# A performance-based acoustical design strategy for centralized air distribution networks

Zakarya Kabbara[1], Arne Dijckmans[2], Sandy Jorens[1], Jitse Van Thillo[1], Ivan Verhaert[1]
[1]University of Antwerp, Faculty of Applied Engineering, Department of Electromechanics, EMIB Research Group, Antwerp, Belgium
[2]Belgian Building Research Institute, Brussels, Belgium

## Abstract

This paper emphasizes the importance of early consideration of acoustic performance and designing silencers in HVAC ductwork systems. Optimally designing silencers is challenging, and the design process still relies on the rule-of-thumb, resulting in workable but not necessarily optimal designs and performances. Thereby, this paper proposes an aero-acoustical simulation-based design strategy to optimize the design process, knowing that the aeraulic and acoustical performances are correlated. By applying this method to a test case with two different ductwork configurations, the strategy demonstrated the importance of early consideration of acoustic performance and silencer design by showing their influence on the system's life-cycle-cost.

### Highlights

- Considering acoustic performance and silencer design is important at an early ductwork design stage
- An aero-acoustical simulation-based design strategy can effectively design silencers
- Acoustic performance and silencer design influence the system's life cycle cost and energy usage

## Introduction

Centralized air distribution systems are essential for preserving a comfortable and healthy indoor climate in many buildings, including residential and commercial ones. Nonetheless, these systems can produce undesired noise (i.e., acoustical problems), which has a detrimental impact on occupant comfort and productivity. Consequently, it is important to consider acoustical comfort when designing centralized air distribution systems.

Mechanical ventilation systems include various possible noise sources and transmission paths, both airborne and structure-borne [1]. Generally, the airborne duct sound is dominant, and therefore, the ductwork system is one of the most important elements influencing the acoustic performance of a centralized air distribution system. In this regard, the ductwork can affect the acoustic performance through several factors, including the system's layout, sizes, and components. Not only the fan noise is transmitted by the ducts, but additional flow noise can be generated in the ductwork components due to air turbulence. The ventilation noise is mainly radiated into the rooms by the air openings, but noises can also be transmitted through duct walls, causing additional noise issues.

Researchers have studied different duct designs and materials to mitigate the noise levels in the ductwork system. In this regard, Rasuo et al. [2] revealed that the duct size influences the airflow velocity and turbulence, affecting the noise levels. Larger ducts can diminish turbulence and noise levels, especially with the existence of bends. Villau et al. [3] reported that acoustic insulation materials could lower noise levels by absorbing sound waves. Additionally, anti-vibration mounts and flexible connectors can be implemented to lower structure-borne noise and vibration [4].

## Problem formulation

### Overview

Silencers, often referred to as sound dampers or noise attenuators, are components that intend to attenuate the noise produced in the air distribution system. Typically, they are installed after the system's components that generate high noise levels, for example, after the inlet and outlet of an air handling unit (AHU), or after pressure damping valves. In most cases, silencers are indispensable to reduce the ventilation noise levels in the rooms to acceptable levels.

However, silencers can have detrimental effects on the ducting system's performance and costs. Improperly designed silencers can cause additional flow noise. In addition to not achieving the desired indoor noise levels, they can defect the aeraulic performance due to their additional resistance (i.e., pressure drops) in the ductwork system, especially when these silencers are oversized. Consequently, this can degrade energy efficiency, increase the energy usage of the air distribution system and increase the fan noise [5]. Moreover, due to oversizing, they can affect the investment cost of the designed system. Furthermore, the improperly sized silencer may need to be replaced, leading to increased installation and maintenance costs.

Sizing silencers is a complicated procedure, as it depends on several variables, such as the ductwork configuration (i.e., layout and sizes), the type of equipment generating noise, and the desired noise level. Although there are some guidelines and practices for sizing silencers [6], [7], they are typically general and may not account for all the specific requirements of a given air distribution system. For instance, the guidelines provide recommendations for


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the silencer types based only on the source noise. Besides, there is no specific recommendation for all the sizing parameters (e.g., silencer length and number of baffles per silencer). However, many ductwork-associated factors may affect the selection of silencer type and size, such as the intensity and location of the noise source, the airflow rate within the duct system, the architectural limitation (i.e., available duct space), the availability of the different type of silencers, and the costs of the silencers.

Consequently, the design process still relies on the rules of thumb and the design engineer's expertise. Ideally, the reliance on the engineer's expertise should ensure the highest acoustic performance without sacrificing the other associated performances and costs. However, unfortunately, this reliance typically results in workable but not necessarily optimally performing and cost-efficient designs.

**Acoustical problems within the state-of-the-art ductwork design methods**

Recent research studies have shown that unconventional duct layouts (see Figure 6 and Figure 7) can result in a more cost-efficient and better aeraulic performance [8]–[11]. Yet, it is vital to note that unconventional ductwork layouts may cause additional acoustical problems that are often overlooked by these researches.

In conventional ductwork layouts, the primary ducts are mainly located in the circulation areas where the acoustical comfort requirements are less strict. When primary ducts pass through an occupied space, a sound breakout from the duct can be a problem when the noise inside the duct is not adequately attenuated (see Figure 1). The larger the exposed surface area of the duct, the higher the duct breakout sound transmission. Duct breakout is mostly of concern for rectangular and flexible round ducts, as the sound insulation of rigid round ducts is much higher.

A second issue to consider is cross-talk. Sound may be transmitted from one room to another via the ductwork, either by transmission via the air openings (see Figure 2), or via duct break-in and breakout (see Figure 3). While cross-talk can limit the sound insulation between distant rooms, it is especially important to check this for adjacent rooms that are directly connected by the ductwork. It may be necessary to install a cross-talk silencer in the duct at the partition wall level.

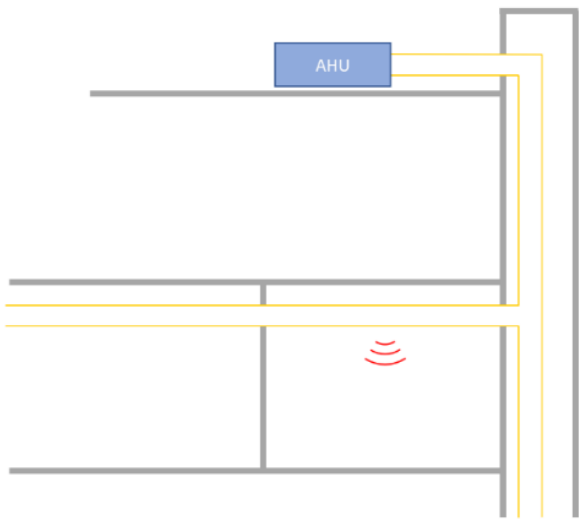


*Figure 1: Duct breakout demonstration*

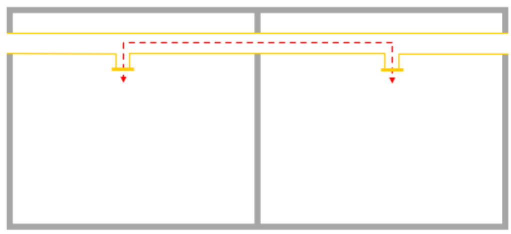

*Figure 2: Cross-talk via air openings*

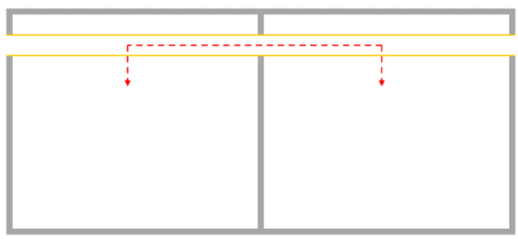

*Figure 3: Cross-talk via duct break-in and breakout*

## Aims and objectives

Currently, the existing ductwork design methods are limited to generating design configurations by accounting only for the aeraulic performance of the ductwork. The acoustical performance assessment and sizing of the silencers are not included in any of the ductwork design methods. They typically take place after deciding on the ductwork configuration (i.e., layout and sizes). The aim of this paper is to highlight the importance of incorporating acoustic design at an earlier stage, i.e., while deciding on the optimal ductwork design configuration.

Optimally designing silencers is complex and involves uncertainty and variability (see Problem formulation section), which makes the design process challenging to ensure optimal acoustical performance in the ductwork system. A simulation-based design strategy can effectively size silencers to satisfy the acoustic requirements. To optimize the performance of the ductwork system, it is important to consider both aeraulic


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and acoustical performances, as they are correlated. Therefore, in this paper, we are proposing a simulation-based aero-acoustical design strategy that we use to show the importance of incorporating acoustic design at an earlier ductwork design stage. Such a simulation-based design strategy aims to effectively place and size silencers while minimizing their costs (i.e., material cost and their influence on the fan energy cost) and while also satisfying the desired acoustic performance.

## Materials and method

### Acoustic model description

To develop the simulation-based strategy, it is essential to use acoustic models to evaluate the acoustic performance in the designed air distribution system. The acoustic models are based on the prediction models in EN 12354-5 [1] and VDI 2081 [12]. The assessment of the acoustic performance involves an initial evaluation of the flow noise level and sound power level reduction of every component in the system. Both the fan and flow noise are flow-dependent and will depend strongly on the flow rates and pressure drops in the system. The generic formula of VDI 2081 for flow noise and sound level reduction are implemented for the following type of elements: fans, straight ducts, bends, area changes, junctions, silencers, air openings, and damper valves. For fans, silencers, air openings, and damper valves measured acoustic data from technical sheets can also be given as input.

### Airborne duct sound

To assess the airborne duct sound radiated by an air opening, an acoustic calculation is performed for the path fan-air opening in octave bands from 63 Hz to 8000 Hz. The radiated sound power level is determined by a sequential calculation, starting at the fan. For each element, the outgoing sound power level ($L_{W,\mathrm{out}}$) is calculated from the incoming sound power level ($L_{W,in}$), the sound power level reduction of the element ($\Delta L_W$) and the flow noise generated in the element ($L_W$), as follows:

$$L_{W,out} = 10lg\left(10^{\frac{L_{W,in}-\Delta L_W}{10}} + 10^{\frac{L_W}{10}}\right) \quad (1)$$

The standardized sound pressure level in the room is then calculated at 1.5 m from the air opening, accounting for both the direct sound and the reverberant field. When more than one air opening is present in a room, the sound power level is determined at 1.5 m from the noisiest air opening, taking into account only the reverberant field contribution of the other air opening(s). This acoustic model has been validated by multiple case studies in dwellings, showing an accuracy of ± 3 dB when sufficiently accurate input data are available [13].

### Duct breakout

The sound pressure level $L_{p,\mathrm{breakout}}$ caused by duct breakout is calculated from [12]:

$$L_{p,breakout} = L_{W,in} - R_{ia} + 10\,lg\left(\frac{S_k}{S_1 A}\right) + K_0 + 3 \quad (2)$$

where $L_{W,in}$ [dB] is the sound power level in the duct, $R_{ia}$ [dB] is the sound insulation of the duct from inside to outside, $S_k$ [m$^2$] is the visible surface area of the duct in the room, $S_1$ [m$^2$] is the cross-sectional area of the duct, $A$ [m$^2$] is the acoustic absorption area of the room and $K_0$ [dB] is the room's angular dimension (dependent on the location of the duct in the room).

### Cross-talk

The standardized level difference ($D_{nT}$) between two rooms for cross-talk via air openings is calculated from [12]:

$$D_{nT} = 10\,lg\left(\frac{0.16V}{T_0}\right) - 6 - 10\,lg\,S_{a1} + \sum(\Delta L_{W,i}) \quad (3)$$

Where $V$ [$m^3$] is the volume of the receiving room, $T_0$ [s] is the reference reverberation time, $S_{a1}$ [m$^2$] is the area of the air opening in the source room, and the last term represents the total sound power level reduction of the ductwork elements between the air openings, including the end reflection of the air opening in the receiving room.

Cross-talk via duct break-in and duct breakout is evaluated using the following equation [12]:

$$D_{nT} = R_{ai} + R_{ia} + 10\,lg\left(\frac{S_1}{S_{k1}S_{k2}}\right) + 10\,lg\left(\frac{0.16V}{T_0}\right) - K_0 + 3 + \sum(\Delta L_{W,i}) \quad (4)$$

with $R_{ai}$ the sound insulation of the air duct from outside to inside, and $S_{k1}$ and $S_{k2}$ the visible surface areas of the ducts in the source and receiving room. The last term includes the sound level reduction of any elements present between the ducts in the source and receiving room, e.g., a cross-talk silencer.

### Method description

The simulation-based design strategy to place and size the silencers is divided into five stages, as represented in Figure 4. With this proposed strategy, we aim to effectively design silencers in the ductwork system while minimizing their costs.

1. Specify the design input:
   a. The maximum allowed noise levels in the zones. The acoustic requirements will depend on the zone (e.g., office room) and building types (e.g., hospital)
   b. The minimum sound insulation required between the zones, which will also depend on the zone and building types. The sound insulation for cross-talk should be at least 10 dB higher than the requirement so that its contribution to the global sound transmission is negligible.
   c. Architectural constraint: specify the space limitation of the intended ductwork system for design
2. Acoustic performance assessment: the acoustic performance assessment can be divided into three parts.
   a. Assessing the noise levels in zones from air openings
   b. Assessing the noise levels in zones due to duct breakouts
   c. Cross-talk assessment: the acoustic assessment for cross-talk is only applied for neighboring rooms sharing the same duct (Figure 2 and Figure 3)
3. Generate the location for all potential silencers for all zones that do not satisfy their noise levels (specified in


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1.a.) or do not satisfy the sound insulation requirements (specified in 1.b). Typically, the location of silencers in ductwork are:

a. After the fan (flow-dependent)
b. At the entrance of every zone (flow-dependent) or silencers between the rooms (cross-talk silencers, flow-independent)
c. After pressure valves (flow-dependent)

4. Select the most appropriate silencer for sizing: after knowing the location of all the potential silencers in (stage 3), we have to select the most appropriate silencer for sizing (stage 5). Thereby, we choose to size the flow-dependent silencers first, starting from the upstream silencers (i.e., silencers closer to the fan) until reaching the downstream ones (i.e., silencers closer to the air openings).
   After sizing the flow-dependent silencers, we select the flow-independent ones (silencers between the rooms to eliminate cross-talk noises) for sizing. We opt for this order of selection (i.e., first flow-dependent and then flow-independent) as it is typically followed by the design engineers. Further investigation on the most optimal silencer selection is planned for future work.
5. Sizing the silencers: After selecting the most appropriate silencer for sizing (stage 4), we can start sizing this silencer. Sizing is achieved while generating a pool of potential silencer sizes that can be installed in the intended location of the silencer, while respecting the architectural constraint, specified in stage 1.c. The selected silencer is sized to satisfy the maximum allowed noise levels, specified in stage 1.a, in the zone where the silencer is located while disregarding the flow noise generated in the downstream components.
   In order to achieve optimal silencer sizing with minimal material costs, our method involves beginning with the least expensive silencer (i.e., material cost and its influence on the fan energy costs). If the selected silencer is flow-dependent, we conduct an acoustic assessment to assess the acoustic performance in zones affected by air openings and duct-breakouts. Whereas, if the silencer is flow-independent, we only conduct the acoustical assessment associated with the cross-talk. If the noise levels satisfy the specified values in 1.a and 1.b, the silencer is sized accordingly. If not, we proceed by selecting the next available silencer, which has a higher cost, reassessing, and repeating the process until the noise levels are satisfied with the cheapest possible silencer.

Repeat steps 2-5 until all silencers are effectively sized at minimal costs.

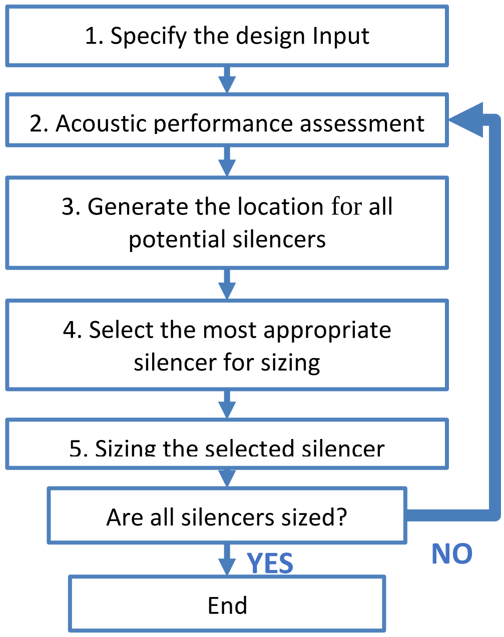


*Figure 4: Silencer sizing strategy*

## Test case

To illustrate the importance of incorporating acoustics in the ductwork design at an early stage, we applied our developed simulation-based sizing strategy to two ductwork configurations (see Figure 6 and Figure 7) for the same floor of a university building (see Figure 5). The floor comprises three classrooms, two PC rooms, and one water closet (WC). The ductwork sizes were developed for the two design layouts while minimizing the ductwork aeraulic life cycle cost (LCC) using a previously developed design algorithm illustrated in [14], [15]. The aeraulic LCC includes the system's ductwork material, installation and maintenance costs, and the ductwork's fan energy costs. Figure 6 represents the unconventional design configuration, which offers an advantage in terms of aeraulic LCC compared to the conventional ductwork configuration represented in Figure 7 (results are presented in the next section). However, the unconventional configuration may be exposed to additional noises, such as the duct breakout noise in room D (Figure 6) and crosstalk noises between neighboring rooms sharing the same duct. Herewith, the aim of this test case is to assess whether the aeraulically more cost-efficient LCC configuration (unconventional configuration) would retain its cost-efficiency advantage over the conventional configuration, when considering the acoustical performance and silencer sizes into the LCC.

To assess the LCC, it was assumed that the system is a constant air volume (CAV) system, running at full load. The operating time is 87,600 hours over the life-cycle.


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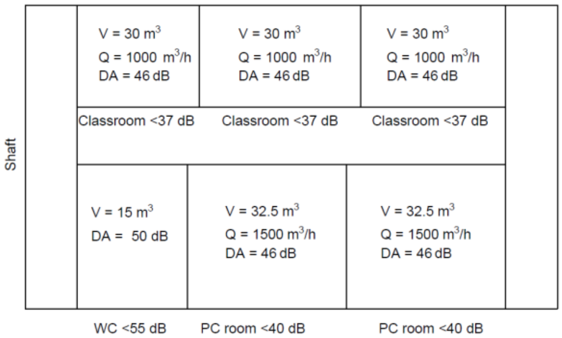


*Figure 5: Test case floor plan. Q is the nominal airflow rate, and DA is the required sound insulation*

## Results and discussion

The detailed sizes of the ductwork system from both configurations without silencers are presented in Appendix A. Design configuration 1 and Appendix B. Design configuration 2. Moreover, the ductwork-associated costs and the noise levels at full load in every room, without silencers, are shown in Table 1. The ductwork-associated costs are only due to ducts and fittings; no other components (e.g., constant air volume (CAV) valve and air openings) are included. The material costs are estimated using a price list that is averaged among numerous Belgian engineering firms. Before sizing the silencers, Configuration 1 (unconventional layout – Figure 6) has the advantage over Configuration 2 (conventional layout – Figure 7) in terms of having lower Ductwork material and fan energy. In this regard, the LCC for Configuration 1 was also 6.8% lower than Configuration 2.

For sizing the silencers, the noise level constraints are presented in Figure 5. It should be noted that some assumptions were made to simplify the test case while still preserving the paper's primary aim. These assumptions are:

- There are no duct leakages in the system
- No noise level constraint in the corridor
- The architectural constraints are neglected
- Pressure drops from silencers with no baffles are neglected
- The fan used is the same (i.e., radial fan with rearwards curved blades, with fan speed = 2356 rpm [12]) for both configurations, and it is followed by the same silencer (i.e., TROX MS 200/80 [16])
- The silencers used are from TROX manufacturer [16]
- Noise radiation by the CAV valves directly to the rooms is neglected

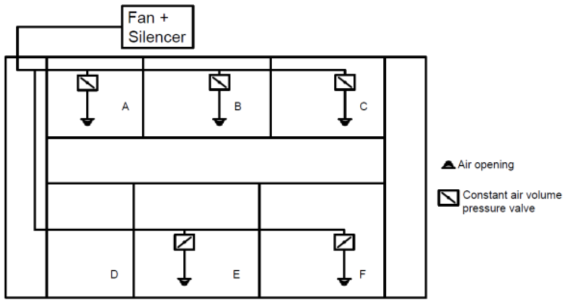


*Figure 6: Configuration 1 - unconventional ductwork layout*

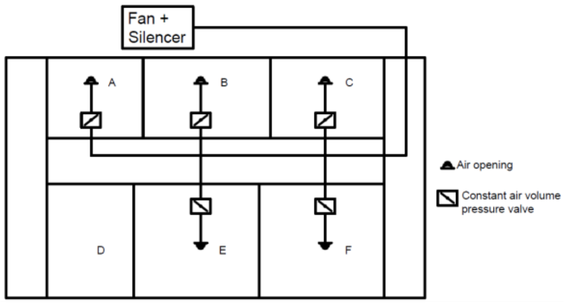


*Figure 7: Configuration 2 - conventional ductwork layout*

*Table 1: Design outputs before implementing silencers*

| | | Conf 1 | Conf 2 |
|---|---|---|---|
| **No silencers** | **Ductwork material cost (€)** | 4,217 | 4,541 |
| | **Fan energy cost (€)** | 9,817 | 10,519 |
| | **LCC (€)** | 14,034 | 15,060 |

For configuration 1, the noise level at the WC (i.e., D), due to the duct breakout, was already below the noise level constraint for the room (see Table 1). Therefore, there is no need for an additional silencer to attenuate the duct breakout noise. The noise levels exceeded the noise level constraints for all the other rooms in both configurations. Consequently, silencers are needed to attenuate the noise levels and achieve the desired noise constraint. Additionally, it is important to notice that for configuration 1, there might be additional silencers due to the cross-talk problem that might occur between neighboring rooms.

Using the simulation-based strategy presented in the method description section, the desired noise levels in all rooms were achieved for both ductwork configurations. Figure 8 and Figure 9 display the location of the silencers in each configuration. The necessary silencer sizes and the acoustic performance after sizing the flow-dependent silencers are presented in Table 2.

*Table 2: flow-dependent silencer sizes and acoustic performance in rooms, D is the diameter, H is the height, W is the width, L is the length, and IT is the insulation thickness*

| | Conf 1 | Conf 2 |
|---|---|---|
| **Noise levels in rooms [dB]** | **A: 36.4**<br>**B: 36.4** | **A: 36.0**<br>**B: 35.9** |

| | | |
|---|---|---|
| | **C: 36.1**<br>**D: 36.0**<br>**E: 35.6**<br>**F: 37.9** | **C: 35.9**<br>**D: -**<br>**E: 38.8**<br>**F: 36.7** |
| **Silencer sizes in rooms**<br>**[D [mm] x IT[mm] x L[m]]**<br>**or**<br>**[H[mm] x W[mm] x IT[mm] x L[m]]** | **A: 315x50x1.5**<br>**B: 315x50x1.5**<br>**C: 315x100x1**<br>**E: 0.5x100x1**<br>**F: 400x100x1.5** | **A: 315x50x1.5**<br>**B: 315x50x1.5**<br>**C: 315x50x1.5**<br>**E: 355x50x1**<br>**F: 500x100x1** |

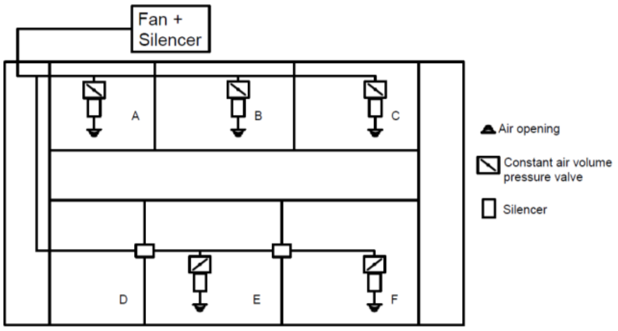


*Figure 8: Configuration 1 - ductwork design with silencers*

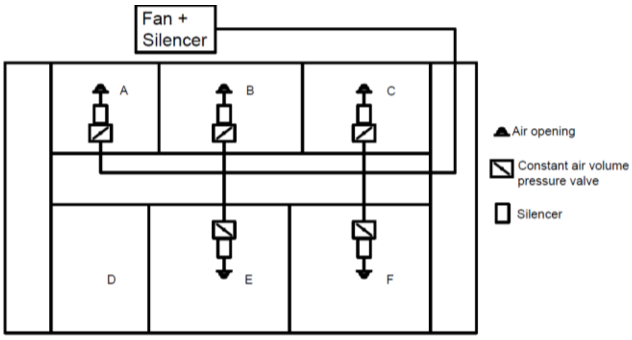


*Figure 9: Configuration 2 - ductwork design with silencers*

Following sizing the flow-dependent silencers, cross-talk (flow-independent) silencers are sized. To do so, the minimum attenuation needed for cross-talk silencers was estimated. From there, silencers were effectively sized at their minimal cost (see Table 3).

*Table 3: Minimum attenuation needed for cross-talk silencers and their suitable silencer sizes, D is the diameter, H is the height, W is the width, L is the length, and IT is the insulation thickness*

| | **Conf 1** |
|---|---|
| **Minimum TL [dB] For cross-talk silencers between rooms** | **A-B & B-C:**<br>[-, <0, <0, <0, <0, <0, -, -] |
| | **D-E:**<br>[-, 3.7, 6.3, 0.4, <0, <0, -, -] |
| | **E-F:**<br>[-, 2.3, 1.3, <0, <0, 12.7,-,-] |
| **Cross-talk silencer sizes between rooms**<br>**[D [mm] x IT[mm] x L[m]]**<br>**or**<br>**[H[mm] x W[mm] x IT[mm] x L[m]]** | **D-E:** 450x800x100x0.1<br>**E-F:** 400x50x0.5 |

After sizing all the silencers, the LCCs of the designs were updated, as shown in

Table 4. Although the desired noise levels were achieved for both rooms, there was an imbalanced influence on the cost for every design configuration after choosing the appropriate silencer design. For configuration 1, there was a 4.7% increase in the fan energy costs due to the cross-talk silencer (D-E) between the WC and PC room. This rectangular silencer with baffles increases the pressure drop in the system, and consequently, the fan energy usage and costs. On the other hand, there was no increase in fan energy cost for configuration 2, as all sized silencers have no baffles (once again, the pressure drop for silencers with no baffles is assumed to be negligible). Additionally, by comparing the two configurations, the silencer material costs in configuration 1 were 26.11% higher than in configuration 2. Apart from the differences in the silencer sizes and types between the two configurations, configuration 1 required two additional silencers (D-E and E-F) to solve the cross-talk noise issues (see Figure 8).

*Table 4: Design outputs after sizing the silencers*

| | | **Conf 1** | **Conf 2** |
|---|---|---|---|
| **With silencers** | **Ductwork material + silencer cost (€)** | 4,217 + 2,769 | 4,541 + 2,046 |
| | **Fan energy cost (€)** | 10,303 | 10,519 |
| | **LCC (€)** | 17,289 | 17,106 |

Overall, the LCC for configuration 1 was 6.8% lower than configuration 2 without considering acoustics and sizing the silencers. However, after sizing the silencers, this LCC became 1% higher. Although the LCC of Configuration 1 after sizing the silencer is only 1% higher, this percentage could significantly vary depending on the ductwork configuration design and the intended case for design (e.g., intended floor plan and room types). In this regard, it is crucial to incorporate acoustics performance and silencer designs at an earlier stage, i.e., before deciding on the final ductwork configuration. Such an approach is important not only to ensure acoustical comfort but also to achieve cost-effective designs.

Moreover, not ensuring acoustical comfort at an early stage can lead to other costly measures. To be more specific, for designs with acoustical discomfort, some retrofitting measures may apply, leading to additional unnecessary costs of the design and disruption in the building. Early consideration of silencer designs and acoustics performance can avoid the need for later expensive adjustments. For example, imbalanced ductwork design can result in the necessity of installing pressure dampers (e.g., variable air volume (VAV) or CAV valves) to balance the system [17], [18]. However, a lot of noise can be radiated due to closed valves. Consequently, this could be difficult and or more expensive to solve when the valves are placed inside rooms with stricter acoustic requirements. In this regard, one solution could be to place the valve in less stricter area (e.g., corridor). For configuration 2, it is possible to place the CAV valve in the corridor. On the other hand, it would not be possible for configuration 1 without adjustment in the layouts. Another solution is to modify the ductwork sizes and achieve as balanced system as possible. Yet, this solution may not be viable for VAV systems. Some rooms may demand high flow rates (there VAV valve is almost fully opened), while other rooms demand lower flow rates (the VAV valve is almost fully closed). Consequently, the closed VAV valve can be radiating high noises, regardless of the ductwork design sizes.

## Conclusion and future work

In conclusion, the main aim of this paper is to show the need for early consideration of acoustic performance and silencer design in ductwork design. As designing silencers can be challenging, especially with the absence of a standard guideline to optimally size silencers, we developed a basic aero-acoustical simulation-based design technique that is capable of efficiently designing silencers at minimal costs. By applying this strategy to a test case of two different ductwork configurations designed for the same floorplan of a university building, we successfully demonstrated the significance of acoustic performance and silencer design at an early stage. The test case findings showed that the ductwork configuration with the lower LCC without taking into account acoustics and silencer designs became more expensive after these factors were considered.

The results of this study also offer crucial insights for designers and engineers, highlighting the necessity of taking into account acoustic performance and silencer design from the outset of the design process to produce a cost-efficient and well-performed design.

Further work is anticipated to build on the findings of this paper to produce a holistic aero-acoustical simulation-based design strategy that can optimally design silencers in ductwork systems. This upcoming work can be summed up as follows:

- Ensure the optimal selection of silencers for sizing (see Method description section, stage 4)
- Include direct sound radiation from components that directly radiates high noises (e.g., CAV, and VAV valves)
- Considering the partial load behavior, so that the method is suitable for both CAV and VAV systems

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## Appendix A. Design configuration 1

BN represents the beginning node of the duct, and EN represents the end node of the duct

| BN* | EN* | H [m] | W [m] | D [m] | L [m] |
|---|---|---|---|---|---|
| 104 | 103 | 0.7 | 0.35 | 0.533 | 0.1 |
| 103 | 101 | 0.7 | 0.35 | 0.533 | 1 |
| 101 | 201 | 0.7 | 0.35 | 0.533 | 2 |
| 201 | 202 | 0.7 | 0.35 | 0.533 | 1.5 |
| 202 | 602 | 0.9 | 0.5 | 0.726 | 5 |
| 602 | 702 | 0 | 0 | 0.5 | 1 |
| 702 | 703 | 0.8 | 0.45 | 0.649 | 1.5 |
| 703 | 706 | 0.9 | 0.5 | 0.726 | 3.25 |
| 706 | 806 | 0 | 0 | 0.5 | 0.5 |
| 806 | 906 | 0 | 0 | 0.5 | 0.2 |
| 906 | 1006 | 0 | 0 | 0.5 | 0.5 |
| 706 | 707 | 0 | 0 | 0.4 | 3.25 |
| 707 | 709 | 0 | 0 | 0.45 | 3.25 |
| 709 | 809 | 0 | 0 | 0.355 | 0.5 |
| 809 | 909 | 0 | 0 | 0.355 | 0.2 |
| 909 | 1009 | 0 | 0 | 0.355 | 0.5 |
| 202 | 203 | 0.8 | 0.4 | 0.609 | 2 |
| 203 | 205 | 0 | 0 | 0.45 | 2 |
| 205 | 207 | 0 | 0 | 0.45 | 3 |
| 207 | 208 | 0 | 0 | 0.315 | 3 |
| 208 | 209 | 0 | 0 | 0.315 | 2.5 |
| 209 | 309 | 0 | 0 | 0.315 | 0.5 |
| 309 | 409 | 0 | 0 | 0.315 | 0.2 |
| 409 | 509 | 0 | 0 | 0.315 | 0.5 |
| 207 | 307 | 0 | 0 | 0.315 | 0.5 |
| 307 | 407 | 0 | 0 | 0.315 | 0.2 |
| 407 | 507 | 0 | 0 | 0.315 | 0.5 |
| 203 | 303 | 0 | 0 | 0.355 | 0.5 |
| 303 | 403 | 0 | 0 | 0.315 | 0.2 |
| 403 | 503 | 0 | 0 | 0.315 | 0.5 |

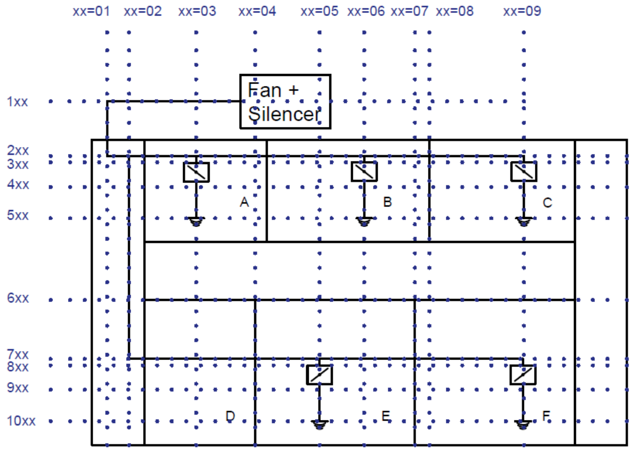


*Figure 10: Configuration 1 scheme, representing the beginning and end node for every duct in the ductwork system*

## Appendix B. Design configuration 2

BN represents the beginning node of the duct, and EN represents the end node of the duct

| BN* | EN* | H [m] | W [m] | D [m] | L [m] |
|---|---|---|---|---|---|
| 102 | 106 | 0.7 | 0.4 | 0.533 | 10 |
| 106 | 606 | 0.7 | 0.4 | 0.533 | 2 |
| 606 | 605 | 0.7 | 0.4 | 0.533 | 1 |
| 605 | 604 | 1 | 0.7 | 0.911 | 2.5 |
| 604 | 603 | 1 | 0.5 | 0.762 | 5.5 |
| 603 | 703 | 0 | 0 | 0.5 | 1 |
| 703 | 803 | 0 | 0 | 0.45 | 1 |
| 803 | 903 | 0 | 0 | 0.4 | 0.2 |
| 903 | 1003 | 0 | 0 | 0.355 | 0.5 |
| 603 | 601 | 0 | 0 | 0.355 | 5.5 |
| 601 | 501 | 0 | 0 | 0.355 | 1 |
| 501 | 401 | 0 | 0 | 0.315 | 1 |
| 401 | 301 | 0 | 0 | 0.315 | 0.2 |
| 301 | 201 | 0 | 0 | 0.315 | 0.5 |
| 603 | 503 | 0 | 0 | 0.4 | 1 |
| 503 | 403 | 0 | 0 | 0.355 | 1 |
| 403 | 303 | 0 | 0 | 0.355 | 0.2 |
| 303 | 203 | 0 | 0 | 0.315 | 0.5 |
| 604 | 704 | 0 | 0 | 0.5 | 1 |
| 704 | 804 | 0 | 0 | 0.5 | 1 |
| 804 | 904 | 0 | 0 | 0.5 | 0.2 |
| 904 | 1004 | 0 | 0 | 0.5 | 0.5 |
| 604 | 504 | 0 | 0 | 0.4 | 1 |
| 504 | 404 | 0 | 0 | 0.4 | 1 |
| 404 | 304 | 0 | 0 | 0.4 | 0.2 |
| 304 | 204 | 0 | 0 | 0.315 | 0.5 |


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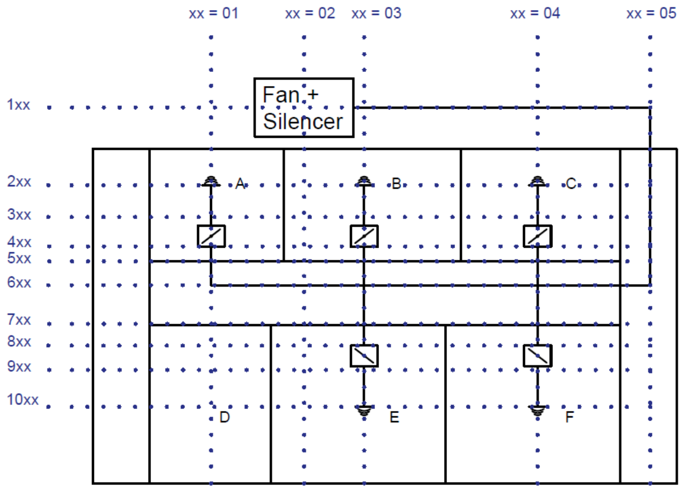


*Figure 11: Configuration 2 scheme, representing the beginning and end node for every duct in the ductwork system*


https://doi.org/10.26868/25222708.2023.1229