

Effects of sound absorbing facades on the acoustical quality in different simulated inner courtyard situations

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Abstract – Residential perimeter blocks can shield traffic noise, but the acoustical quality may be sub-optimal in the inner courtyards. This study investigated how effective sound-absorbing facade surfaces and balcony soffits as well as an absorbing floor (lawn) influence the acoustical quality in inner courtyards. Room acoustical simulations were carried out for eight generic and two real-world models with very large numbers of transmission paths. Facades (reflecting, fully absorbing, partially absorbing), balcony soffits (reflecting, absorbing) and courtyard floor (reflecting, absorbing) were varied. A range of room acoustical parameters were evaluated, namely, reverberation time T_{20} , early decay time EDT , strength G , speech transmission index STI , and Dietsch's echo criterion EK . The simulations revealed that fully absorbing facades are an effective measure to improve the acoustical quality in inner courtyards, while partially absorbing facades result in smaller improvements. In fact, each additional storey of absorbing facades further improves the situation. In the case of non-absorbing facades, absorbing balcony soffits or an absorbing floor in the inner courtyard are not very effective as individual measures and may even increase disturbances due to echoes. The same holds true for situations with absorbing facades. Their feasibility should therefore be clarified for the individual situation in question.

Keywords: Courtyards, Room acoustical simulation, Room acoustical parameter, Absorbing facade

1 Introduction

Urban development in densely populated, noise polluted areas is often based on the perimeter block design. This creates inner courtyards that are not exposed to transportation and other external noise sources, allowing dwellings that have access to a quiet side [1]. However, residents may be exposed to annoying noise from daily life in the courtyard itself, or the acoustic quality in the courtyard may be poor [2]. A very special example is the disturbance caused by low-frequency traffic noise, which is insufficiently shielded by the buildings but forms resonances in the courtyard [3]. In such courtyards, the structure and material of the facades play a major role in addition to the ground plan and height of the buildings.

Sound propagation in urban environments is affected by sound reflection from surfaces, diffraction from edges, scattering from structured surfaces and sound absorption from materials (e.g. [4–7]). Today, these factors are usually considered in the acoustical design of rooms (room acoustics).

However, the effect of these parameters on the acoustical urban (built) environment, especially concerning the acoustical quality of outdoor spaces, has not been studied extensively.

In street canyons [8–10] and squares [11, 12], sound-absorbing surfaces reduce the sound pressure level created by traffic noise as well as by other sound sources [10]. Sound-diffusing facades in street canyons may reduce the sound pressure level under certain conditions [13], but may sometimes have no significant effect [10, 14]. Furthermore, both scattering and absorption of facades in an urban square can influence the acoustic quality [10].

With regard to courtyards, one study analysed the effects of different types of courtyards on lighting and acoustics using some early-stage computer simulation tools [15], and found that courtyard surface is crucial for illumination of lower storeys, while the courtyard form determines the sound level. The investigations are limited to a single point source with somewhat arbitrary frequency characteristics, which was placed in the centre of the courtyard. For the receiver points on the facades, only the A-weighted sound pressure level was analysed and no other acoustic parameters. These limitations limit the reliability

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of the results. One case study used more advanced software to analyse the effect of different materials for facades and floors and of different geometries in a partly open courtyard [16]. Only sound pressure levels due to road traffic noise were calculated. For the investigated sound sources outside the inner courtyard, it was found to be sufficient to cover parts of the facade of the ground floor with absorbent material and to adapt the design of the entrance area.

Further, a “*non-exhaustive narrative review paper*” [17] gives some references to literature on courtyards and “*a series of recommendations*”. Here, two of the studies cited should be mentioned. One study deals with noise annoyance in inner courtyards due to acoustic defects such as strong flutter echoes and long reverberation [18]. In case studies and computer simulations, the effects of absorption and sound scattering by vegetation, wood decking, street furniture etc. were analysed, and positive effects were observed. In the other study, a series of measurements were carried out in outdoor spaces of residential complexes with different building layouts [19]. Among other findings, long reverberation times were observed. An empirical method was proposed to predict acoustic metrics (reverberation time, sound pressure level attenuation) based on openness, size-related parameters, and the room constant of the outdoor spaces. In addition to these studies, a recently published review presents a compilation of software tools for facade acoustics with regard to the interaction of sound and the building envelope, including software tools for room acoustics [20]. Five categories were analysed: environmental noise modelling, sound insulation, noise mapping, auralization and three-dimensional geometry manipulation. In this context, the software ODEON was described as one of the suitable tools in the category “environmental noise modelling”.

One recent study in Germany focused on the acoustical design of courtyards [21, 22], regarding sound pressure level reduction in dB(A) from traffic noise through various measures. No evaluation of reverberation time, speech intelligibility and echo disturbance was documented.

In Switzerland, there were several activities related to the improvement of the acoustical quality of urban built environments [23–26]. One focus was on the development and activation of acoustical potentials of urban open spaces, especially in inner courtyards, whereby also some recommendations for planners were prepared [25, 26]. Another focus was on noise and acoustical quality in courtyards [2, 25–28]. Courtyards with reflecting, absorbing and scattering facades were simulated and auralised to be used in laboratory listening experiments. In one of these experiments, participants were asked to rate the acoustical quality of various sound situations such as conversations, children’s play or ball bouncing. It was found that courtyards with moderately sound-absorbing facades were rated as more pleasant than reflecting facades [2]. Furthermore, a correlation to well-established room acoustical parameters was shown [1, 27], which are usually used for speech or music, e.g., in classrooms, theatres, opera houses and concert halls. In a follow-up study, auralised situations of moving sources, namely, car pass-by situations for different routes, facade types and building positions were used in

listening experiments. The experiments revealed that sound-absorbing facades reduce noise annoyance in inner courtyard situations [28]. While giving a wealth of insights, the experiments were limited insofar as they were only carried out for a single courtyard and only for a few transmission paths from source to receiver.

For practical purposes, i.e., for new construction projects comprising the acoustical planning and dimensioning of inner courtyards, available literature on the acoustics of courtyards lead to various questions regarding implementation: Is it sufficient to only have the soffits of balconies in inner courtyards covered with absorbent material? How large should the proportion of absorbent facades be, and where are the optimal locations of absorbing facades? What does the floor of the inner courtyard potentially contribute? Are there rules of thumb on sound absorption that apply to a large variety of different courtyard designs?

The objective of this study was to address the above questions with a range of room acoustical simulations. The simulations were carried out for eight generic and two real-world models with very large numbers of transmission paths, systematically varying facade type (reflecting, fully absorbing, partially absorbing), balcony soffits (reflecting, absorbing) and courtyard floor (reflecting, absorbing). Only sources and receivers in the inner courtyard were investigated. The outcomes were evaluated for a range of room acoustical parameters. The present work is based on a bachelor thesis [29], which was extended here by additional evaluations.

2 Methods

2.1 Overview

A series courtyard models were designed, in which the amount of sound-absorbing facade surface, the type of balcony soffit and the type of courtyard floor were varied. The room acoustical simulations were carried out for several room acoustical parameters with the commercial software tool ODEON (ODEON A/S Lyngby Denmark). The so-called matrix method was used, which means that a very large number of transmission paths were calculated.

In summary, the following questions – substantiating the general questions identified in Section 1 – were to be answered with the presented study:

- How strong is the effect of individual measures in the inner courtyards (fully/partially absorbing facades, absorbing balcony soffits, absorbing inner courtyard floor)?
- How strong is the effect of combinations of measures (absorbing facades + absorbing balcony soffits; absorbing facades + absorbing inner courtyard floor, absorbing facades + absorbing balcony soffits + absorbing inner courtyard floor)?
- Do the conclusions obtained from the whole set of transmission paths also remain valid when considering individual groups of transmission paths, e.g., only those on the courtyard floor which is often accessible to the public?

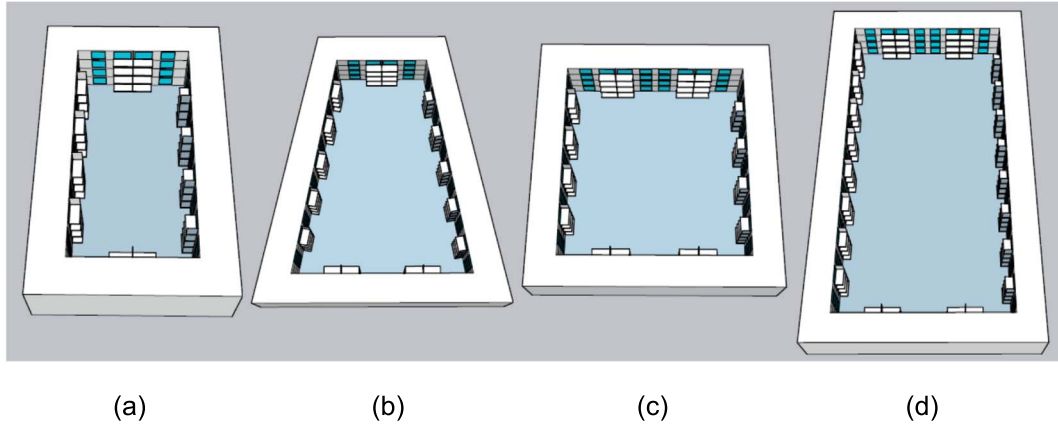


Figure 1. The four generic models with four storeys: (a) R1/4 (47.2 m $\times$ 24 m), (b) T/4 (56.5 m $\times$ 44 m/24 m), (c) R2/4 (47.2 m $\times$ 44 m), (d) R3/4 (87.4 m $\times$ 44 m). Not shown: models with the same ground plan but seven storeys: R1/7, T/7, R2/7, R3/7.

2.2 Courtyard models

2.2.1 Geometry of courtyard models

The main part of the investigations was carried out with generic models. These are plausible courtyards without a real built or planned model. Based on a facade element with balcony and privacy screen, eight generic courtyards with different floor areas and number of storeys were created. The modelling was simplified in accordance with the principles of simulation with ODEON. As an example, the railing of the balcony was not modelled because it only causes sound scattering at very high frequencies. Four different floor plans were created (Fig. 1). From these, four courtyards with four storeys with a total height of 12 m (R1/4, T/4, R2/4, R3/4), and four courtyards with seven storeys with a total height of 21 m (R1/7, T/7, R2/7, R3/7) were built. Overall, the area that could be provided with absorbent material amounted to a maximum of 46–49% of the total facade, depending on the model.

Besides the generic models, two models (Z and M) were based on existing real-world courtyards (Fig. 2).

All 3D models were created with SketchUp 2021 (Trimble Inc., Westmoor Drive USA) and imported into the room acoustics simulation software ODEON [30] with the help of the ODEON plug-in SU2Odeon 2.03. They were recreated in as much detail as possible. For example, benches and different materialization of the floor in the courtyard were reproduced.

2.2.2 Location of the source and receiver positions

Source/receiver positions (each receiver is also a source) were placed in all models according to the same rules. On each balcony, one source/receiver was positioned exactly in the centre at a height of 1.2 m above the balcony (ear height of a seated person). Accordingly, no source/receiver points were placed on facades without balconies. In the courtyard, the source/receivers were positioned in a grid of 6.5 m $\times$ 9.5 m, at a height of 1.6 m above the floor (ear height of a standing person). An example can be found in Figure 3, and Table 1 shows the number of source/

receiver positions and resulting transmission paths for all models.

2.2.3 Sound absorption and scattering coefficients

For the room acoustical simulation, the sound absorption coefficients listed in Table A1 of Appendix A were used. The sound absorption coefficients were derived from plausible assumptions using, among other factors, existing products, e.g., of absorbing balcony soffits and sound-absorbing noise barriers based on porous absorption. The absorption coefficients of the absorbing facades and balcony soffits are shown in Figure 4. In our models, the inner courtyards were surrounded by a completely absorbing shell, set around the courtyards, to model their “ceiling” (opening toward the sky) and to absorb sound transmitted through other openings such as gateways.

With regard to scattering, it should be noted that the simulation software ODEON uses a special method ([30] section 9.5). First, each surface must be assigned a scattering coefficient (user defined scattering coefficient). Second, the software selects a simplified method to automatically account for the scattering caused by diffraction (reflection based scattering coefficient) [31, 32]. The final scattering is calculated from the two scattering coefficients. In all simulations presented here, “reflection based scattering” was activated.

Although only a single number between 0 and 1 needs to be entered for the user scattering coefficient, the scattering is calculated in ODEON as a function of frequency. The number corresponds to the scattering coefficient at medium frequencies (707 Hz). ODEON sets the coefficients for the other frequency bands to appropriate values, with lower frequencies having less scattering and higher frequencies having more scattering (section 9.5 in [30]).

For the determination of the user scattering coefficients, the rules of the manual of the software ODEON were basically followed. On the one hand, a table with examples was taken into account ([30] section 4.5 p. 60), and on the other hand, a rule of thumb was applied, which is based on a theoretical model [33]. In accordance with the design of

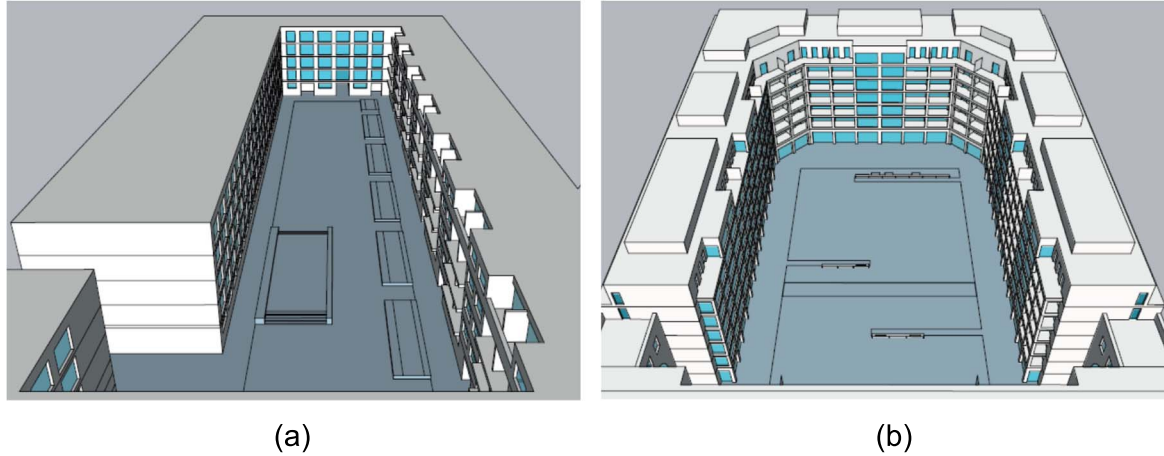


Figure 2. Two models of real courtyards. (a) model Z; Length 109 m, width 31 m, height 15 m, (b) model M; Length 70 m, width 42 m height 23 m. The width refers in both models to the main part of the inner courtyard, which in the drawing covers the largest area.

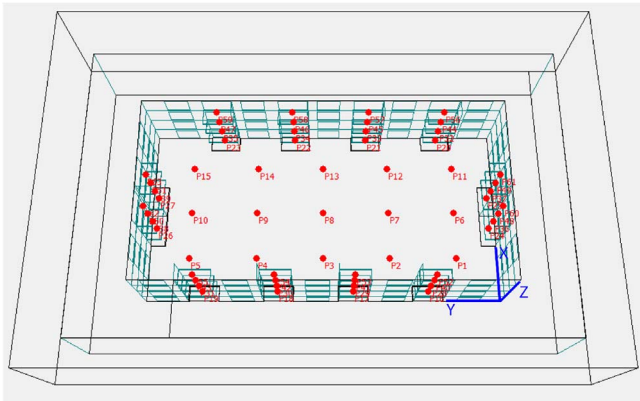


Figure 3. Perspective view of the generic model R1 (4 storeys) in ODEON with all 63 source/receiver positions.

the surfaces found in the majority of new buildings, the surfaces were assumed to be flat in our models. The scattering on balconies, privacy screens etc., caused by diffraction, is taken into account by ODEON using the method as described above. As a result, the “user scattering coefficients” of the surfaces were mostly very low. Specifically, 0.05 was set for the window surfaces, and 0.1 for the remaining façade surfaces as well as for the floors of the courtyard. For a few slightly structured floor surfaces (with small-scale elements such as street furniture) of the real Z and M, higher values were chosen (e.g., 0.3, depending on structural deepness). Importantly, for the facade elements where the absorption coefficient was varied, the scattering coefficient was not changed. This means that all scattering coefficient values remained unchanged during all simulations.

2.2.4 Variants for calculations

The following variants were calculated for the generic models: (i) facade (absorbent, reflective), (ii) balcony soffits (absorbent, reflective), (iii) courtyard floor (absorbent,

reflective), and (iv) combinations thereof. For the absorbent floor of the courtyard, lawn absorption was used. For models M and Z, only the facade and balcony soffits were varied, while the original floor material was used unaltered in the models. Finally, in all models, the facades – starting at the bottom – were progressively fitted with absorbent material, storey by storey. Of course, the window areas on the facades were not set to absorbent. An overview of the calculated variants can be found in [Tables B1–B4 in Appendix B](#).

2.3 Room acoustical parameters

In accordance with a previous study [27], the following five room acoustical parameters listed in [Table 2](#) were selected; the definitions and additional details on the parameters are given in the references indicated in the table.

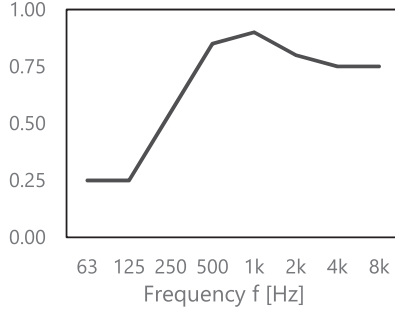
As T_{20} and EDT were strongly correlated in the presented study (not shown), the focus is on T_{20} later in the results.

For a realistic determination of the STI , the background noise would have to be included. However, as such investigations were beyond the scope of this study, the results on STI are only exemplarily presented in the following.

As an attempt to check for the presence of echoes, the EK according to Dietsch and Kraak was used. The EK does not seem to be well established yet [30]: “The method is not bullet proof there may be cases over as well as under detection”. Improvements were suggested ([38, 39]) but were not further developed or implemented in ODEON. As a just noticeable difference (JND) is currently unavailable, we used a threshold of $EK = 1.5$ in this study where, according to [30], 90% of humans hear an echo, and counted the number of transmission paths at which the threshold is exceeded. The threshold is set relatively high. However, considering that the echo criterion is not that well established and that our application does not involve music or speech performances, the threshold seems reasonable.

Table 1. Number of source/receiver positions and resulting transmission paths in the studied courtyards.

Model	Number of source/receiver positions		Number of transmission paths	
	4 storeys	7 storeys	4 storeys	7 storeys
R1	63	99	3'906	9'702
T	90	138	8'010	18'906
R2	94	142	8'742	20'022
R3	150	222	22'350	49'062
Z		140		19'460
M		152		22'952

**Figure 4.** The absorption coefficient of the absorbing facades and balcony soffits used for the simulations (see also Table A1 in Appendix A).

2.4 Recommended values for room acoustical parameters in courtyards?

There are only few indications regarding reasonable values for room acoustical parameters in courtyards, and there is only one available study on this topic [27]. The latter study shows that a decrease in *EDT* and *G* and an increase of *STI* is associated with an improved acoustical quality. However, if a large proportion of the facade is highly absorbent – which is hardly achievable in practice – the acoustical quality can slightly deteriorate [2]. For the echo criterion *EK*, no correlation to the acoustic quality was found in [27]. However, things might differ in the context of the present study, because in [27] the values of *EK* are relatively low.

For the **reverberation time T_{20} and EDT** , recommendations for speech [40, 41] suggest a target range of 1.2–1.5 s for very large rooms, which seems plausible in view of [27] and experience, but still needs to be verified. It should be noted that arbitrarily low reverberation times cannot be achieved anyway, because window surfaces and other structures of the facade will always remain sound reflecting.

Regarding **strength G** , the main interest is how much *G* is reduced in comparison to other calculated variants.

There are contradictory statements about the **speech transmission index STI** . On the one hand, *STI* is positively correlated with acoustical quality, but on the other hand, a low *STI* is desirable for privacy (e.g., from balcony to balcony). As mentioned above, *STI* is not discussed in detail in the following.

Finally, for the **echo criterion EK** , it seems plausible that a minimum number of exceedances of $EK = 1.5$ should

be aimed for: Experience clearly shows that in courtyards the presence of echoes and flutter echoes is criticised. Here, it is important to note that the introduction of sound absorption does not necessarily result in a reduction of echoes. On the contrary, sound-absorbing surfaces can even increase the audibility of echoes.

2.5 Room acoustical simulation

For the room acoustical simulation, the state-of-the-art software ODEON version 16.11 ([30]; www.odeon.dk) was used, based on geometric acoustics (image-source method combined with a modified ray tracing algorithm). Since there are many possibilities of source/receiver point combinations in courtyards (cf. Section 2.2.2), it seemed reasonable to use the matrix method described by Probst [42] and implemented in ODEON since version 16 for all room acoustical parameters (function *3DMatrix*). In this way, combined source/receiver positions are defined, and it is possible to calculate the impulse response from all source positions to all receiver positions in an automated way. Note that the transmission paths from sources to receivers at the same position were finally not evaluated in this study.

An important configuration parameter of the ODEON software regarding both, computation time and simulation accuracy, is the number of rays to be used for the simulations. The ODEON software does provide an estimation of the optimal number of rays. This generally leads to accurate simulation results in “normal” rooms, but for rooms with strong one-sided absorption, such as courtyards which are fully open upwards, this estimation may not be adequate. Moreover, in the special situation of courtyards with an extraordinarily large number of transmission paths, the number of sound rays cannot simply be set very high in favour of a low calculation uncertainty. For this reason, sensitivity analyses were carried out for a group of similar simulations before starting the main simulations. The minimum number of rays yielding reliable results was determined by using the JND as a criterion: The number of rays was increased until only a small amount of transmission paths (5% for *EDT*; 15% for T_{20}) changed more than one JND (which, however, resulted in only a very small change in the mean value of *EDT* and T_{20} of 10^{-4} – 10^{-3} s). For the generic models with basic shapes R1, R2 and T, the number of rays required was two million, regardless of the number of storeys. In contrast, four million and five million rays were necessary for the R3/7 and R3/4 model, respectively.

Table 2. Room acoustical parameters of this study with their description, Just Noticeable Difference (JND) and references.

Parameter	Description	JND	Reference
T_{20}	Reverberation time (Mean of octave bands 500 Hz and 1000 Hz)	5%	[34]
EDT	Early Decay Time (Mean of octave bands 500 Hz and 1000 Hz)	5%	[34]
G	Strength (Mean of octave bands 500 Hz and 1000 Hz)	1 dB	[34]
STI	Speech transmission index	0.03	[35, 36]
EK	Dietsch's echo criterion		[37]

The real courtyard models Z and M were calculated with six and five million rays, respectively. Using this approach, computation times of up to 24 hours per variant resulted.

Furthermore, additional investigations were carried out to validate the reliability of the simulations (see Sections 2.6 and 3.6 on validation measurements), besides the following considerations on source/receiver positions and input parameters:

Randomisation of the source/receiver positions:

The source/receiver positions were always distributed in the same way for all models. With a series of separate simulations, we checked how much the results change with a random placement of the sources/receivers within a certain range (max. ± 0.9 m in the courtyard, max. ± 0.5 m on the balcony). This exercise showed that the differences in results are small (clearly below JND).

Variation of the scattering coefficient: Simulations with a variation of the scattering coefficient of $\pm 40\%$ were carried out. These variations only weakly affected the results (again clearly below JND).

Variation of the absorption coefficient: The absorption coefficient of the absorbing facades and balcony soffits was varied in two models by ± 0.1 . Compared to the variation of the degree of scattering, the computed room acoustical parameters changed slightly more, but still below JND. Also, the conclusions derived from the results of the main study remained unaffected.

2.6 Validation measurements

To validate, at least partially, the results of the simulations within our study, room impulse responses were measured and evaluated in the courtyard M according to the standards [34, 35]. During the measurements, the temperature was 0 °C and the relative humidity was 75%. The latter values were used for dedicated ODEON simulations, which were done specifically to compare measurements with simulations. Otherwise, the simulations for comparison were carried out as for the main study (i.e., with the same absorption and scattering coefficients as for the main simulations). The measurements and simulations were performed for two source positions and four receiver positions as shown in Figure 5.

2.7 Statistical analysis

All analyses were performed with MATLAB Version R2021b (The MathWorks, Inc., Natick, MA, USA). Normality tests (Kolmogorov-Smirnov und Shapiro-Wilk; Q-Q plots) revealed that the data is not normally distributed. Therefore, non-parametric statistical tests were applied. Here, the statistical analysis was performed in two steps.

First, the effect of materialization on the room acoustical parameters was analysed separately for each of the 10 courtyard models (cf. Section 2.2.1). As the same transmission paths were studied for each materialization, repeated measures were considered in the analyses. To that purpose, the Friedman test (the non-parametric equivalent to the analysis of variance with repeated measures) with Nemenyi post hoc test (with adjustment for multiple comparisons) was applied.

Second, the effects of the two variables “number of storeys” and “ground area” on the room acoustical parameters were studied for the data of the eight generic models (single data set for all eight models). Here, mean values of the computed room acoustical parameters, averaged over all transmission paths per storey (including ground floor), were used as input for the analyses (5–8 values per model, depending on the number of storeys). Ground floor had four values (cf. Fig. 1). As these (averaged) observations are independent, the Kruskal-Wallis test followed by Dunn’s test (with Bonferroni correction for multiple comparisons) for pairwise comparisons was applied.

Tested effects were considered to be significant if the p -value of the observed results, or more extreme results, under the null hypothesis was < 0.01 . This low significance limit was set here due to the large number of transmission paths and thus observations in the first analysis. As the high number of transmission paths resulted in significant effects even for small changes in the mean value, the interpretation of the results will focus on relevance (i.e., strength) of effects rather than their significance. In the second analysis, where the number of observations was substantially smaller, in contrast, p -values of the studied effects are reported. As all comparisons presented here are statistically significant ($p < 0.01$), no further comments on this are made in the following account.

3 Results

An example of resulting values of T_{20} is shown as box-plots in Figure C1 in the Appendix C. However, it turns out that restricting the presentation to mean values (average of all receiver positions) and reporting ranges of the standard deviation is well suited to visually support the major statements, so results will be reported in this “condensed form” in the following account.

3.1 Effect of individual measures

Figure 6 shows the mean values of the simulation results for the investigated room acoustical parameters and the

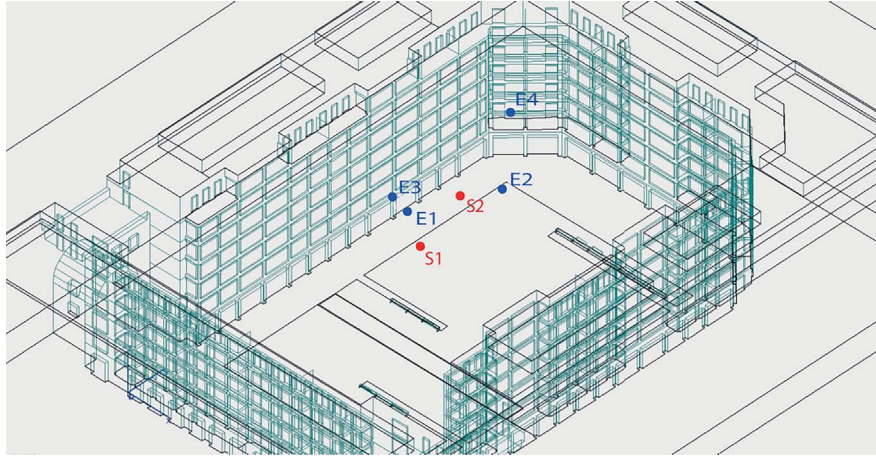


Figure 5. Positions of the room acoustic measurements in inner courtyard M, shown in the ODEON model. Red circles mark the transmitter positions (S1 & S2) and blue circles mark the receiver positions (E1–E4).

percentages of transmission paths with $EK \geq 1.5$ for the three individual measures (fully absorbing facades; absorbing balcony soffits; absorbing inner courtyard floor) compared to the situation without measures (fully reflecting inner courtyards). Note that p -values are not reported here, as all effects are highly significant (cf. Section 2.7). For sake of clarity, the standard deviations are not presented in the figures. For EDT and T_{20} they are approximately 0.3–0.5 s for the smaller models and 0.5–0.7 s for the larger ones. For G , they are some 3–5 dB for the generic models and for model M, and some 6–7 dB for model Z. For the STI , they are about 0.07–0.09, with higher values for larger models.

Generally, Figure 6 reveals that the situation improves (decreasing T_{20} and G , increasing STI) in the order no measures < absorbing balcony soffits < absorbing inner courtyard floor < fully absorbing facades. For EK , the situation is less clear, although absorbing balcony soffits and – to a lesser degree – inner courtyard floor tend to deteriorate the acoustical quality (increased EK , i.e., more echoes). Note that STI is not further discussed in the following account (cf. Section 2.3), except for Section 3.4.

3.2 Effect of partially absorbing facades

Figure 7 shows the effect of partially absorbing facades for T_{20} and G . The presentation of the percentage of transmission paths with $EK \geq 1.5$ is not shown here because the effects are relatively small and overall no clear dependence on the fraction of absorbing facades is seen.

In these calculations, the absorbent facade area increases storey by storey from the bottom to the top, while the balcony soffits and inner courtyard floor remain reflecting. The results reveal that the acoustical quality (as indicated by lower T_{20} and G values) continuously improves with increasing fractions of absorbing facades (i.e., number of storeys).

3.3 Effect of combinations of measures

Figure 8 shows the effect of combined measures, namely (i) absorbing facades + absorbing balcony soffits, (ii)

absorbing facades + absorbing inner courtyard floor, and (iii) absorbing facades + absorbing balcony soffits + absorbing inner courtyard floor, compared to no absorbing elements and only absorbing facades. Again, as for the individual measures, the standard deviations are not presented in the figures for the sake of clarity; the standard deviations are in the same range as indicated for the individual measures in Section 3.1.

For T_{20} , the additional gain with combined measures is small compared to fully absorbing facades alone; only for the higher buildings (> 4 storeys) a small improvement is visible. For G , the gain with combined measures is larger; here, the improvement is mostly in the order of absorbing facades < absorbing facades + floor < absorbing facades + soffits < absorbing facades + soffits + floor. Here, the improvement (i.e., additional reduction in G by combined measures) reach up to 3 dB. For EK , the situation is again less clear, although all measures tend to worsen the situation (i.e., increase EK and thus the echoes), particularly if the absorbing facades are combined with absorbing soffits and/or ground floor.

3.4 Effect of floor area and number of storeys for fully absorbing facades

In this section, the effect of floor area (or floor plan) and number of storeys on the effect of fully absorbing facades on the investigated room acoustical parameters for the generic models is shown. Figure 9 shows the changes in the room acoustical parameters between reflective and fully absorptive facades (with reflecting balcony soffits). EK is not shown, as the effect of the absorbing facade is relatively small.

For all four parameters (EDT , T_{20} , G and STI), the effect of the absorbing facade is significantly lower for the courtyards with four storeys than for those with seven storeys ($p < 0.01$). Besides, also the floor plan has a significant ($p < 0.01$), though somewhat smaller effect. Here, significant differences ($p < 0.01$) are indicated with differing capital letters (A, B, C). The same letter for two floor plans

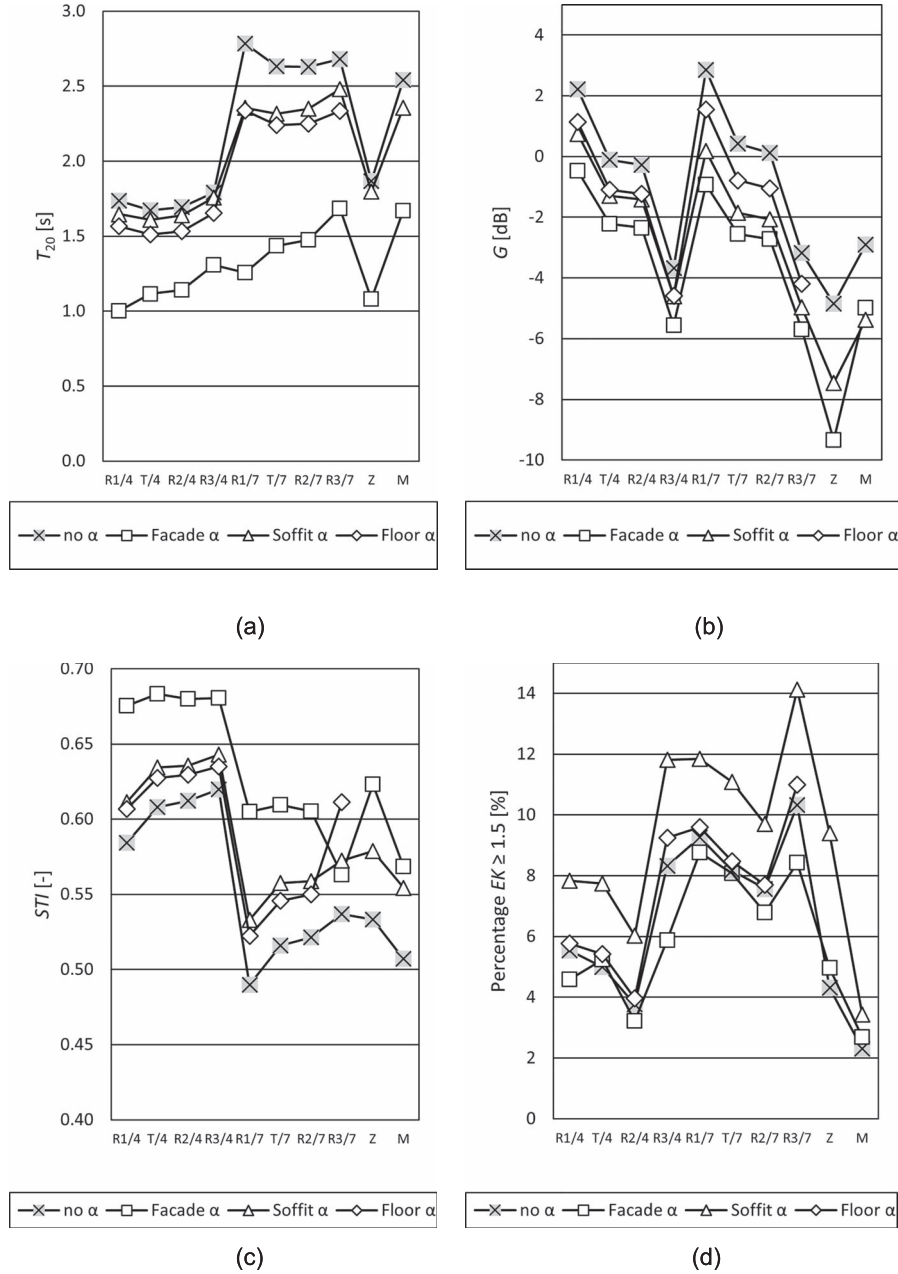


Figure 6. Mean values of (a) reverberation time T_{20} , (b) strength G , (c) speech transmission index STI , and (d) percentage of transmission paths with $EK \geq 1.5$ for three individual measures (fully absorbing facades [facade α]; absorbing balcony soffits [soffit α]; absorbing inner courtyard floor [floor α]) in comparison to the situation without measure [no α].

indicates that their changes are of the same population ($p \geq 0.05$), while different letters indicate that their changes are from different populations ($p < 0.05$). As a reading example: The change of EDT for four floors (Fig. 9a) is significantly ($p < 0.05$) different between R3 (capital letter A) and R1 (different letter B), while the change for T and R2 are neither significantly differently to each other nor from R1 or R3 (same letters A/B, thus belonging to both populations A and B, $p \geq 0.05$). In Figure 9d, there are even three populations as indicated by three letters A, B and C. Similar results for reflective vs. fully absorptive facades are obtained in the case of fully absorbing balcony soffits. Also, similar conclusions can be drawn from the comparison

of the model-dependent effect of fully reflecting compared to fully absorbing balcony soffits, with fully absorbing facade (not shown).

3.5 Individual groups of transmission paths

So far, all transmission paths – from source/receiver positions on the ground floor and all balconies – were analysed together. Here, the question arises whether the results from all transmission paths also apply to individual sub-groups of transmission, e.g., only those in the courtyard, an area which is often publicly accessible. An additional

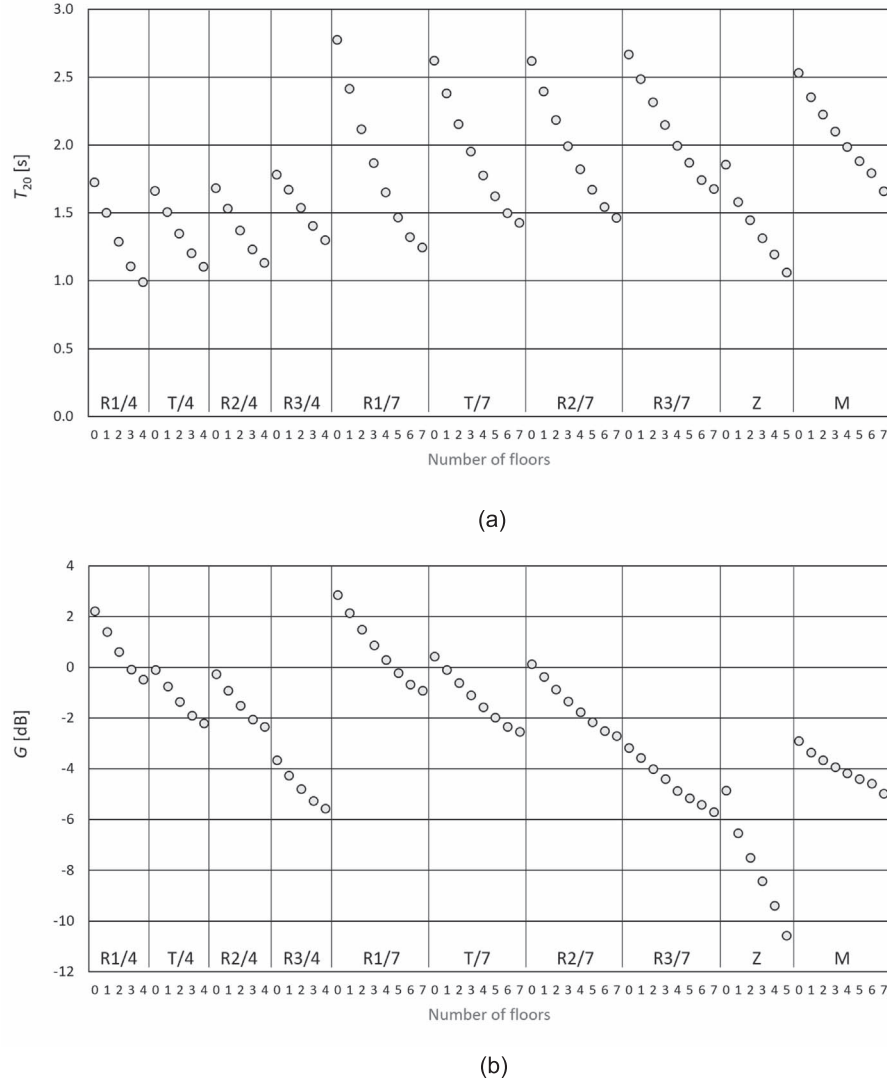


Figure 7. Mean values of (a) reverberation time T_{20} and (b) strength G for partially absorbing facades (reflecting balcony soffits; reflecting inner courtyard floor). X-axis values show increasing fractions of absorbing facades from ground to uppermost storey, for the 10 studied courtyard models.

data analysis was therefore carried out to analyse whether the results presented in Sections 3.1–3.4 for all transmission paths (all positions to all positions) as reference group also apply to the following subgroups: (i) Courtyard $\rightarrow$ balconies (all positions from the courtyard to all positions on the balconies), (ii) Ground floor balconies $\leftrightarrow$ ground floor balconies (all positions from ground floor balconies to all positions on ground floor balconies), (iii) Balconies $\leftrightarrow$ balconies (all positions from balconies to all positions on balconies), and (iv) Courtyard $\leftrightarrow$ courtyard (all positions from the courtyard to all positions on the courtyard).

The individual analyses revealed that only in relatively few cases larger differences between the groups and the reference group occurred, especially in model Z and to some extent in R3/4. In general, however, no systematic discrepancies were identified, which suggests a generalizability of the presented results also for the above subgroups (details not shown).

3.6 Simulation validation

The results of the room acoustical measurements compared with the corresponding simulated values in the courtyard M are listed in Table 3.

Table 3 reveals that the differences between measurement and simulation for T_{20} are mostly below the JND (see Table 2), except for S2-E4 where it lies just above. In contrast, the simulated values of EDT deviate generally strongly (above JND) from the measurements. The strong discrepancy may be due to EDT (measured from the first 10 dB level drop) reacting very sensitively to the low density of reflections compared to the reverberant tail. Thus, even small temporal shifts or different intensities of the first incoming reflections can lead to a strong change in EDT . With regard to the strength G , the simulation underestimates the measurements by 2.7 ± 0.7 dB on average, which is clearly above the JND. Given the above observed good

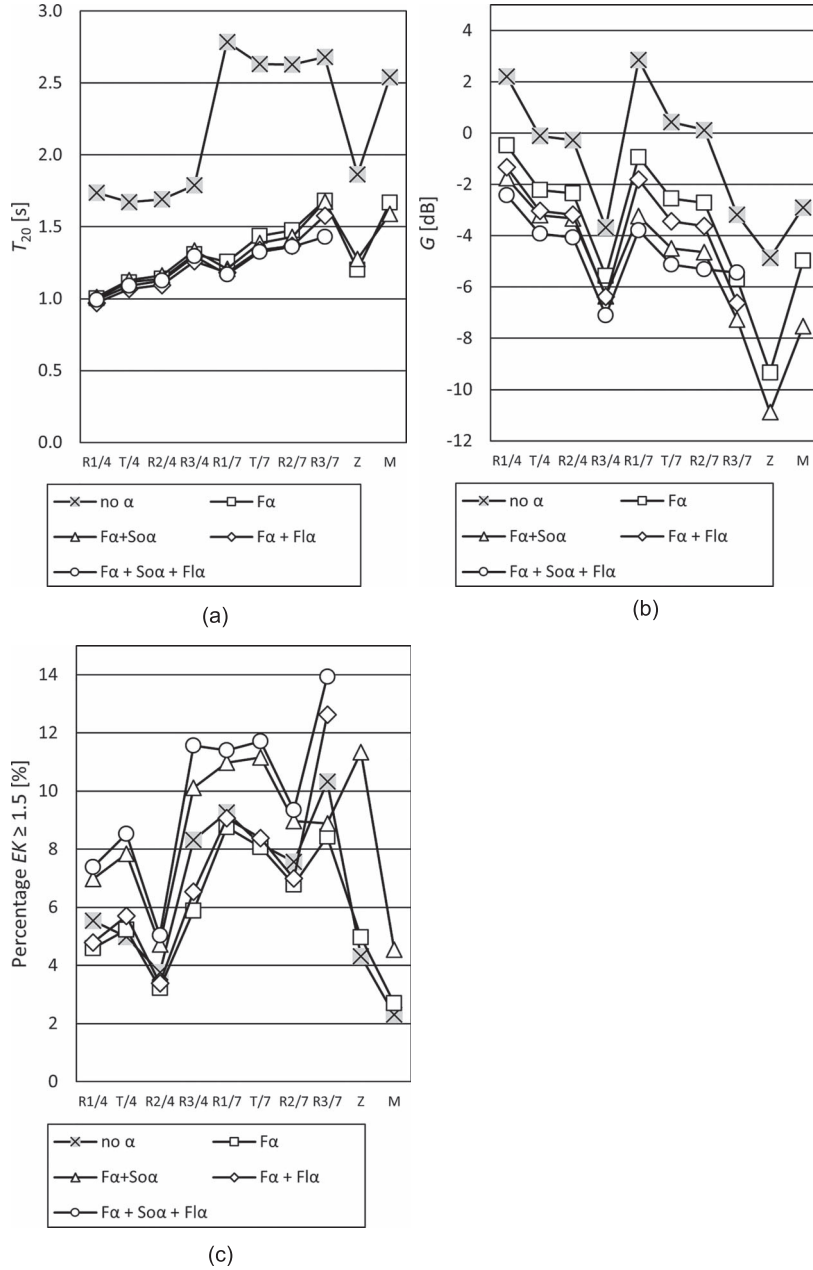


Figure 8. Mean values of (a) reverberation time T_{20} , (b) strength G and (c) percentage of transmission paths with $EK \geq 1.5$ for three combined measures (F α + So α : absorbing facades + absorbing balcony soffits; F α + Fl α : absorbing facades + absorbing inner courtyard floor; F α + So α + Fl α : absorbing facades + absorbing balcony soffits + absorbing inner courtyard floor) in comparison to the situations without measure (no α) and fully absorbing facades (F α).

agreement for T_{20} and poor agreement for EDT , the rather large underestimation of G is also likely to be related to the early sound reflections, which strongly contribute to G , and the intensity of which may have been calculated too low in some cases during the simulation. Further, the STI is overestimated on average by 0.14 ± 0.10 by the simulations (again, above JND), while the differences in EK are relatively small, with an average overestimation of 0.05 ± 0.15 (well below the chosen threshold of $EK = 1.5$) in the simulation.

Overall, larger differences between simulations and measurements thus do occur, particularly for EDT , G and STI , but these are at least partly also attributable to measurement uncertainties. For a more meaningful validation, a more extensive and systematic measurement campaign would be necessary, which was beyond scope of the current study. Nevertheless, the validation indicates that, despite uncertainties, the simulations are suited to yield not only at least the magnitudes of the resulting room acoustical parameters, but in particular also to reliably disclose

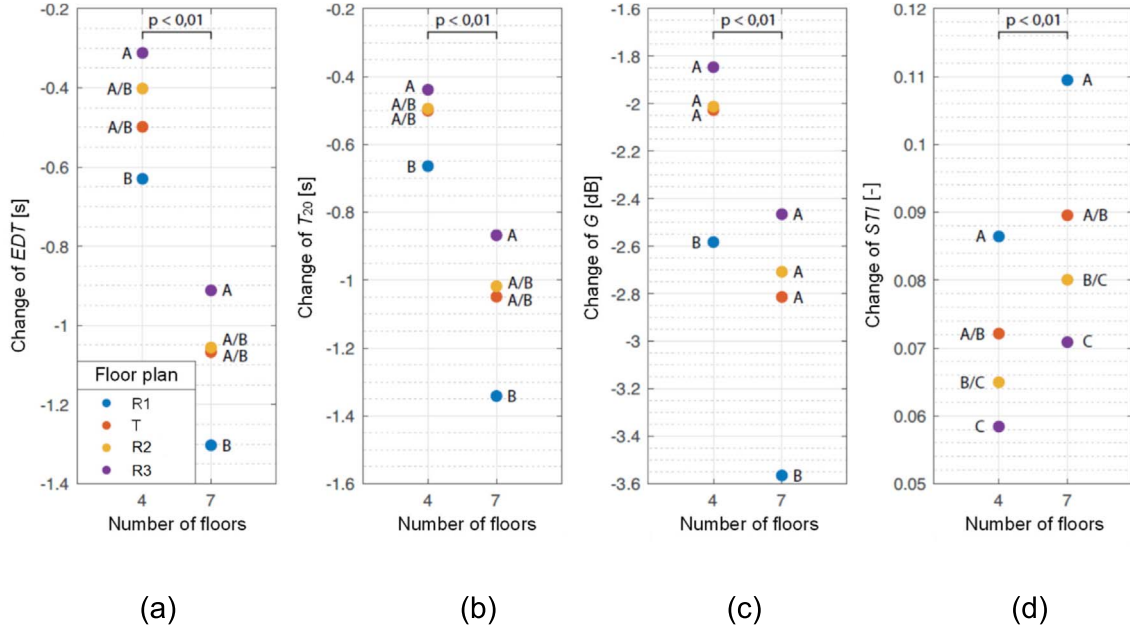


Figure 9. Model-dependent changes of the room acoustical parameters (a) EDT , (b) T_{20} , (c) G and (d) STI between fully absorbing compared to fully reflecting facade, pooled over floor materialisation (reflecting and absorbing), with reflecting balcony soffits. Differing capital letters (A, B, C) indicate significant differences between floor plans ($p < 0.01$). Significance between models with 4 and 7 storeys are indicated with connection markers ($p < 0.01$).

Table 3. Results of the room acoustical measurements in the inner courtyard M for the eight measured source-receiver combinations in comparison to the corresponding simulated values.

Transmission path	S1-E1	S1-E2	S1-E3	S1-E4	S2-E1	S2-E2	S2-E3	S2-E4
T_{20} Meas. in s	2.64	2.63	2.68	2.74	2.37	2.33	2.65	2.73
T_{20} Simul. in s	2.64	2.57	2.73	2.66	2.49	2.39	2.65	2.57
T_{20} Difference in s	0.00	-0.06	0.05	-0.08	0.12	0.06	0.00	-0.16
T_{20} Difference in %	0	-2	2	-3	5	3	0	-6
EDT Meas. in s	0.15	2.63	1.45	2.43	0.29	0.72	1.64	1.05
EDT Simul. in s	0.27	2.61	2.84	2.78	0.49	0.88	3.88	1.92
EDT Difference in s	0.12	-0.02	1.39	0.35	0.20	0.16	2.24	0.87
EDT Difference in %	80	-1	96	14	69	22	137	83
G Meas. in dB	10.3	3.1	8.9	2.5	11.5	10.7	7.8	6.7
G Simul. in dB	7.6	0.9	6.1	-0.8	8.4	8.3	4.0	5.0
G Difference in dB	-2.7	-2.2	-2.8	-3.3	-3.1	-2.4	-3.8	-1.7
STI Meas.	0.64	0.56	0.59	0.57	0.62	0.58	0.6	0.61
STI Simul.	0.85	0.61	0.84	0.54	0.83	0.78	0.76	0.69
STI Difference	0.21	0.05	0.25	-0.03	0.21	0.20	0.16	0.08
EK Meas.	0.77	0.71	0.73	0.63	0.62	0.63	0.64	0.55
EK Simul.	0.74	1.07	0.74	0.62	0.57	0.55	0.64	0.75
EK Difference	-0.03	0.36	0.01	-0.01	-0.05	-0.08	-0.01	0.20

differences between different types of facades, which was the main objective of the current study.

4 Discussion and recommendations

In this study, a large simulation exercise was performed to systematically study the effects of absorbing facades, absorbing balcony soffits and absorbing ground floors, as well as combinations of these measures, on the acoustical quality of inner courtyards of perimeter blocks. To our

knowledge, no such study with systematic variation of the materialization for a wide range of inner courtyards is available to date. So far, studies either comprised calculation results or psychoacoustic experiments for a limited range of specific situations in built environments. The scientific basis regarding acoustic quality in courtyards is still small. At least, there is a reliable study with listening experiments [2, 27] and there are expert groups in practice which, based on practical experience, developed relatively clear ideas on how to improve the acoustic quality in built environments [43], a topic which closely coincides with the goals presented

here. With the large resulting data set, our study thus contributes to more reliable rules of thumb for the acoustical planning and dimensioning of inner courtyards.

4.1 Effects and usefulness of different measures

The simulations revealed that fully absorbing facades in most cases clearly improve the acoustical situation. The rather long reverberation times T_{20} of 1.7–2.8 s in the courtyards without absorbing facades are strongly reduced by 0.9 ± 0.5 s with fully absorbing facades for the generic models and by 0.7 s and 0.8 s for the real models Z and M, respectively, to around 1.0–1.7 s (Fig. 6). The effect of the absorbing facades is thus large and very clearly perceptible everywhere. Likewise, G is reduced with fully absorbing facades by 2.6 ± 0.6 dB for the generic models, and by 4.5 dB (Z) and 2.1 dB (M) for the real world models (Fig. 6), which is a well perceptible and – considering the accordingly reduced reverberation time – representing a very positive reduction. Furthermore, many of the studied courtyards show only a slight reduction or increase in the EK ; only in two courtyards (R3/4 and R3/7) the EK increases somewhat more by about 2% (Fig. 6). However, the addition of absorption cannot per se be expected to reduce echo interference. Indeed, absorbing balcony soffits and floor increased EK (Fig. 6). One explanation for this could be the following. As we know from indoor room acoustics, it is important where the absorption is applied. Additional absorption can lead to echoes becoming more audible. The echo reflections are originally physically present, but are acoustically masked by other reflections. However, if these other reflections are absorbed, there is no longer acoustic masking, and the echoes become audible.

Thus, the effect of fully absorbing facades is overall positive and clearly perceptible, so that absorbing facades appear to be highly recommendable. Further, the storey-by-storey addition of absorbing facades revealed that for T_{20} as well as for G (Fig. 7) the additional reduction per storey added is quite constant without noticeable kink point. While the reduction per storey added is in most cases slightly more than one JND for T_{20} , it is usually less than one JND for G . Thus, with regard to a sufficiently strong effect, there are no arguments for not cladding all storeys in the investigated inner courtyards with absorbing material.

In contrast to the facades, the effect of absorbing balcony soffits in reducing the reverberation times EDT and T_{20} is much lower, although they are still in the range of the just perceptible difference (JND) or even distinctly higher. The same finding applies to G . Somewhat surprisingly, the echo disturbance increases in all courtyard models. Obviously, the sound field is clearly affected here in such a way that certain echoes are no longer masked.

The floors of the inner courtyards can also affect the acoustic quality. While it cannot be made fully absorbing, materialisation with grass allows estimating the potential maximum effect. As expected, absorbing floors reduced T_{20} less than the fully absorbing facades, but the changes are still clearly above one JND (Fig. 8) while the reduction of G is just about one JND (Fig. 8). As for the soffits, EK

increases in all models, which may be due to the fact that reflections on the ground are somewhat reduced and thus in certain situations the remaining reflections are no longer masked, as already discussed above. In the examined generic models, absorbing floors as well as absorbing balcony soffits are therefore not recommended as the only measures in inner courtyards, because (i) the positive effects are too small, and (ii) echo disturbances can be increased.

Combining the measures (absorbing facades, balcony soffits and courtyard floor) was not found to substantially improve the situation (Fig. 8). First, while combining absorbing balcony soffits and facades reduced G by some 1–3 dB compared to solely absorbing facades, it hardly improved the situation for T_{20} . Also, the echo disturbances increased quite strongly everywhere. Second, likewise, the additional effect of combining an absorbing courtyard floor with an absorbing facade is negligible for T_{20} , while G is additionally reduced by about 1 dB. Again, the echo disturbances increase slightly. Finally, the combination of all measures neither strongly changes T_{20} nor G compared to the two combined measures discussed above, but strongly increases the proportion of echo disturbances, which is highest in this case. In conclusion, it is questionable whether any combination of the measures is sensible in the courtyard models investigated here, since only minor improvements result compared to solely absorbing facades, while the combinations of measures are associated with a pronounced increase in echo disturbances.

4.2 Validity and applicability of the results for the practice

Regarding the validity and applicability of the results for the practice of acoustic design of courtyards, the following aspects should be considered.

First, a selection of courtyard models including design parameters such as the percentages of window areas had to be made for this study. This limitation was addressed by choosing “worst case” models that are rather problematic with regard to echoes and flutter echoes. With structured facades, the problem is certainly alleviated.

Second, this kind of study can only be carried out with the help of simulations. We are not aware of any inner courtyards with sound-absorbing facades or balcony soffits. But even if we had access to such real buildings, a (systematic) variation of the corresponding surfaces would be practically impossible. Systematic measurements in real situations are therefore practically impossible. Measurements in physical scale models would be an alternative, but the effort involved would also be very high. Besides, another alternative would be to use numerical methods based on wave theory, possibly combined with geometric methods. For the current application in such an extensive study, however, no sufficiently powerful numerical tools based on wave theory are available do date. The simulation methods based on geometric acoustics used here are therefore the most feasible approach, even more so as they are well established for room acoustic simulations, not least on the basis of round robins [45, 46].

Third, the question arises as to whether the commercial software ODEON used for room acoustic simulation on the basis of geometric acoustics is sufficient for the purpose of the present study, especially since the wave phenomena are not or only in a very approximate way taken into account. Here, it should be noted that ODEON is one of the world's well established software, which not only successfully participated in the above-mentioned round robins and, according to the manufacturers of ODEON, was classified there as one of the “*unquestionable reliable*” softwares [47], but also conducted its own dedicated round robin [47, 48]. Further, the software was also successfully applied from early on for the simulation of outdoor spaces, such as Roman theatres [49], as well as in an outdoor study that was not concerned with inner courtyards, but with urban streets [50]. A validation in the latter study revealed that ODEON yields reliable results for sound pressure level and reverberation time T_{30} . In this respect, also two ongoing studies comparing simulations and measurements in outdoor settings are worth mentioning, of which first results were recently presented [51, 52]. One of the studies [51] includes the software ODEON with first results for an inner courtyard 18.7 m wide, 29.7 m long and about 20 metres high, that shows reasonably acceptable agreement with regard to sound pressure level. In addition, our study undertook its own efforts at validation, with input parameter variation (Section 2.5) and validation with measurements (Section 2.6). Comparison of the latter with corresponding simulations (Section 3.6) revealed – depending on the parameter – either good agreement (particularly for T_{20} , which is in agreement with the above mentioned validation of T_{30} in [50]), or larger deviations (in particular for EDT and G) than expected from studies of indoor rooms (cf. [44–47]).

Finally, a further aspect worth mentioning regards the simulation of accessible real situations, here the models M and Z, without sound-absorbing measures. For a large courtyard [53], improvements were shown when the virtual model could be calibrated with the help of room acoustic measurements. Today a corresponding tool called “Genetic Material Optimizer” is integrated in the ODEON software [30, 54]. However, the use of the tool for the Z and M models (combined with measurements) was unfortunately beyond the scope of this study.

In conclusion, the methodological approach to do simulations with ODEON seems feasible, given the range of available validation exercises supporting the applicability of the software. Also, as the objective of the present study was to compare different situations calculated in the same way and with the same geometries, many sources of error are eliminated. With regard to the evaluated mean values (cf. Section 3), it can be therefore assumed that their uncertainty lies within the range of JND.

4.3 Outlook

The results presented here, together with basic knowledge of room acoustics and experience, provide good practical aids (rules of thumb) for the design of courtyards.

Our study, however, does not address the question which absorbent facade materials are suitable in practice. Here, systematic material developments are necessary. While there are solutions on the market at least for balcony soffits, solutions for facades are largely missing, even if ideas are presented [55, 56]. In addition, interesting approaches can be found in research, e.g., for greened facades [57–59] or rigid mineral foams [60]. Besides, while our study briefly deals with the questions of shape and structure of the facades as well as the question of guideline values, these questions should be studied systematically and in more detail in future. Finally, further investigations using room acoustic simulations and virtual environments including audio and audio-visual experiments [61] can provide additional useful insights.

5 Conclusions

In this study, a large simulation exercise was performed to systematically study the effects of absorbing facades, absorbing balcony soffits, absorbing ground floors, and combinations thereof, on the acoustical quality (as quantified by various room acoustical parameters) of inner courtyards of residential perimeter blocks. As an example, the reverberation time T_{20} , which is around 2.2 seconds on average for the non-treated models, could be reduced by 40% on average with completely absorbing facades. The results suggest the following rules of thumb for the acoustical planning and dimensioning of inner courtyards:

- Fully sound-absorbing facades are an effective measure to improve the acoustic quality of inner courtyards of residential perimeter blocks.
- Partially sound-absorbing facades bring substantially less improvement, and each additional storey that is designed to be absorbing brings a perceptible positive effect, so that as much of the facade as possible should be absorbent.
- In the case of non-absorbent facades, the benefit of only absorbing balcony soffits and/or inner courtyard floor (lawn) is questionable, because reverberation time and sound levels are only slightly improved, while increased disturbances due to echoes can occur.
- Also, in the case of sound-absorbing facades, additional absorbing balcony soffits and/or floor (lawn) are questionable for the same reasons. A potential benefit of these measures has to be investigated in each individual case.

With exceptions, the group-wise evaluation (e.g., for transmissions from floor to balconies instead of all transmission paths) mostly lead to the same conclusions, although slightly different outcomes for individual groups may result. Despite the above rules of thumb, for specific projects it is thus still useful to determine whether a design should be optimised for all transmission paths, or possibly in higher priority for a group of transmission paths, such as the area on the courtyard floor.

What is the practical approach when planning courtyards? In any case, acoustics should be included in the design from the beginning. This can happen in the first phase in the form of rules of thumb, which can be taken from this study, but which are also generally known with regard to room acoustics. In addition, depending on the complexity of the project, e.g., if the question of echoes and flutter echoes is involved, a dedicated room acoustical simulation will be helpful. Finally, expert guidance from an acoustics consultancy will clarify when rules of thumb work and when additional simulation tools are necessary.

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Conflicts of interest

The authors declare no conflicts of interest.

Data availability statement

Data are available from the corresponding author on request.

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Appendix A

Table of sound absorption coefficient

Table A1. Sound absorption coefficients for the materials of the different models of courtyards (Models: G: generic models; Z and M: real world models).

Material	Frequency in Hz								Used in model
	63	125	250	500	1k	2k	4k	8k	
Absorbing facade/balcony soffit	0.25	0.25	0.55	0.85	0.90	0.80	0.75	0.75	all
Brick wall	0.02	0.02	0.03	0.03	0.04	0.05	0.07	0.07	generic and Z
Windows	0.18	0.18	0.06	0.04	0.03	0.02	0.02	0.02	all
Smooth concrete (balconies & privacy screen)	0.01	0.01	0.01	0.02	0.02	0.02	0.05	0.05	all
Rough concrete (reflective floor)	0.02	0.02	0.03	0.03	0.03	0.04	0.07	0.07	all
Lawn	0.15	0.15	0.25	0.40	0.55	0.60	0.60	0.60	all
Plastered brick wall	0.01	0.01	0.01	0.02	0.02	0.02	0.02	0.02	M
Gravel floor	0.07	0.07	0.12	0.20	0.27	0.30	0.30	0.30	Z
Stone slabs	0.01	0.01	0.01	0.015	0.02	0.02	0.02	0.02	M
Wood (benches)	0.05	0.05	0.08	0.10	0.12	0.12	0.12	0.12	M and Z

Appendix B

Variants of materialisations of the simulated courtyards

Table B1. 11 variants of materialisations of the generic models R1, T, R2, R3 with 4 storeys (F = Facade; 1, 2, 3, 4 = storeys; Ba = Balcony soffit; Fl = Floor of courtyard; r = reflecting; α = absorbing).

Var.	1	2	3	4	5	6	7	8	9	10	11
F4	r	r	r	r	r	r	r	α	α	α	α
F3	r	r	r	r	r	r	α	α	α	α	α
F2	r	r	r	r	r	α	α	α	α	α	α
F1	r	r	r	r	α	α	α	α	α	α	α
Fl	r	r	α	α	r	r	r	r	r	α	α
Ba	r	α	r	α	r	r	r	r	α	r	α

Table B2. 14 variants of materialisations of the generic models R1, T, R2, R3 with 7 4 storeys (F = Facade; 1, 2, 3, 4 = storeys; Ba = Balcony soffit; Fl = Floor of courtyard; r = reflecting; α = absorbing).

Var.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
F7	r	r	r	r	r	r	r	r	r	r	α	α	α	α
F6	r	r	r	r	r	r	r	r	r	α	α	α	α	α
F5	r	r	r	r	r	r	r	r	α	α	α	α	α	α
F4	r	r	r	r	r	r	r	α	α	α	α	α	α	α
F3	r	r	r	r	r	r	α	α	α	α	α	α	α	α
F2	r	r	r	r	r	α	α	α	α	α	α	α	α	α
F1	r	r	r	r	α	α	α	α	α	α	α	α	α	α
Fl	r	r	α	α	r	r	r	r	r	r	r	r	α	α
Ba	r	α	r	α	r	r	r	r	r	r	r	α	r	α

Table B3. 8 variants of model Z (F = Facade; 1, 2, 3, 4 = storeys; Ba = Balcony soffit; r = reflecting; α = absorbing).

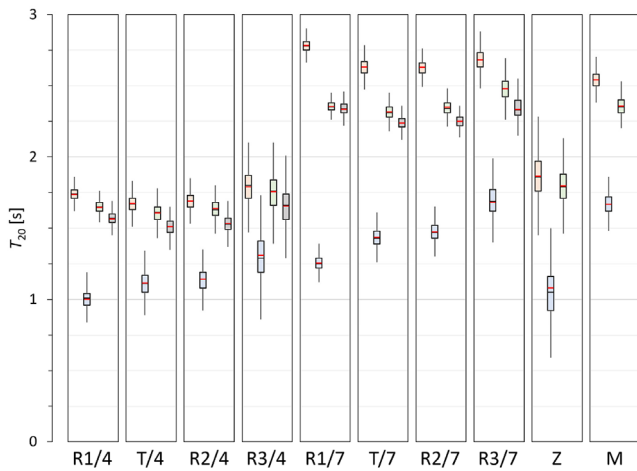
Var.	1	2	3	4	5	6	7	8
F5	r	r	r	r	r	r	α	α
F4	r	r	r	r	r	α	α	α
F3	r	r	r	r	α	α	α	α
F2	r	r	r	α	α	α	α	α
F1	r	r	α	α	α	α	α	α
Ba	r	α	r	r	r	r	r	α

Table B4. 10 variants of model M (F = Facade; 1, 2, 3, 4 = storeys; Ba = Balcony soffit; r = reflecting; α = absorbing).

Var.	1	2	3	4	5	6	7	8	9	10
F7	r	r	r	r	r	r	r	r	α	α
F6	r	r	r	r	r	r	r	α	α	α
F5	r	r	r	r	r	r	α	α	α	α
F4	r	r	r	r	r	α	α	α	α	α
F3	r	r	r	r	α	α	α	α	α	α
F2	r	r	r	α	α	α	α	α	α	α
F1	r	r	α	α	α	α	α	α	α	α
Ba	r	α	r	r	r	r	r	r	r	α

Appendix C

Example of box plot of results

**Figure C1.** Example of box plot with mean values of reverberation time T_{20} for three individual measures in comparison to the situation without measures. From left to right: situation without measure □; fully absorbing facades □; absorbing balcony soffits □; absorbing inner courtyard floor □.