C	0	-1	-1	-1	-1	-1	-1	-2	0
C_{tr}	-1	-2	-2	-2	-2	-2	-3	-4	-1

Frequency	M 1317 [dB]	M 1318 [dB]	M 1319 [dB]	M 1401 [dB]	M 1402 [dB]	M 1403 [dB]	M 1404 [dB]	M 1405 [dB]	M 1406 [dB]
50	-	-	-	12.5	12.7	12.5	12.2	-	12.5
63	13.5	13.6	13.0	12.8	12.1	11.5	11.8	11.8	12.3
80	10.6	11.0	10.1	10.9	9.6	9.4	9.4	9.6	10.1
100	14.5	14.7	13.4	13.9	12.8	12.2	13.0	13.0	13.6
125	12.7	14.7	12.9	13.8	13.2	12.6	13.1	12.8	14.4
160	11.9	13.1	13.0	13.7	12.6	12.4	13.4	12.7	14.0
200	15.9	16.8	17.2	17.7	16.9	16.0	16.8	17.3	18.8
250	17.7	19.9	20.2	21.9	20.6	20.7	21.6	22.1	23.7
315	18.0	19.3	20.0	21.4	21.2	21.2	22.5	22.5	24.6
400	19.4	21.0	21.2	23.8	24.4	24.6	26.1	26.1	27.2
500	22.1	23.5	24.9	28.5	28.9	28.3	29.9	29.9	28.5
630	19.6	20.9	22.2	23.8	24.6	25.9	28.1	27.5	28.5
800	18.1	19.1	19.0	20.1	22.1	23.5	26.8	26.3	27.9
1000	21.3	22.6	21.9	24.0	27.1	28.4	32.9	32.1	33.4
1250	20.1	21.2	21.2	23.3	25.0	24.9	31.7	31.6	34.0
1600	19.8	20.7	20.6	22.1	24.4	24.2	31.2	31.1	34.0
2000	18.9	19.5	19.3	19.9	23.0	22.8	29.7	29.7	30.5
2500	20.2	20.5	20.4	21.2	24.7	23.9	32.1	32.7	33.4
3150	20.3	20.9	20.9	21.5	23.8	23.4	32.1	32.2	32.3
4000	20.2	20.8	20.8	21.3	23.1	22.7	32.8	33.0	32.8
5000	20.2	20.7	20.5	21.2	23.4	22.8	31.2	31.3	31.7
R_w / R'_w	20	21	21	22	25	25	29	29	30
C	0	-1	-1	0	-1	-1	-1	-1	-1
C_{tr}	-1	-1	-1	-1	-3	-3	-5	-5	-4
$D_{n,e,w}$ / $D'_{n,e,w}$	26	27	27	28	30	31	35	35	36
C	-1	-1	-1	-1	-1	-2	-2	-2	-2
C_{tr}	-1	-1	-1	-1	-2	-3	-5	-5	-5

Frequency	M 1501 [dB]	M 1502 [dB]	M 1504 [dB]	M 1505 [dB]	M 1506 [dB]	M 1507 [dB]	M 1601 [dB]	M 1602 [dB]	M 1604 [dB]
50	18.4	15.7	15.5	14.2	14.4	15.2	19.8	12.8	12.2
63	31.1	11.7	10.2	13.2	13.1	14.4	33.0	11.0	12.7
80	32.4	5.9	6.4	10.9	10.4	10.0	35.0	6.9	9.2
100	36.0	6.7	8.7	11.5	10.0	9.8	37.2	11.4	14.1
125	41.9	9.8	11.3	12.9	11.5	11.4	42.6	11.9	15.6
160	39.3	8.8	12.7	14.3	13.0	13.5	41.7	9.1	14.5
200	44.8	10.1	14.2	15.0	13.8	14.0	42.3	11.7	18.3
250	44.9	11.5	17.2	17.4	16.4	16.6	47.2	13.9	21.5
315	52.4	13.2	17.6	16.8	16.4	15.9	51.5	15.2	22.4
400	54.3	13.9	20.4	16.2	17.9	17.5	54.7	18.9	25.7
500	58.9	16.6	24.1	18.0	21.9	23.0	59.9	19.6	29.8
630	62.0	15.9	18.3	16.2	18.0	19.2	63.8	18.9	24.2
800	62.2	16.1	19.0	15.3	18.7	20.5	65.6	18.2	21.4
1000	64.7	17.2	19.8	18.0	21.1	22.1	67.6	20.3	25.0
1250	65.3	16.2	19.0	17.6	21.5	21.9	70.4	19.7	25.2
1600	63.5	15.3	17.2	16.8	19.2	19.3	68.1	19.6	23.6
2000	60.6	14.7	16.7	16.3	19.6	19.4	64.9	18.8	20.7
2500	60.8	15.1	16.9	16.4	19.4	19.6	65.1	20.0	21.8
3150	62.6	15.8	17.6	17.0	20.6	20.5	67.9	20.8	22.2
4000	70.1	15.8	17.5	17.3	20.2	19.8	74.5	20.3	22.2
5000	70.5	15.8	17.0	16.9	19.1	18.9	73.0	20.1	22.1
R_w / R'_w	58	16	18	17	20	20	59	20	23
C	-2	-1	0	0	-1	0	-2	-1	0
C_{tr}	-7	-1	0	0	-2	-1	-7	-2	-1
$D_{n,e,w}$ / $D'_{n,e,w}$	65	23	25	24	27	27	66	27	30
C	-2	-1	0	0	-1	0	-2	-1	0
C_{tr}	-7	-1	0	0	-2	-1	-7	-2	-1

Frequency	M 1605 [dB]	M 1606 [dB]	M 1607 [dB]	M 2001 [dB]	M 2002 [dB]	M 2003 [dB]	M 2004 [dB]	M 2007 [dB]	M 2008 [dB]
50	14.1	14.8	14.6	28.1	13.1	14.5	13.7	11.9	11.8
63	15.6	15.0	15.0	34.2	7.7	11.5	12.5	9.8	10.2
80	11.2	10.6	10.3	33.7	8.3	11.1	9.9	9.8	9.2
100	14.2	13.5	13.7	42.7	5.7	6.5	6.6	6.6	6.5
125	16.6	14.6	15.0	39.9	0.9	1.6	2.1	1.1	0.8
160	15.7	13.6	13.4	39.2	4.8	4.6	4.8	4.5	4.2
200	18.0	17.1	16.6	30.1	7.2	6.8	7.8	5.8	5.5
250	19.7	19.3	19.5	40.7	12.7	9.5	10.6	7.7	7.4
315	21.5	21.4	21.7	52.3	11.7	10.4	12.8	9.3	7.9
400	19.8	23.6	24.4	56.5	8.4	14.6	17.0	15.2	13.2
500	23.1	26.6	29.6	60.6	10.5	15.7	18.9	18.2	16.4
630	21.8	24.7	26.6	64.3	11.1	19.8	23.1	18.9	16.9
800	19.2	23.0	24.1	68.0	12.1	20.0	23.4	17.2	14.6
1000	22.0	28.7	30.2	67.4	11.5	18.9	21.7	14.7	12.9
1250	20.8	28.3	28.7	74.7	11.8	18.0	21.9	16.2	14.7
1600	21.4	27.2	27.0	77.3	13.9	18.0	23.2	18.8	17.0
2000	20.3	25.3	24.6	78.9	14.8	20.9	25.5	19.8	17.4
2500	21.8	27.0	25.8	80.2	15.5	21.7	27.1	20.6	18.3
3150	22.0	26.1	25.2	68.2	16.2	21.8	29.1	22.9	19.6
4000	22.1	25.8	25.2	73.7	16.2	22.1	30.8	23.2	19.6
5000	21.7	25.1	24.6	74.3	16.0	22.6	31.2	23.4	19.5
R_w / R'_w	21	26	26	56	13	18	21	17	16
C	0	-1	-1	-6	-1	-1	-2	-1	-2
C_{tr}	-1	-3	-3	-11	-2	-4	-5	-4	-4
$D_{n,e,w}$ / $D'_{n,e,w}$	28	33	33	64	20	25	28	25	23
C	0	-1	-1	-7	0	-1	-1	-2	-1
C_{tr}	-1	-3	-3	-12	-2	-4	-5	-5	-4

Frequency	M 2009 [dB]	M 2010 [dB]	M 2011 [dB]	M 2012 [dB]	M 2013 [dB]	M 2014 [dB]	M 2015 [dB]	M 2016 [dB]	M 2017 [dB]
50	12.2	12.0	-	-	12.1	12.6	23.2	23.6	11.6
63	9.8	9.7	9.9	9.6	8.6	8.7	34.8	34.5	4.6
80	9.2	9.0	9.5	9.3	8.2	8.5	33.5	34.1	3.1
100	6.2	6.3	6.3	6.3	5.3	5.3	37.5	38.2	8.2
125	1.2	1.1	1.8	0.8	0.5	1.4	36.3	35.6	11.3
160	4.7	4.5	4.7	4.6	4.6	5.1	34.2	34.2	5.5
200	6.0	6.6	6.8	6.6	6.8	6.9	24.8	24.5	8.3
250	8.6	8.5	9.3	9.1	10.4	10.9	38.3	37.3	12.6
315	8.2	9.2	10.3	9.0	10.2	10.7	51.0	48.4	10.6
400	13.7	15.2	16.5	14.6	14.2	15.5	55.6	52.5	12.4
500	17.0	18.4	18.3	17.1	15.1	16.7	60.1	59.0	11.4
630	16.3	17.4	18.2	17.0	14.4	15.6	63.3	57.9	10.8
800	13.1	14.6	17.2	15.4	12.7	13.3	67.0	65.8	10.6
1000	12.6	13.8	16.3	14.9	12.9	13.4	67.9	63.6	9.2
1250	14.8	15.7	17.0	15.8	13.9	14.8	74.0	68.8	9.4
1600	16.2	17.7	18.2	16.4	15.3	16.7	74.0	70.7	10.7
2000	16.8	18.4	18.1	16.2	16.0	17.2	75.6	71.5	11.1
2500	18.0	19.3	18.4	16.8	16.6	18.1	75.3	61.5	11.2
3150	18.9	21.2	19.3	17.0	17.7	19.6	66.2	58.6	12.1
4000	19.1	21.5	19.2	17.0	17.8	20.0	72.0	67.7	12.8
5000	19.3	21.7	19.0	17.1	17.8	19.8	71.9	72.6	13.0
R_w / R'_w	15	17	17	16	15	16	52	52	11
C	-1	-2	-1	-1	-1	-1	-7	-7	0
C_{tr}	-3	-4	-3	-3	-3	-3	-12	-12	-1
$D_{n,e,w}$ / $D'_{n,e,w}$	23	24	25	23	22	23	60	59	18
C	-1	-1	-2	-1	-1	-1	-8	-7	0
C_{tr}	-4	-4	-4	-3	-3	-3	-13	-12	0

Frequency	M 2018 [dB]	M 2019 [dB]	M 2024 [dB]	M 2025 [dB]	M 2026 [dB]	M 2027 [dB]	M 2028 [dB]	M 2029 [dB]	M 2030 [dB]
50	11.1	9.1	11.7	11.6	12.3	14.0	12.9	12.7	12.9
63	5.0	5.6	3.9	3.8	4.2	3.0	3.7	2.7	3.4
80	2.9	7.1	4.5	4.2	5.4	4.8	5.4	4.2	5.3
100	9.8	5.8	13.3	13.3	15.0	14.1	15.3	14.4	14.7
125	10.8	3.5	14.8	14.8	15.3	14.8	14.3	13.9	14.1
160	6.8	5.1	10.6	10.6	13.8	8.4	10.6	7.1	8.5
200	8.8	4.2	12.8	12.5	15.7	9.8	12.4	7.8	9.7
250	14.2	6.6	16.4	16.0	18.8	13.4	15.9	11.2	13.0
315	12.6	6.5	14.0	13.1	15.8	12.6	15.8	11.9	14.8
400	13.1	5.6	14.4	13.9	18.1	15.1	18.7	15.7	19.8
500	12.4	5.9	19.2	18.7	22.9	18.8	22.2	16.8	21.5
630	12.0	6.2	23.0	23.3	28.4	21.5	26.4	21.9	24.8
800	12.4	7.2	27.2	22.6	28.4	23.0	29.0	21.1	24.4
1000	11.8	6.3	27.6	22.3	29.0	21.9	25.9	19.5	23.1
1250	12.4	6.2	26.2	25.4	33.3	22.6	28.3	20.7	23.9
1600	14.1	6.8	24.5	24.1	34.6	24.7	29.3	22.5	24.5
2000	14.7	7.3	27.3	27.5	36.0	25.7	29.9	24.6	27.0
2500	15.0	7.4	26.7	27.0	34.4	25.3	29.4	23.5	26.8
3150	15.8	7.9	26.3	26.9	34.6	26.1	31.2	24.0	27.7
4000	16.4	8.2	27.8	26.9	32.1	25.8	31.1	25.0	28.6
5000	16.8	8.4	26.9	27.3	32.6	26.2	29.9	24.3	27.3
R_w / R'_w	14	7	23	23	27	22	25	20	23
C	-1	0	-1	-2	-1	-1	-1	-1	-1
C_{tr}	-2	-1	-3	-4	-4	-4	-4	-3	-4
$D_{n,e,w}$ / $D'_{n,e,w}$	21	14	31	30	35	29	33	27	30
C	-1	0	-2	-1	-2	-1	-2	-1	-1
C_{tr}	-1	0	-4	-4	-5	-4	-5	-3	-4

Frequency	M 2031 [dB]	M 2032 [dB]	M 2033 [dB]	M 2101 [dB]	M 2102 [dB]	M 2103 [dB]	M 2104 [dB]	M 2106 [dB]	M 2107 [dB]
50	10.1	9.9	8.9	16.0	-	-	15.1	-	-
63	3.6	1.8	2.2	30.3	30.7	29.5	14.5	14.9	14.0
80	4.3	3.8	3.8	30.2	29.6	30.3	7.7	7.9	7.8
100	15.0	14.6	14.0	36.2	35.8	36.5	6.9	7.3	7.5
125	11.5	11.5	10.1	33.7	33.9	32.7	3.8	3.4	6.0
160	5.5	6.2	5.7	32.6	33.1	32.2	4.2	4.1	6.2
200	7.8	8.7	9.4	26.9	28.4	26.9	7.4	7.7	9.2
250	8.5	9.5	13.0	40.9	40.2	41.5	6.5	7.0	8.1
315	10.6	12.1	9.2	49.5	49.0	49.9	7.1	6.7	8.8
400	14.0	15.8	9.0	48.9	50.8	49.3	10.9	10.1	12.2
500	15.7	16.4	10.8	56.3	56.1	57.0	14.9	13.9	14.9
630	16.7	17.6	13.0	59.6	58.9	60.6	15.9	14.6	16.1
800	16.9	18.6	15.8	61.9	61.7	62.8	12.9	11.7	13.2
1000	17.5	18.6	14.9	62.7	62.6	63.4	12.1	10.9	12.1
1250	16.8	18.3	14.6	65.8	65.2	66.0	14.1	11.8	13.4
1600	17.8	19.6	16.2	66.4	65.4	66.6	16.5	13.3	14.9
2000	18.3	20.3	16.7	65.4	65.3	66.2	17.0	13.3	14.9
2500	18.6	20.2	16.7	64.0	64.4	68.4	18.1	13.6	15.1
3150	20.2	21.8	17.0	62.8	61.9	71.2	19.4	14.9	16.2
4000	20.4	22.3	17.7	72.8	71.5	75.1	19.5	15.2	16.4
5000	20.0	21.8	17.3	74.3	73.7	74.2	19.2	15.4	16.8
R_w / R'_w	17	18	14	52	53	52	15	13	14
C	-1	0	0	-6	-5	-6	-1	-1	0
C_{tr}	-2	-2	-1	-11	-10	-11	-3	-2	-2
$D_{n,e,w}$ / $D'_{n,e,w}$	24	26	22	59	60	59	22	20	21
C	0	-1	0	-5	-5	-5	-1	-1	0
C_{tr}	-2	-3	-2	-10	-10	-10	-3	-2	-1

Frequency	M 2108 [dB]	M 2109 [dB]	M 3001 [dB]	M 3002 [dB]	M 3005 [dB]	M 3011 [dB]	M 3012 [dB]	M 3013 [dB]	M 3014 [dB]
50	-	-	16.6	15.9	14.0	16.4	-	16.2	16.0
63	14.1	17.1	9.6	9.6	7.8	7.8	6.6	5.8	6.3
80	8.2	11.1	5.6	4.7	4.6	4.0	3.7	3.1	3.5
100	7.7	10.0	2.7	1.8	3.2	5.6	5.8	7.3	6.9
125	5.0	4.9	6.0	2.7	7.5	5.3	5.7	8.0	7.7
160	6.2	5.3	5.6	4.0	7.5	5.6	6.5	8.2	8.0
200	9.2	8.8	9.1	8.9	10.8	9.0	9.9	11.6	11.3
250	8.2	9.0	9.6	9.8	7.7	8.3	9.9	11.6	11.6
315	9.8	9.0	7.5	7.6	6.9	8.6	9.8	11.9	11.7
400	13.5	10.9	7.4	7.8	8.9	8.1	9.3	12.2	12.1
500	15.9	12.2	9.1	9.2	9.6	9.4	11.2	14.2	14.2
630	17.0	15.0	9.2	9.8	9.4	10.1	11.6	15.3	15.0
800	15.5	15.2	10.0	10.4	9.4	10.9	12.9	17.0	16.4
1000	13.4	14.9	11.3	11.7	10.9	12.0	14.0	19.2	18.5
1250	14.6	15.7	11.1	11.5	10.2	12.5	14.6	22.4	21.2
1600	16.4	17.1	11.4	11.7	10.9	12.6	14.2	24.2	21.4
2000	16.4	16.8	11.8	11.8	11.4	12.7	14.2	26.3	20.7
2500	17.0	16.7	11.9	11.9	11.1	12.9	14.2	28.2	21.2
3150	18.6	17.0	12.4	12.6	11.7	13.4	14.4	31.3	22.5
4000	18.6	17.8	12.7	12.9	12.2	13.9	15.1	33.3	23.2
5000	18.3	18.0	12.7	13.3	12.4	14.2	15.5	31.3	23.2
R_w / R'_w	16	15	11	11	11	12	13	19	18
C	-1	0	0	0	-1	0	0	-1	-1
C_{tr}	-3	-2	-1	-1	-1	-1	-1	-3	-3
$D_{n,e,w}$ / $D'_{n,e,w}$	23	22	18	18	18	19	20	26	25
C	-1	0	0	0	0	0	0	0	0
C_{tr}	-2	-2	-1	-1	-1	-1	-1	-3	-2

Frequency	M 3015 [dB]	M 3016 [dB]	M 3017 [dB]	M 3018 [dB]	M 3019 [dB]	M 3020 [dB]	M 3102 [dB]	M 3103 [dB]	M 3105 [dB]
50	-	16.4	16.1	16.2	-	-	15.9	-	-
63	5.3	5.8	9.8	8.4	8.3	9.1	4.4	6.0	8.5
80	3.9	4.2	5.3	4.9	5.0	5.8	1.6	3.0	3.6
100	7.4	9.5	3.7	4.9	6.8	3.5	8.9	9.4	8.7
125	8.0	10.4	4.3	4.8	6.8	3.4	11.0	12.6	5.7
160	8.6	10.1	4.7	5.6	7.9	4.5	12.7	13.5	11.1
200	12.1	13.1	10.3	11.3	12.6	9.4	13.5	14.0	17.0
250	12.1	13.9	10.2	11.2	12.6	9.4	9.4	10.5	14.9
315	12.0	13.9	8.8	9.8	11.3	7.7	10.0	11.6	11.7
400	12.3	14.9	9.2	10.6	12.0	8.0	12.1	14.2	11.8
500	14.1	16.9	10.8	12.7	14.3	9.7	13.8	16.4	16.1
630	15.2	18.2	11.3	13.0	14.8	9.9	14.5	17.5	19.3
800	16.3	19.4	12.0	14.5	16.2	10.4	14.3	17.4	18.2
1000	18.7	22.3	13.6	16.4	18.4	11.9	11.9	14.7	16.2
1250	21.8	25.7	13.6	18.8	21.1	11.9	12.8	16.2	17.0
1600	23.8	28.3	13.6	19.9	22.9	12.2	13.2	16.5	17.5
2000	23.0	31.0	13.6	21.4	24.6	12.3	13.4	16.4	17.4
2500	21.5	32.7	13.4	22.9	25.8	12.4	13.6	16.3	17.5
3150	21.3	35.2	13.8	24.6	26.5	13.0	14.2	16.4	17.3
4000	22.2	35.2	14.5	25.1	26.1	13.2	14.4	16.0	16.5
5000	23.0	33.1	14.4	24.8	25.4	13.2	14.3	16.2	16.7
R_w / R'_w	19	22	13	17	19	11	14	16	17
C	-1	-1	-1	-1	-1	0	-1	0	-1
C_{tr}	-3	-4	-2	-3	-4	-1	-1	-1	-2
$D_{n,e,w}$ / $D'_{n,e,w}$	26	29	20	24	26	19	21	23	24
C	-1	-1	0	-1	-1	-1	-1	0	0
C_{tr}	-3	-4	-1	-3	-3	-2	-1	-1	-1

Frequency	M 3106 [dB]	M 3107 [dB]	M 3108 [dB]	M 3109 [dB]	M 3110 [dB]	M 3111 [dB]	M 3112 [dB]	M 3113 [dB]	M 3114 [dB]
50	-	15.0	15.6	-	-	-	-	-	-
63	8.8	8.8	9.0	9.4	15.8	9.7	9.1	11.0	10.6
80	3.6	4.3	4.6	4.5	12.6	4.6	4.4	5.4	5.2
100	9.0	9.3	9.2	9.1	15.7	10.5	10.9	10.4	10.9
125	6.2	6.4	6.9	6.4	8.2	11.6	12.6	13.9	14.9
160	11.3	11.8	12.3	12.1	10.0	14.3	14.2	14.8	15.0
200	17.1	18.4	18.4	18.6	14.1	16.6	14.9	14.7	15.1
250	15.6	16.6	16.5	16.9	13.8	14.5	13.7	14.1	14.7
315	12.6	13.0	13.5	14.0	12.3	13.7	15.7	16.2	17.1
400	12.8	13.5	14.1	14.5	12.0	15.1	17.7	18.2	19.1
500	17.1	18.2	19.0	19.3	15.2	17.4	20.1	21.0	22.0
630	20.9	22.6	23.2	23.5	17.6	20.5	23.4	24.2	25.5
800	20.8	23.4	23.8	24.2	18.9	22.7	24.4	25.6	26.7
1000	18.6	21.4	21.9	22.4	19.1	21.9	22.5	24.8	25.6
1250	20.3	23.1	23.7	24.4	20.7	24.0	24.2	27.0	28.2
1600	21.7	24.4	25.1	25.9	22.0	25.1	25.6	28.7	29.9
2000	22.8	24.6	26.4	26.6	22.5	26.0	26.6	29.7	32.1
2500	23.9	25.3	27.0	27.4	22.8	26.9	27.6	31.2	34.0
3150	24.4	25.2	28.0	28.6	23.5	28.3	29.1	32.0	35.6
4000	23.9	24.3	28.1	28.4	23.7	28.4	28.9	29.5	35.0
5000	23.6	24.0	27.7	28.5	24.0	28.0	28.8	27.9	33.9
R_w / R'_w	20	22	23	23	19	22	23	25	26
C	-1	-1	-1	-1	0	-1	0	-1	-1
C_{tr}	-3	-4	-4	-4	-2	-3	-3	-4	-4
$D_{n,e,w}$ / $D'_{n,e,w}$	27	29	30	30	26	29	31	32	33
C	0	-1	-1	-1	0	0	-1	-1	-1
C_{tr}	-3	-3	-4	-4	-2	-3	-4	-4	-4

Frequency	M 3115 [dB]	M 3204 [dB]	M 3205 [dB]	M 3206 [dB]	M 3207 [dB]	M 3208 [dB]	M 3209 [dB]	M 3210 [dB]	M 3211 [dB]
50	-	-	-	17.5	17.8	-	-	-	18.5
63	7.9	11.3	12.3	11.6	12.1	12.2	12.3	12.2	8.6
80	3.4	9.1	8.9	9.1	8.8	9.8	10.5	9.7	7.3
100	8.7	7.9	7.8	8.3	8.1	8.1	8.3	8.9	8.7
125	7.0	5.4	5.2	6.0	5.8	6.2	6.6	6.1	7.3
160	11.5	5.1	5.7	6.8	5.7	6.0	6.9	6.7	9.2
200	18.3	5.5	5.6	7.5	6.3	7.0	7.9	8.4	10.1
250	18.4	6.2	6.7	9.4	7.7	8.4	9.8	10.1	11.8
315	13.4	6.3	6.5	9.3	8.0	8.5	10.0	10.3	12.4
400	14.7	6.8	7.1	10.6	8.6	10.1	11.9	12.0	14.5
500	20.0	7.9	8.3	12.3	10.4	11.6	13.7	14.1	16.8
630	22.2	9.0	10.0	15.0	13.0	13.9	16.3	16.6	20.2
800	23.4	9.8	10.8	17.6	15.1	16.9	18.8	19.7	23.8
1000	23.7	9.9	11.0	19.4	16.5	18.2	20.8	21.3	25.9
1250	27.1	10.9	12.5	21.2	18.3	20.1	22.5	23.0	28.6
1600	28.7	11.0	12.3	22.6	19.3	20.8	23.8	24.2	30.5
2000	29.5	11.2	12.6	24.0	20.9	22.3	25.4	25.9	33.8
2500	29.7	11.0	12.2	24.2	21.7	24.1	26.5	26.9	35.0
3150	32.5	11.1	12.2	22.7	21.4	25.7	27.1	27.5	31.2
4000	32.0	11.4	12.4	21.4	21.1	26.8	27.6	28.1	29.0
5000	31.6	11.1	12.1	20.3	20.3	26.2	27.3	28.0	27.0
R_w / R'_w	24	10	11	18	16	17	19	19	22
C	-2	0	0	-1	-1	-1	-1	-1	-1
C_{tr}	-5	-1	-1	-4	-3	-3	-4	-4	-4
$D_{n,e,w}$ / $D'_{n,e,w}$	31	17	18	25	23	24	26	27	29
C	-1	0	0	-1	-1	-1	-1	-2	-1
C_{tr}	-5	-1	-1	-4	-3	-3	-4	-4	-4

Frequency	M 3212 [dB]	M 3213 [dB]	M 3214 [dB]	M 3215 [dB]	M 3301 [dB]	M 3302 [dB]	M 3303 [dB]	M 3304 [dB]	M 3305 [dB]
50	18.9	-	-	-	18.0	-	-	-	19.2
63	7.8	8.8	9.0	9.5	27.2	7.8	8.1	8.0	7.7
80	6.2	6.4	6.7	6.2	21.6	6.0	6.8	6.3	6.2
100	9.1	7.3	6.5	5.9	21.9	5.6	5.5	9.3	9.1
125	7.9	5.4	5.1	4.0	20.4	3.4	3.6	6.0	6.9
160	9.8	7.5	6.3	6.2	19.5	5.9	6.0	8.7	9.0
200	10.9	8.3	7.2	6.7	20.5	5.7	5.7	8.7	9.0
250	12.7	9.3	7.4	6.6	27.1	6.1	6.1	10.3	10.8
315	13.6	9.4	7.1	6.1	31.0	5.7	6.0	10.7	12.0
400	16.1	11.3	8.3	7.1	31.8	6.5	6.9	12.6	13.6
500	18.8	13.5	9.5	8.1	36.9	7.6	8.1	14.4	15.5
630	22.2	16.3	11.1	9.3	39.0	8.6	9.0	17.5	18.6
800	25.4	20.0	12.5	10.2	41.7	8.8	9.5	20.8	21.7
1000	28.0	21.4	12.5	10.2	44.6	9.3	10.1	23.1	24.1
1250	30.5	23.7	13.8	11.2	47.9	10.3	11.1	25.9	26.5
1600	32.5	25.3	13.3	11.1	49.4	10.2	11.1	27.1	27.7
2000	35.9	28.4	13.3	11.3	50.3	9.7	10.8	27.9	27.9
2500	36.7	30.8	13.2	11.2	48.0	10.0	10.9	28.3	28.1
3150	35.7	29.8	13.3	11.5	46.7	10.9	11.5	26.1	25.7
4000	37.8	27.0	13.4	11.3	51.0	11.2	11.9	24.5	24.6
5000	38.4	25.3	13.4	11.8	54.5	11.6	12.1	24.0	24.5
R_w / R'_w	24	19	12	10	38	9	10	20	21
C	-2	-1	0	0	-2	0	0	-1	-1
C_{tr}	-5	-4	-1	-1	-7	-1	-1	-4	-4
$D_{n,e,w}$ / $D'_{n,e,w}$	31	26	19	17	45	16	17	27	28
C	-1	-1	0	0	-2	0	0	-1	-1
C_{tr}	-5	-4	-1	-1	-6	0	-1	-4	-4

Frequency	M 3306 [dB]	M 3309 [dB]	M 3311 [dB]	M 3312 [dB]	M 3316 [dB]	M 4001 [dB]	M 4002 [dB]	M 4003 [dB]	M 4004 [dB]
50	-	18.3	-	19.1	14.5	17.6	28.9	15.3	28.3
63	7.4	7.4	7.0	6.9	9.6	8.7	23.4	11.4	32.9
80	6.2	6.5	6.8	6.1	6.6	11.0	28.8	8.1	30.7
100	9.5	8.0	6.7	8.3	5.7	10.2	29.6	13.8	27.6
125	6.8	4.9	3.8	5.2	5.8	9.4	33.0	13.3	30.0
160	9.2	7.3	6.4	8.5	5.5	13.9	30.9	14.9	31.4
200	9.1	6.9	5.7	8.4	5.6	16.6	34.3	19.3	33.4
250	11.3	9.0	6.1	10.2	5.6	16.6	33.2	17.9	33.4
315	11.9	9.1	6.1	11.4	5.3	19.9	31.9	20.7	31.2
400	13.8	10.6	6.7	12.5	5.2	23.3	32.9	23.7	30.0
500	16.0	12.5	8.0	14.6	5.9	21.3	35.7	24.4	34.0
630	19.1	15.4	9.2	17.5	6.8	20.3	40.2	21.1	38.0
800	22.2	18.2	10.0	20.7	6.5	24.7	44.0	26.0	43.1
1000	24.5	20.5	10.6	23.3	6.2	24.4	47.2	25.3	44.9
1250	27.1	22.7	11.5	25.4	6.8	23.9	47.7	25.7	46.8
1600	28.3	24.3	11.5	27.1	7.3	22.2	46.8	24.1	44.8
2000	28.6	25.7	11.2	28.0	7.5	23.8	43.5	25.8	45.5
2500	28.9	27.7	11.3	28.3	8.1	24.8	41.2	26.7	42.1
3150	26.5	26.9	11.9	26.0	8.4	24.3	37.9	26.5	38.4
4000	25.7	25.2	12.5	24.7	8.5	22.2	32.9	25.2	33.4
5000	25.5	24.7	12.6	24.3	8.8	20.6	29.3	22.5	28.9
R_w / R'_w	21	18	10	20	7	23	40	25	40
C	-1	-1	0	-1	0	-1	0	-1	-1
C_{tr}	-4	-4	-1	-4	0	-2	-2	-2	-3
$D_{n,e,w}$ / $D'_{n,e,w}$	29	25	17	27	14	30	47	32	47
C	-2	-1	0	-1	0	0	0	-1	-1
C_{tr}	-5	-3	-1	-4	0	-2	-2	-2	-3

Frequency	M 4005 [dB]	M 4101 [dB]	M 4102 [dB]	M 4103 [dB]	M 4104 [dB]	M 4105 [dB]	M 4106 [dB]	M 4108 [dB]	M 4109 [dB]
50	15.0	20.6	7.4	6.6	6.0	9.3	-	-	-
63	8.1	34.3	5.8	9.4	8.8	5.7	6.6	6.6	5.4
80	13.2	33.9	4.0	8.9	8.2	4.3	5.6	2.9	2.9
100	16.3	34.4	8.0	11.0	10.9	8.5	8.6	6.8	7.3
125	17.3	39.5	6.7	13.6	13.2	6.9	8.7	6.2	5.3
160	20.4	41.4	6.1	13.3	13.6	7.8	7.7	5.8	6.0
200	25.4	43.0	14.1	21.1	21.5	15.1	14.6	9.8	12.2
250	23.8	43.6	17.7	23.9	24.4	18.7	19.0	13.8	16.2
315	26.1	50.6	19.1	25.6	26.6	20.3	20.0	19.1	17.4
400	26.9	55.1	22.7	26.2	27.0	23.5	23.5	21.9	23.4
500	28.6	55.5	23.3	27.9	28.5	23.6	23.6	21.6	22.2
630	23.1	56.3	22.7	26.0	26.3	22.8	24.6	20.3	21.3
800	28.7	56.6	23.5	25.7	27.5	24.7	25.7	18.9	23.1
1000	31.0	59.0	21.7	25.1	26.2	23.2	23.3	18.9	20.5
1250	30.8	66.4	23.8	25.5	25.9	24.3	24.3	19.7	22.3
1600	32.5	69.5	22.1	27.7	28.7	22.7	24.1	20.1	21.4
2000	30.2	69.7	23.2	28.5	28.8	23.7	25.4	19.8	21.4
2500	33.3	68.2	23.7	31.4	32.2	25.0	25.6	20.3	21.9
3150	34.0	63.4	23.5	30.5	31.7	24.5	24.8	20.3	21.7
4000	30.2	73.5	23.3	30.1	30.9	23.6	23.9	19.2	20.2
5000	29.2	76.2	22.5	30.6	31.5	22.7	23.4	19.2	20.2
R_w / R'_w	30	57	23	27	28	24	24	20	21
C	-1	-2	-2	-1	-1	-2	-1	-1	-1
C_{tr}	-3	-7	-4	-3	-4	-5	-4	-3	-3
$D_{n.e.w}$ / $D'_{n.e.w}$	37	64	30	35	35	31	31	27	29
C	-1	-2	-2	-2	-1	-2	-1	-1	-2
C_{tr}	-3	-7	-4	-4	-4	-4	-4	-3	-4

Frequency	M 5003 [dB]	M 5004 [dB]	M 5006 [dB]	M 5007 [dB]	M 5008 [dB]
50	14.6	9.8	9.9	10.5	10.6
63	5.1	4.6	3.2	4.3	4.6
80	9.0	5.6	5.1	6.5	6.1
100	10.0	5.6	5.0	2.8	6.0
125	4.5	7.4	1.7	6.9	8.5
160	5.4	7.7	3.0	4.7	6.6
200	4.6	5.5	4.0	9.7	11.1
250	6.0	7.0	4.9	6.9	8.5
315	5.0	6.6	4.5	8.1	9.9
400	5.5	6.4	4.4	9.1	10.8
500	6.0	6.8	5.0	10.4	12.5
630	6.3	6.2	5.2	10.6	14.1
800	7.0	7.6	5.1	14.8	18.3
1000	7.8	8.0	4.7	17.1	20.4
1250	9.1	8.6	5.0	19.3	21.7
1600	9.5	9.5	5.4	21.5	22.5
2000	9.4	10.2	6.1	22.5	22.2
2500	9.6	10.6	6.5	20.4	21.3
3150	10.4	11.1	6.5	20.3	20.0
4000	10.9	10.7	7.0	19.0	21.3
5000	11.0	10.8	7.5	17.6	21.2
R_w / R'_w	8	9	6	16	18
C	0	0	-1	-1	-1
C_{tr}	-1	-1	-1	-4	-3
$D_{n.e.w}$ / $D'_{n.e.w}$	16	16	13	-	-
C	-1	0	0	-	-
C_{tr}	-1	-1	-1	-	-

Development of windows with good sound insulation in the open position

The project ”Development of windows with good sound insulation in the open position” has been performed by DELTA – a part of FORCE Technology and HSHansen a/s. In general, the sound insulation properties of three different window types are investigated. The window types are: I) Further development of the ”supply air window”” II) ”an ordinary window” with an internal solution and III) ”an ordinary window” with an external solution.

A significant number of laboratory measurements with the various window types has been conducted, as mockup-solutions as well as more complete prototype solutions and a few field measurements. This report accounts for the performed measurements and the derived conclusions.

For the entire project it may be concluded that work and tests have been carried out with three types of windows, with a wide range of sound insulation, dimensions and constructions/solution principles. For the three types of windows, laboratory measured sound insulation of R_w+C_{tr} of 26, 12 and 17 dB respectively has been obtained, which should be compared to a sound insulation of an ordinary open window, which has been measured to R_w+C_{tr} of 5-8 dB.

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