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Improving HVAC ductwork designs while considering fittings at an early stage

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Abstract

HVAC engineers are challenged to design air distribution systems with optimal performance while satisfying a long list of requirements, including maintaining the desired indoor air quality, thermal and acoustical comfort, minimizing energy usage, and life-cycle cost. One major part of the air distribution system is the ductwork system. The pressure drops in the ductwork system are vital to consider while designing it. Within this regard, fittings generate substantial pressure losses in the ductwork system. They frequently dominate the pressure drop in the ductwork system. Therefore, having the appropriate fitting design in the system is important to achieve a superior ventilation system. Due to the considerable impact of fittings on the pressure drop in the ductwork system, many associated studies have been conducted. Some of these studies intend to optimize the shape of the fittings to reduce their generated pressure drops. Other studies are devoted to accurately estimating the pressure drop generated from the fitting, as the current estimations using analytical equations can lead to deviations in estimating the pressure drop. However, efficiently sizing the fittings has not received enough consideration in the current design methods. To be more specific, the existing methods do not adequately account for sizing the fittings at an early design stage, which may result in an inefficient ventilation system. Therefore, a review is conducted in this paper to investigate how the existing design methods consider sizing their fittings and establish why considering them at an early design stage results in better-performing designs.

1. Introduction

1.1 Background:

Nowadays, there is a compelling need for high-quality air distribution systems that provide the desired Indoor Air Quality (IAQ) and achieve a healthy indoor environment. However, the performance criteria of an air distribution system go well beyond simply supplying and extracting enough air in a facility to create a healthy environment. It must always satisfy occupants by maintaining IAQ [1] while considering acoustical and thermal comfort and monitoring changes in demand conditions (caused, for example, by varying building occupancy and shifting weather conditions) [2], [3]. All this must also be accomplished using the least amount of energy possible by designing and operating energy-efficient systems. Energy-efficient air distribution systems are now a prerequisite to meet in order to achieve the minimum energy usage for buildings, as the share of the ventilation is up to 50% of the building's electricity consumption [4]. Achieving energy-efficient air distribution systems is crucial to realize a climate-neutral Europe by 2050 and fulfilling the European green deal [5].

For non-residential buildings, where the system complexity exceeds the typical 'all-in-one-box' solutions often available in dwellings, air distribution system design is typically conservative and inefficient. Due to the absence of a standard benchmark that can guide engineers to result in a well-designed air distribution system, HVAC engineers are challenged to design and operate air distribution systems with a high standard of performance concerning IAQ, comfort (e.g., acoustical and hygrothermal), and the other features related to the ventilation system [6]. The challenges increase further with the current urge to achieve a healthy indoor environment, reduce energy usage, and avoid excessive material to diminish greenhouse gas emissions and contribute to climate change [7], [8]. Additionally, all this has to be achieved within a limited budget and time.

Ductwork has a large impact on the performance of an air distribution system. Therefore, an effective ductwork design is a prerequisite to the efficient performance of the air distribution system. A well-designed ductwork system must be able to extract and supply the desired loads (i.e., conditioned airflow rates) from and to the ventilation zones while respecting the restrictions on all features affected by design, e.g., limited dimensions of ducts due to the restriction in the available building space (false ceiling). On the other hand, poorly designed ductwork can result in an underperforming system that cannot achieve the IAQ and comfort in the desired zones. Additionally, there can be excess energy usage due to the increase of pressure drops and installation of excessive ductwork material, which increase the life cycle cost (LCC) [9], [10].

1.2. Fittings' impact on the pressure drop

The ductwork includes ducts (i.e., rectangular and circular), fittings (e.g., Tees, bends, transitions, and cross-overs), and additional decentral components (e.g., heating coils and silencers) to achieve a well-performed system. Pressure losses in the ductwork are caused by the conversion of mechanical energy into thermal energy. There are two distinct forms of pressure losses in duct systems: Friction pressure losses and local pressure losses. Friction pressure losses result from the air rubbing against the duct walls or the viscous interaction between sections of the air stream flowing at different speeds [11]. Local pressure losses are a result of changes in the air stream's area, which might happen due to changes in the duct's area (e.g., due to a transition fitting) or changes in the air stream's direction (e.g., due to a bend or a branched junction) [12], [13].

Fittings, which generate local pressure drops, significantly impact the pressure drop in the ductwork system [14]. Contrary to pipework, the ductwork pressure drops incurred by fittings are frequently the dominant factor in the system [15]. Their impact on the pressure drop could be more significant than equipment components (i.e., silencers) [16]. Usually, the higher the impact on the pressure drop, the higher the effect on the aeraulic and acoustical performance of the system [3]. A higher pressure drop in the ductwork system leads to higher energy usage from the fan, as the fan energy usage is directly proportional to the pressure drop. The designer needs to realize the impact of the pressure drops on energy usage and the overall performance of the HVAC system.

1.3 Problem formulation

Due to the significant impact of the fittings on the pressure drop, hence, the system performance, much research has been dedicated to develop optimized fitting shapes [13], [17]–[19]. The optimization is mainly to reduce the pressure drops in the fittings and, therefore, in the ductwork, to ensure energy-efficient utilization and reduction in energy usage. This is accomplished by adjusting the geometry of the airflow region, smoothing the boundary surfaces, and profiling the channel walls following the shapes of the flow zones [13]. Recently, Zhang et al. [20] reviewed some methods that optimize the Tees and elbows (i.e., bends) with a guided vane while changing the radius and or the curvature of the guide vane (e.g., [21]) and proposed a further reduction of resistance by changing the leading and the trailing edge of the guide vane for an elbow. Other approaches to reduce the pressure drops in fittings include the installation of a wedge-shaped drag reduction component with suitable height [22] and unique profiling components [23].

Furthermore, numerous researches have been devoted to investigate the accuracy of the pressure loss prediction in fittings using computational fluid dynamics (CFD) simulations and experimental measurements [18], [22], [31], [23]–[30]. Without reliable pressure drop values, sizing the ductwork becomes difficult and may not result in a well-performed or cost-effective system. Additionally, knowing the pressure drop in the design phase is vital to design balanced systems that can effectively deliver air between ventilation zones, whereas improperly balanced systems causes poor ventilation in zones [32], [33]. For fittings, however, the existing guides (e.g., CIBSE and ASHRAE) do not include all the databases for duct fittings used in the ductwork. Therefore, this shortage in the database requires designers to use intelligent guesses of the pressure drops for these fittings during their design calculations [34]. In addition to not having the database for all the fittings used in ductwork, the estimation of the pressure losses from fittings can also differ depending on the guidelines followed [15], [34], [35], leading to discrepancies in the pressure drop estimation. Furthermore, many studies have reported that the pressure loss between two or more interactive fittings is less than between two or more similar individual fittings. However, the percentage decrease depends on the arrangement and combination of the fittings [36]–[38]. This indicates that the pressure loss across many closely installed fittings determined by adding the pressure losses across individual fittings, as supplied in the CIBSE guide and the ASHRAE handbook, is overestimated. Within this regard, research attempts are engaged to develop numerical CFD models to accurately determine pressure drops from fittings and the combination of fittings [38]–[40].

Although the abovementioned studies realize the importance of (properly designed) fittings in a ductwork system, insufficient attention has been paid to incorporate those insights into the overall design methods. The current design methods poorly consider sizing the fittings at an early design phase, which may lead to an inefficient ventilation system due to their significant impact on the pressure drop in the system. Therefore, this paper aims to review how fittings are sized in the current design methods, highlight the shortcomings of sizing fittings in both literature and practice, and emphasize how considering fittings at an early design stage may lead to improved designs.

2. Numerical estimation of pressure drops in fittings

Before highlighting how the current design methods consider fittings in the design phase, it is vital to understand their pressure drop numerical estimation and underscore some confusion that may lead to wrong assessments.

Pressure drops, Δp *[Pa]*, from fittings can be numerically calculated by implementing Equation 1.

$$\Delta p = \rho \zeta \frac{v^2}{2} \qquad \text{Equation 1}$$

$$Area = \frac{Aiflow\ rate}{v} \qquad \text{Equation 2}$$

- *ζ [dimensionless] is the pressure loss coefficient for the specific fitting*
- *ρ [Kg/m^3] is the density*

- *v [m/s] is the velocity, which can be estimated by implementing Equation 2. In the design phase, the airflow rate in every section is constant. Therefore, the design velocity varies while variating the area.*

As stated before, the pressure loss coefficient can be determined from existing databases available in the guideline resources. However, to numerically estimate the pressure drops from fittings, it is vital to distinguish which velocity (i.e., inlet or outlet velocity) should be referred to in Equation 1. Referring to the proper velocity depends on the fitting type and on which resource is chosen to determine the pressure loss coefficients (e.g., SMACNA, ASHRAE, Idelchik). For bends, Inlet and outlet velocities are equal for fittings with equal inlet and outlet areas. Thus, either inlet or outlet velocity can be referred to while estimating the pressure drop. For transitions, i.e., fittings with unequal inlet and outlet areas and velocities (e.g., reducer), referring to the correct velocity highly depends on the resource used to determine the friction coefficient. For instance, by using the pressure loss coefficients in a transition from ASHRAE, outlet velocity for supply systems and inlet velocities for extraction should be referred to, no matter which of the velocities is higher [41]. On the other hand, for SMACNA [42], the upstream velocity should be referred to, if the upstream area is smaller than downstream area. On the other hand, the downstream area should be referred to, if the downstream area is smaller than the upstream area. Nevertheless, all sources, apart from ASHRAE, agree that the pressure loss coefficients for junctions (i.e., Tees, Wyes) are based on the velocity pressure of the combined flow [15] (see Figure 4).

3. Fittings consideration in the existing design methods

Presently, ductwork design is not a purely scientific endeavor but rather a work of art. Engineers could design different duct systems for the same conditioned space, with varied duct layouts and sizes [43]. This variation in design configuration is due to the absence of a standard method that can optimally design an air distribution system. Currently, numerous approved design methods are available [9], [44] that can be used to design the air distribution system. However, every designed system's balancing, performance, and cost-effectiveness could differ depending on the chosen design method. Thereby, the doubt of which duct design method is the most optimal for the same conditioned space arises. All the current design methods share the same problem of poorly accounting for fitting sizing at an early stage. They cannot correctly recognize the appropriate pressure drop reward that can be achieved due to changing the fittings inlet and or outlet sizes. Identifying the proper pressure drop reward by optimally sizing the fittings contributes to a well-performed, balanced, and cost-effective ductwork system. A literature study is undertaken to understand how the current design methods consider sizing fittings in the design process and how that would affect the performance of their intended system.

Generally, the current design methods can be divided into two main categories: conventional non-optimization methods, which are the commonly used methods in practice, and optimization methods.

3.1 Conventional methods (Non-optimization)

The traditional non-optimization methods are equal friction, velocity reduction, equivalent length, and static regain. Some of these methods are integrated into common design tools such as Revit [45]. All these methods make assumptions on the variables based on the design engineer's experience and recommendations from guidelines [6], [9], [44], e.g., airflow velocity and friction losses, given a fixed design flow rate at nominal conditions for every demand zone. Sizing the ductwork is applied from the assumed variables and the estimated design flow rate in every section. Although the methods are straightforward, they hardly obtain a balanced design system [46]–[48]. Moreover, the resulting designs do not consider prevailing local economic conditions. In other words, the developed designs are usually conservative and inefficient, where they are workable but not necessarily optimal in terms of investment and operational costs [6], [49].

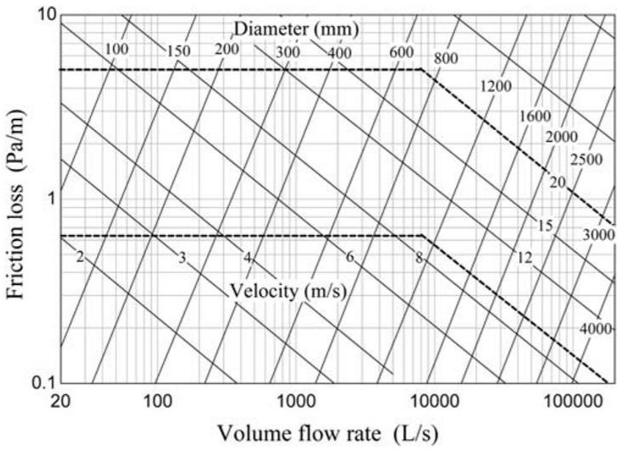


Figure 1: The variation of friction loss as a function of volume flow rate (SI units) [9]

The equal friction and velocity reduction methods are the most straightforward methods compared to the others [6]. Generally, they are also the most commonly used methods in practice to design air distribution networks. In the equal friction method, the ductwork sizing starts by specifying the friction loss per unit length recommended by the guidelines for every section. The duct size is determined so that it yields to the specified friction loss per unit length (for example, by using Figure 1). In the velocity reduction method, velocities recommended by the guidelines are adopted for the duct sections [9], [41], [50]. Duct sizes are estimated by implementing Equation 2. In both methods, fitting inlet and outlet sizes are then inherited from its surrounding ducts. Herewith, fitting sizing may not be ideal, as the recommendation was given to duct sizing regardless of its surrounding fitting type.

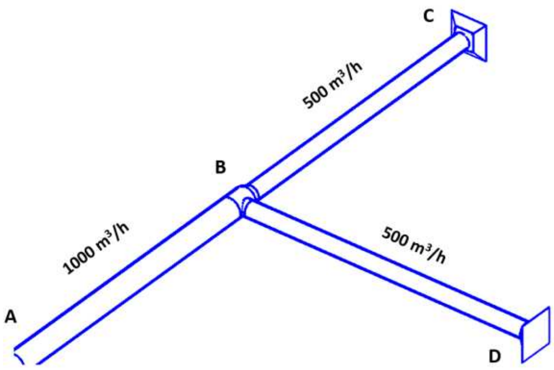


Figure 2: Simplified supply ductwork system

To clarify, consider the simplified example of the supply ductwork system presented in Figure 2. In this example, both BC and BD are terminal ducts with the same length and design airflow rate. By using either the equal friction or the velocity reduction method, the two ducts (i.e., BC and BD) would, generally, have the same recommendations and thus result in the same duct sizes (see sizing 1 in Table 1). However, by having the same sizes, the branched part of the Tee at B would inevitably generate a higher pressure drop than its straight part. By referring to Table 1 – Sizing 1, the pressure drop in section BD is more than two times higher than the pressure drop in section BC. This difference in pressure drops would lead to an imbalanced system. Imbalances would accumulate further, considering a ductwork system with more fittings. Nevertheless, while accounting for the fittings at an early design phase, a more balanced design can be recognized. To demonstrate this, we developed the design configuration presented in Table 1 - Sizing 2. By referring to the sizes in Table 1 - Sizing 2, the pressure drops in sections BC and BD were almost the same, leading to a better-balanced system.

Table 1: Design outputs of the simplified ductwork system

	Section	**Element**	**Type**	**Flow**	**Inlet size**	**Outlet size**	**Length**	**Inlet velocity**	**Outlet velocity**	**Total Pressure Loss**	**Section Pressure Loss**
Sizing 1	AB	Duct	Circular	1000 m^3/h	315 ø mm	315 ø mm	5 m	3.6 m/s	3.6 m/s	2.3 Pa	2.3 Pa
		Fittting	-		-	-	-	3.6 m/s	3.6 m/s	-	
	BC	Duct	Circular	500 m^3/h	200 ø mm	200 ø mm	5 m	4.4 m/s	4.4 m/s	5.95 Pa	7.66 Pa
		Fittting	Straight Tee		315 ø mm	200 ø mm	-	3.6 m/s	4.4 m/s	1.71 Pa	
	BD	Duct	Circular	500 m^3/h	200 ø mm	200 ø mm	5 m	4.4 m/s	4.4 m/s	5.95 Pa	16.45 Pa
		Fittting	Branched Tee		315 ø mm	200 ø mm	-	3.6 m/s	4.4 m/s	10.5 Pa	
Sizing 2	AB	Duct	Circular	1000 m^3/h	355 ø mm	355 ø mm	5 m	2.8 m/s	2.8 m/s	1.3 Pa	1.3 Pa
		Fittting	-		-	-	-	2.8 m/s	2.8 m/s	-	
	BC	Duct	Circular	500 m^3/h	200 ø mm	200 ø mm	5 m	4.4 m/s	4.4 m/s	5.95 Pa	7.58 Pa
		Fittting	Straight Tee		355 ø mm	200 ø mm	-	2.8 m/s	4.4 m/s	1.63 Pa	
	BD	Duct	Circular	500 m^3/h	250 ø mm	250 ø mm	5 m	2.8 m/s	2.8 m/s	2.05 Pa	7.75 Pa
		Fittting	Branched Tee		355 ø mm	250 ø mm	-	2.8 m/s	2.8 m/s	5.7 Pa	

Often for further simplification of the ductwork design problem, the equivalent length method is typically utilized in residential buildings [51]. The method assigns a value for every fitting type that is equivalent to a straight duct length with an equivalent pressure drop [52]. Depending on the fitting, equivalent lengths are numerical values that can be found in the appendices of the ASHRAE or ACCA manuals [44], [49], [51], [53]. However, the equivalent length values are conservative to favor oversizing the fan to achieve all the desired airflows of the system [49]. Oversizing the fan causes less efficient fan operation, which increases energy usage and cost while also decreasing fan reliability [54].

The static regain method is generally more complicated than the abovementioned methods [55]. It aims to maintain the same static pressure whenever the branch duct diverges (i.e., whenever a junction occurs). This process is achieved by changing the area in the section downstream from the junction, resulting in decreasing the velocity pressure along the flow path. By this, the total pressure decreases due to the frictional losses. However, the static pressure is regained by reducing the velocity pressure. This process is graphically represented in Figure 3, where the static pressure variation follows the bottom curve line of the graph. The static pressure, $\Delta P_{stat_{1-2}}$, increase due to the decrease in duct velocity from 1 to 2. With this, a regain factor, *R [dimensionless]*, is introduced to consider the energy loss while converting the kinetic energy (i.e., velocity pressure) to potential energy (i.e., static pressure) [47], [50]. By using the Bernoulli equation for steady, incompressible, and frictionless streamline flow, the static pressure losses, $\Delta P_{stat_{1-2}}$ and $\Delta P_{stat_{2-3}}$ can be estimated using Equation 3 and Equation 4, respectively.

$$\Delta P_{stat_{1-2}} = R\frac{\rho}{2}(V_1^2 - V_2^2)$$ *Equation 3*

$$\Delta P_{stat_{2-3}} = \frac{\rho}{2}V_2^2(\zeta_{2-3} + \left(\frac{fL}{D}\right)_{2-3})$$ *Equation 4*

With,

- *f [Pa / m] being the friction factor*
- *D [m] is the duct diameter*

Obtaining the same static pressure at 1 and 3 is achieved by equating Equation 3 and Equation 4, resulting in Equation 5

$$V_2\left(\zeta_{2-3} + (fL)_{2-3}\sqrt{\frac{\pi V_2}{4Q_2}} + R\right) - RV_1^2 = 0$$ *Equation 5*

With,

- *Q [m^3/s] is the airflow rate*

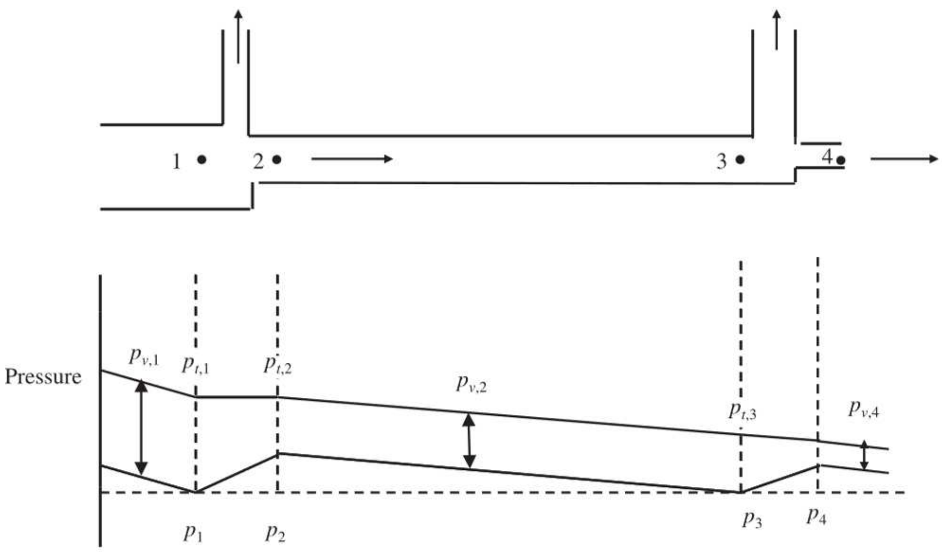


Figure 3: Example representing the pressure distribution for static regain design, where P_t is total pressure, P is static pressure, and P_v is dynamic pressure [9]

Ideally, designing the system so that the static pressure is equal at each diverging junction cuts down the additional flow resistance and can presumably balance the system [9], [47]. This method first selects the velocity in the main supply section. Selecting the velocity sets the initial velocity pressure and the duct size for the main section. From there, by solving for V_2, the outlet area can be known using Equation 5. In the classical static regain method [41], [44]. R-values between 0.5 and 0.95 are used. However, Tsal and Behls [55] illustrate that there is an uncertainty in R prediction due to the splitting of mass at junctions, and the dynamic losses between junctions are insufficiently regarded. Thus, the authors concluded that “the classical static regain method using an R-factor should not be used since R is not predictable” [41], [47]. Tsal and Behls [55] used the energy equation to develop an expression for the static pressure to tackle the unpredictability issue of the R-factor. Only two junction nodes were included in the applied energy equation. Mathews et al. [46] find that using the energy equation between only two junction nodes is biased and an ineffective alternative and suggested applying it on an appropriate control volume. The latest proved, on a proper control volume, that the energy equation's application does not provide an explicit expression for the static pressure regain across a junction, in contrast to Tsal and Behls' findings. Another problem with the static regain method is the unverified claim that equal static pressure at consecutive junctions can guarantee equal flows in identical branches [47], [55]. Mathew et al. showed that when equal flows are required, the total pressure balancing is violated irrespective of the static pressures. Yet, equal static pressure before junctions does not directly relate to the balancing problem [47], [56].

3.2 Optimization methods

Since the 1960s, much research has been dedicated to developing a design optimization of air distribution systems [57]–[59]. The design optimization objective mainly intends to minimize the life cycle cost [59]–[61]. Among many computer-aided numerical optimization methods utilized for ductwork optimization are the Reduced Gradient [62], Quadratic Search, and Modified Lagrange multiplier [6], [63]. Since all these methods are continuous, they cannot effectively handle discrete characteristics like nominal duct sizes. Although, if the continuous design outputs do not match the nominal sizes, they can be rounded to match the upper or the smaller nominal size. However, this may deviate the design from the optimization as fittings pressure drops can change significantly while slightly changing their inlet and/or outlet sizes.

The most widely known design optimization method is the T-method [6], [59], [64], which also optimizes the sizing of the ductwork based on dynamic programming [6]. Its procedure consists of system condensing, fan selection, and system expansion. At each phase of the calculations, the goal is to minimize the objective function, i.e., LCC. The method starts with system condensing. This process reduces a multiple-part duct system to a single hypothetical duct section with the same hydraulic properties and ownership cost as the full system. According to Tsal et al. [11], [59], Equation (1.41) in [59] allows for the replacement of two or more converging or diverging sections and the common section at a junction with a single condensed section. Each supply and return system can be combined into a single section by using this equation from junction to junction in the direction of the root section (fan) (a single resistance). After condensing the ductwork into a single hypothetical duct (i.e., condensed system), the optimum fan pressure is calculated and used to size the fan. Finally, the system is expanded to distribute the available fan pressure throughout the system. Contrary to the system condensing, the expansion process begins at the root section and moves toward the terminals. Mathews and Claassen [46] find that optimizing the duct network fails while applying the T-method on sections with junctions or crosses. Due to misreferring the ζ-coefficients in the design process to the belonging section.

Asiedu et al. [60], [65] developed a design method based on a segregated genetic algorithm (SGA), and Fong et al. [66], [67] used a non-revisiting genetic algorithm (NrGA) and non-revisiting particle swarm optimization (NrPSO). For these methods, the design method starts by sizing the ducts then the fittings inherit their inlet and outlet sizes from their surrounding ducts, similar to equal friction and velocity reduction methods (Section 3.1). Crossover and mutation are applied to one or more randomly selected sections to optimize the design without justifying why the picked duct section (gene) for a change (either by mutation or crossover) is more effective than any other section. Overall, the methodology proved its effectiveness on a small test case with few fittings. However, it is more likely to be trapped in a local optimum when dealing with more extensive test cases, e.g., conventional systems (further explained in the next paragraph). Recently, Jorens et al. [6], [48], [68], [69] developed an air distribution network design (ADND) optimization algorithm, which focuses on optimizing the layout and sizes of the ductwork. For duct sizing, the method used a local search heuristic method, with a steepest-descent-mildest-ascent strategy as an optimization move strategy. This strategy is supposed to achieve the best possible improvement and least possible deterioration, of the optimization objective (i.e., minimizing the ductwork material costs), in every move (i.e., change of duct size). The method gradually reduces duct sizes, starting with the largest duct until a maximum fan pressure constraint is surpassed. The size of each duct is then gradually increased until the maximum pressure constraint is met, starting with the smallest ducts for this stage. At an early phase of the algorithm [69], it was assumed that the fittings losses were negligible. For this, the previous steepest-descent-mildest-ascent approach proved to be effective. However, later, by considering the fittings in the design process [68], to make the design method closer to practice, the approach of gradually decreasing the sizes of the largest ducts and then increasing the sizes of the smallest ducts might not be ideal.

Selecting which section is the most ideal for a change, whether by mutation, crossover, or local search, is important to maximize the optimization potentials. However, the ideal selection would highly depend on the surrounding fittings of the selected duct section for optimization. Some fittings' pressure drop can significantly change by simply changing one of their inlet or outlet size. For example, considering the fittings in Figure 4, there is a considerable difference in pressure drops generated by the two fittings while only changing one size. In the Tee case, the pressure drop change (i.e., 11.25 Pa) due to a change in its inlet size was relatively 16.5 times higher than the pressure drop change that occurred by changing the inlet size of the transition. Thus, the branched part of the Tee fitting is considered sensitive since its pressure drop changes considerably by varying only one of its sizes (inlet or outlet). On the other hand, the transition is regarded as a non-sensitive fitting, as its pressure drop slightly changes while changing one of its sizes. The significant change in pressure drop means reaching the pressure constraints with fewer optimization moves, i.e., fewer size optimization changes in duct sections. This may, therefore, trap the design optimization potentials in a local optimum. Within this regard, while choosing which section to optimize (i.e., change in size for improved objective) in the ductwork system, it is crucial to account for the surrounding fittings for every duct section.

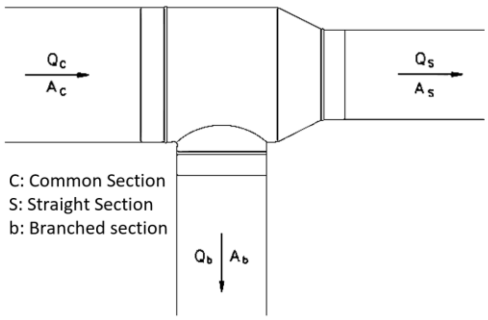
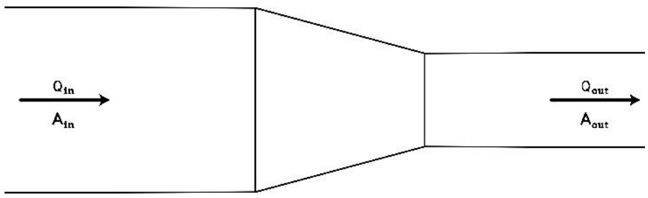
Branched Tee (SD5-9 Tee, Diverging [50])			Reducer (SD4-1 Transition, Round to Round, Supply Air Systems [50])		
					
Din [mm]	Dout [mm]	Pressure drop [Pa]	Din [mm]	Dout [mm]	Pressure drop [Pa]
315 ø	0.2 ø	30.75	0.4 ø	0.315 ø	0.6
355 ø	0.2 ø	19.5	0.355 ø	0.315 ø	1.28

Figure 4: Variation of fittings pressure drops while changing their inlet size

4. Test case

To realize the importance of considering fittings at an early design stage, we demonstrated a simplified supply ductwork test case established in Figure 5. This test case aims to compare the design configurations generated using the two most conventionally used design methods, i.e., equal friction and velocity methods, and a design configuration that we developed while focusing on appropriately sizing every existing fitting in the system. We used the trial and error approach in the latest design method to result in the best possible design configuration. The trial and error approach is accomplished by, first, assessing the performances of all possible fittings sizes. Then, searching for the most appropriate sizes between all the possible sizes. With this test case, we aim to compare the three generated design configurations based on the balancing criteria and the LCC, which, for this paper, includes the ductwork's material, installation, and fan energy costs.

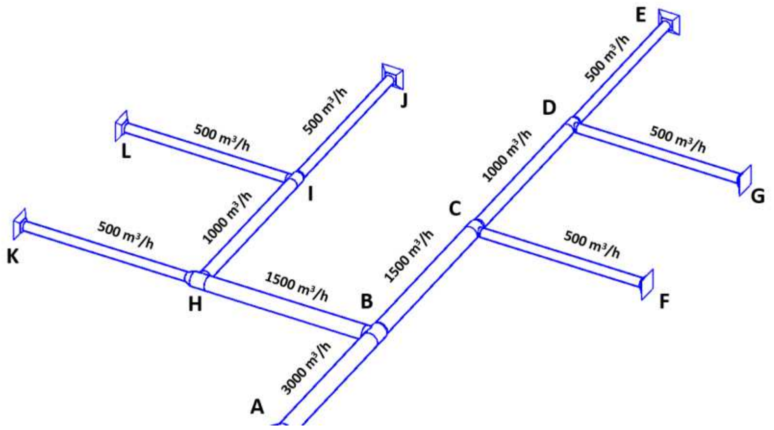


Figure 5: Simplified ductwork example

The design airflow for every terminal is 500 m^3/h, and the length of every duct is 5 m. Paths [A; E] and [A; L] consist of exactly the same duct types. The design configurations are generated by respecting the guideline's recommendations for every duct section. To commit to the size standards, the design size for every duct section is rounded to the closest duct size standard. The output sizes of the three generated design configurations are established in Appendix A.

4.1. Aeraulic assessment: Implementation on Revit

The pressure drop calculations were made using Revit software . The pressure drop assessments behind the software are made as follows:

The pressure drop in ducts was estimated using Darcy-Weisbach Equation:

$$\Delta p = f \frac{L}{D_H} \rho \frac{v^2}{2} \quad \text{Equation 6}$$

With,

- *L [m] is the length of the duct,*
- *D_H [m] is the hydraulic diameter,*
- *ρ [Kg/m^3] is the air density (assumed to be 1.2 Kg/m^3),*
- *V [m/s] is the air velocity,*
- *f [] is the friction factor, estimated using Cole-brook white equation:*

$$\frac{1}{\sqrt{f}} = -2\,log\,(\frac{\epsilon}{3.7D_H} + \frac{2.51}{Re\sqrt{f}}) \quad \text{Equation 7}$$

- *ϵ [m] is the roughness of the duct (assumed to be 1.5 x 10^{-4} for galvanized-steel ducts)*
- *Re is Reynold's number, estimated using* Equation 8

$$Re = \frac{\rho v D}{\mu} \quad \text{Equation 8}$$

- *μ [] is the fluid viscosity (assumed to be 1.562 x 10^{-5})*

The pressure drop in fittings are estimated using Equation 1. the pressure loss coefficient values are looked up in the fitting database of ASHRAE according to their type, inlet and outlet size and airflow rate.

Revit estimates the pressure drop at every path as the summation of the pressure drops for every individual component associated with the path. This means that Revit computes the pressure drop for each component individually, then add them up to have the total pressure drop for the entire path.

4.1.1. Equal friction and Velocity methods

For the equal friction method, the first (and only) design parameter to choose is the friction loss per unit length for the duct sections. Once the friction loss parameters have been established, Revit automates the duct sizing process. Similarly, for the velocity method, in which the user chooses the velocity in each duct section, Revit automates the design process as necessary.

The chosen friction factor was 0.6 Pa/m for the equal friction method. For the velocity method, the chosen velocities were 5 m/s and 3 m/s for main duct sections (AB, BC, and BH) and branched duct sections, respectively. Once again, these values are typically chosen according to the design engineer's experience or rules of thumb. In this example, the chosen values are based on the recommendations by the guidelines [9], [44], [70].

It is also important to note that these input parameters (i.e., friction factor and velocities) might not be the exact same in the final design. This is because duct sizing can only be done in discrete, standardized sizes. Therefore, there may be variations when the duct size is rounded to the closest discrete value.

4.1.2 Designing while considering fittings at an early stage

Unlike the previous methods, the ductwork is now not sized based on assumed values for the velocity or pressure loss per meter. Instead, the impact of each duct section (i.e., duct and it surrounding fittings) on the total life cycle costs (i.e., material, installation and energy costs) is used as incentive to size the ductwork. As there is currently no method that takes into account the impact of fittings on the life cycle costs, trial and error will be used to size the ductwork.

In ductworks, adjusting the duct-section size (i.e., duct size and its surrounding fittings sizes) can influence the fan energy cost, as the designed pressure drop in the ductwork system is changing. It also influences the ductwork material and installation cost, as the size of the installed duct is changing. Yet, it is important to notice that the energy costs and material and installation costs are conflicting. To be more specific, decreasing the duct and its surrounding fittings sizes increases the pressure drop, and thus, the fan energy costs, but decreases the material and installation costs, and vice versa. Nevertheless, it is vital to mention that the fan energy cost is only affected by the pressure drop at the critical path (See Equations 9 and 10), where the critical path is the path with the highest design pressure drop among all the other paths in the ductwork system. Thus, the other paths can be referred to as non-critical paths. To achieve a balanced ductwork system, the other paths (i.e., non-critical paths) would require additional pressure drop (e.g., using balancing dampers) so that their design pressure drop is equal to the pressure drop at the critical path. With that being said, the LCC of the duct-sections (i.e., ducts and their surrounding fittings) in the critical paths would include the fan energy costs along with the ductwork material and installation costs. On the other hand, the LCC of the duct-sections in the non-critical paths would only include the ductwork material and installation costs, without including the fan energy costs.

For this reason, we opt to start our sizing with the duct sections at the critical path. As path [A;L] was the critical path for both the velocity and equal friction method, it is assumed that path [A;L] is most likely to be the critical path. Second, all duct sections in the critical path are dimensioned, starting with the duct section located most upstream (i.e., section [A;B]). For every duct section, the LCC of all feasible combinations of sizes (i.e., combination of duct and fittings sizes) are calculated, and the combination with the lowest LCC is selected. To limit the number of combinations, and thus the computation time, a constraint is imposed on the allowed velocity, i.e., the velocity should be between 2 and 5 m/s. Once the duct-sections' sizes are optimized, they cannot be changed anymore.

After sizing the duct-sections at the critical path, we can determine the path's pressure drop (i.e., the pressure drop that influences the fan energy cost). This pressure will also be set as a constraint to size the noncritical paths. Similar to the critical path, the combination of duct and fittings sizes with the lowest LCC will be selected for each duct section, starting with the most upstream section. However, the duct section cannot be part of the critical path. For example, for path [A;F], section [B,C] will be sized first. Moreover, the LCC includes only the material and installation costs and not the energy costs.

4.2. LCC assessment

For this paper, the LCC of the designed ductwork system includes the ductwork material, installation, and fan energy costs. The ductwork's material and installation costs are estimated according to the price list that is averaged according to several Belgian engineering companies (see Appendix B).

Ductwork material costs are only due to the ducts and fittings in the system. Any other component that might be included in the ductwork system (e.g., diffuser or silencers) was not included in the material cost estimations.

Energy costs over the life cycle can be estimated using the following simplified expression (Equation 9).

$$E_p = P_e . E_c . T . PWEF \qquad \text{Equation 9}$$

With,

- *P_e is the fan power [KWh]*
- *E_c is the energy cost [€/KWh]*
- *T is the operation time in the year [hours/year]*
- *PWEF is the present worth escalation factor [dimensionless], which can be estimated using Equation 11*

To assess energy fan power of the designed ductwork system, the following equation is used:

$$P_e = \frac{Q_{fan} \cdot p_{fan}}{10^3 \eta_m \eta_f} \qquad \text{Equation 10}$$

With,

- *η_m being the motor efficiency of the fan [dimensionless]*
- *η_f is the shaft efficiency [dimensionless]*
- *Q_{fan} is the total demand airflow rate [m^3/s]*
- *p_{fan} is the fan's total pressure (i.e., only due to ducts and fittings in the system), which is also equivalent to the total pressure drop at the critical path [Pa]*

$$PWEF = \begin{cases} \dfrac{[\frac{1+J}{1+I}]^a - 1}{1 - \left[\frac{1+I}{1+J}\right]} & if \ \ I \neq J \\ a & if \ I = J \end{cases} \qquad \text{Equation 11}$$

With,

- *J is the escalation rate per year [dimensionless]*
- *I is the annual interest rate [dimensionless]*
- *a is the amortization period [years]*

The assumptions made for this test case can be summarized as follow:

- The system is operating at a constant airflow rate
- The operation time is 4380 hours / year
- The amortization period, *a*, is 20 years
- *I = J*, therefore, *PWEF = a = 20 years*
- $\eta_m = 0.8$ *and* $\eta_f = 0.75$
- $E_c = 0.4$ € / KWh

For this test case, the fan energy costs were only based on the pressure drops generated from ducts and fittings. Pressure drops that might be generated from other components in a ductwork system were not included.

Table 2: Test case cost outputs

	Equal friction method	Velocity method	Design considering fittings at an early stage
Ductwork material cost (€)	3025	3150	3175
Fan energy cost (€)	2672	1852	1280
LCC (€)	5697	5002	4455

Table 2 represents the associated costs of the three design configurations. The ductwork material costs were at their lowest for the design configuration designed using the equal friction method. The material costs, resulting from the design configurations using the velocity method and the design considering fittings at an early design stage, were higher by 4.1% and 5 %, respectively. Although the ductwork material costs were slightly higher in the latest two designs, the fan energy costs were much lower. While considering fittings in the early design phase, the fan's energy costs were lower by 52% and 30% compared with the fan's energy costs for the generated ductwork configurations using the equal friction and velocity method, respectively. The low fan energy cost compensated for the higher ductwork material costs. With this regard, the LCC was also 21.8% and 10.9% lower for the design configuration considering fittings at an early stage than it was for the configurations using the equal friction and velocity methods, respectively.

4.3. Balancing assessment

To comprehend which design is more balanced, we introduced the mean balancing percentage for non-critical paths in every design, where the critical path is, again, the path with the highest pressure drop. The mean balancing percentage is estimated using the following equations:

$$Mean\ balancing\ \% = \frac{\sum_{n=1}^{n=N} Balancing\ \%\ in\ path\ n}{N} \quad \text{Equation 12}$$

$$Balancing\ \% = \frac{Pressure\ drop\ in\ the\ path}{Pressure\ drop\ at\ critical\ path} \times 100 \quad \text{Equation 13}$$

With

- *n being a non-critical path*
- *N is the total number of non-critical paths*

The *Balancing %* is directly proportional to the *Mean balancing %.* Ideally, the *Balancing %* in every path and, consequently, the mean *Balancing %* should be as high as possible. Suppose the *Balancing %* is low in any path. In that case, a balancing damper is needed to generate a higher pressure drop in the paths having shortages in their pressure drops (i.e., pressure drop in the path < pressure drop at critical path). The low *Balancing %* in the path requires a higher pressure drop from the balancing damper in the path to achieve a balanced system. High pressure drops generated from dampers may transmit high noise levels, leading to acoustical discomfort. Even though the high noise levels might be tolerated by installing silencers, this would increase the system's investment cost. Moreover, considering a real-life ductwork system, the air balancing by changing the damper positions is a long-iterative and time-consuming process. To specify, changing the position of one damper in the system alters the airflow rate, not only in the branch which the damper controls but also in all other branches in the system. Consequently, it is very unlikely to set any damper to achieve a balanced system (i.e., the correct airflow rates at terminals) without several iterations [71]. Thereby, a low *Mean balancing %* denotes a low *Balancing %* in the paths. Correspondingly, the balancing process could be even more time-consuming for the installers.

By referring to Table 3, the mean balancing percentage increased by roughly 25-26% in the design configuration while considering fittings in comparison with the other two conventional design methods (i.e., equal friction and velocity methods).

Table 3: Paths' pressure drops and balancing % for the three generated design configurations

	Equal friction method		**Velocity method**		**Considering fittings**	
Paths	PD [Pa]	Balancing %	PD [Pa]	Balancing %	PD [Pa]	Balancing %
AF	23.10	42.1	19.15	50.3	19.85	75.5
AG	24.50	44.6	14.75	38.8	21.95	83.5
AE	14.20	25.9	9.35	24.6	17.75	67.5
AK	29.00	52.8	19.85	52.2	20.05	76.2
AL	54.90	100.0	38.05	100.0	26.30	100.0
AJ	44.60	81.2	32.65	85.8	20.90	79.5
	Mean Balancing %	49.3	Mean Balancing %	50.3	Mean Balancing %	76.4

4.4. General insights

Generally, the ductwork material costs and the fan energy costs are conflicting. Lower material costs correspond to smaller duct sizes in the system. Therefore, higher velocities and pressure drops in the duct sections, leading to an increase in fan energy usage (see Equation 10) and cost. The sizes for the design configuration resulting from the equal friction method were smaller than the other two design configurations (see Appendix A). Therefore, the material costs were lower and the energy costs higher compared to the other two designs.

Although the ductwork material and fan energetic costs are conflicting, decreasing the duct sizes (i.e., decreasing material costs) may not always lead to an increase in the fan energy costs. In fact, it may lead to a more balanced and cost-efficient design. Herewith, it is important to, first, notice that the fan energy costs would only change if the change in the pressure drop was in the critical path, i.e., the path with the highest pressure drop in the system, (see Equation 9 and Equation 10). By decreasing the duct section sizes, increasing the pressure drop in a non-critical path would not increase the fan energy costs as long as its total pressure drop is lower than the total pressure drop in the (initial) critical path. Moreover, it is vital to understand that the increase in the pressure drop in a non-critical path, by decreasing its duct section sizes, would lower the ductwork material costs of the system. Additionally, it would help to achieve a more balanced system. To fulfill these cost and balancing benefits, it is important to account for sizing the ducts and fittings as an interrelated decision in the design process, as done in the design configuration while considering fittings at an early design stage.

To clarify, consider the design configuration, designed while accounting for fittings at an early stage. Path [A; L] is the critical path (see Table 3). For the designed system, all terminal ducts have the same design airflow rate (i.e., 500 m^3/h). By referring to the sizes of this design configuration in A.3. Design configuration outputs while considering fittings at an early design stage, the non-critical paths [A; E] and [A; G] have exactly the same duct section types and sizes except for their terminal duct sections (i.e., [DE] and [DG], respectively). Therefore, up until duct section [CD], the same total pressure drop is generated for both paths. Although both terminal ducts [DE] and [DG] are of the same length and have the same design airflow rate, [DE]'s inlet fittings is a straight Tee and [DG]'s inlet fitting is a branched Tee. A branched Tee relatively generates a much higher pressure drop than a straight Tee with the same inlet, outlet size, and airflow rate. Within this regard, duct section [DE] had a lower diameter (i.e., 200mm) than duct section [DG] (i.e., 250mm). If section [DG]'s diameter is 200mm, its pressure drop would increase by 16.3 Pa. Thus, path [A; G] would become the new critical path, as its total pressure drop (38.25 Pa) exceeds the total pressure drop in the initial critical [A; L] (26.3 Pa). Consequently, the fan energy costs increases, and the system's balancing percentages would change.

5. Conclusion and future work

The purpose of this paper was to emphasize the importance of efficiently sizing fittings to design a well-performed, balanced, and energy-efficient air distribution system. A review has been carried out for several studies dedicated to optimizing the shape of the fitting to achieve lower pressure resistance and for other studies devoted to precisely predicting the pressure drops from fittings. These studies illustrate the importance of the fittings for optimizing the design and performance of air distribution systems. However, more importantly, the paper highlights that the proper sizing of fittings is overlooked and explores how poorly the current design methods consider fittings in their process, which results in workable but not necessarily optimal designs. To help achieving superior design systems, it was recommended to consider sizing fittings and ducts as linked decisions in an early design phase. To support this recommendation, we demonstrated a test case in which we compared generated design configurations using conventional methods and a design configuration while focusing on the fitting sizes at an early design stage. For this test case, the ductwork configuration designed while considering the fittings at an early design stage was up to 26% more balanced and 52% more energy efficient than the conventionally designed ductwork configurations. Additionally, the LCC was up to 21.8% more cost-efficient.

Nonetheless, considering the most appropriate fitting size required a long iterative process to manually try all the different possible sizes of every fitting in the system and result in the most appropriate size. The process would be even more time-consuming for a larger test case, e.g., designing a ductwork system in a midsized or large building with tens or hundreds of terminals. One effective way to realize the most appropriate fitting size could be using (meta)heuristic optimization techniques. (Meta)heuristic techniques have proven their convenience in tackling large combinatorial optimization problems [72], such as the ductwork design problem [6]. They are intuitive and easy to understand by an outsider. This can be explained by the fact that the human brain naturally finds heuristic solutions to optimization problems rather than exact ones. Similarly, in the simplified test case example in section 4, the appropriate fitting size was realized by searching for the most appropriate sizes between all the possible sizes. Accordingly, future research aims to develop an elaborated heuristic optimization algorithm that can identify the most appropriate ductwork design sizes that could be achieved while considering the fittings sizes at an early design stage.

CRediT authorship contribution statement

Z. Kabbara: Writing – original draft, Writing – review & editing, Software, Investigation, Conceptualization.

S. Jorens: Writing – review & editing, Supervision, Conceptualization.
E. Ahmadian: Writing – Review & editing.
I. Verhaert: Writing – review & editing, Supervision, Conceptualization, Funding acquisition.

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A. Appendix – Design sizing outcomes for three designed configurations

A.1. Design configuration outputs using the equal friction method

Section	Element	Flow	Size	Velocity	Velocity Pressure	Length	Loss Coefficient	Friction	Total Pressure Loss	Section Pressure Loss
AB	Duct	3000.0 m³/h	450ø	5.2 m/s	-	5000	-	0.60 Pa/m	3.2 Pa	4 Pa
	Fittings	3000.0 m³/h	-	5.2 m/s	16.5 Pa	-	0.06	-	1.0 Pa	
IL	Duct	500.0 m³/h	225ø	3.5 m/s	-	5000	-	0.68 Pa/m	3.1 Pa	14.1 Pa
	Fittings	500.0 m³/h	-	3.5 m/s	7.3 Pa	-	1.46	-	10.7 Pa	
HI	Duct	1000.0 m³/h	300ø	3.9 m/s	-	5000	-	0.58 Pa/m	2.7 Pa	15.6 Pa
	Fittings	1000.0 m³/h	-	3.9 m/s	9.3 Pa	-	1.36	-	12.7 Pa	
BH	Duct	1500.0 m³/h	355ø	4.2 m/s	-	5000	-	0.54 Pa/m	2.3 Pa	21.2 Pa
	Fittings	1500.0 m³/h	-	4.2 m/s	10.7 Pa	-	1.73	-	18.5 Pa	
HK	Duct	500.0 m³/h	225ø	3.5 m/s	-	5000	-	0.68 Pa/m	3.2 Pa	3.8 Pa
	Fittings	500.0 m³/h	-	3.5 m/s	7.3 Pa	-	0.06	-	0.4 Pa	
IJ	Duct	500.0 m³/h	225ø	3.5 m/s	-	5000	-	0.68 Pa/m	3.2 Pa	3.8 Pa

	Fittings	500.0 m^3/h	-	3.5 m/s	7.3 Pa	-	0.05	-	0.4 Pa	
DE	Duct	500.0 m^3/h	225ø	3.5 m/s	-	5000	-	0.68 Pa/m	3.2 Pa	3.8 Pa
	Fittings	500.0 m^3/h	-	3.5 m/s	7.3 Pa	-	0.0525	-	0.4 Pa	
CD	Duct	1000.0 m^3/h	300ø	3.9 m/s	-	5000	-	0.58 Pa/m	2.8 Pa	3.2 Pa
	Fittings	1000.0 m^3/h	-	3.9 m/s	9.3 Pa	-	0.034	-	0.3 Pa	
BC	Duct	1500.0 m^3/h	355ø	4.2 m/s	-	5000	-	0.54 Pa/m	2.6 Pa	3.2 Pa
	Fittings	1500.0 m^3/h	-	4.2 m/s	10.7 Pa	-	0.045	-	0.5 Pa	
CF	Duct	500.0 m^3/h	225ø	3.5 m/s	-	5000	-	0.68 Pa/m	3.3 Pa	15.9 Pa
	Fittings	500.0 m^3/h	-	3.5 m/s	7.3 Pa	-	1.707	-	12.5 Pa	
DG	Duct	500.0 m^3/h	225ø	3.5 m/s	-	5000	-	0.68 Pa/m	3.3 Pa	14.1 Pa
	Fittings	500.0 m^3/h	-	3.5 m/s	7.3 Pa	-	1.462	-	10.7 Pa	

A.2. Design configuration outputs using the velocity reduction method

Section	Element	Flow	Size	Velocity	Velocity Pressure	Length	Loss Coefficient	Friction	Total Pressure Loss	Section Pressure Loss
AB	Duct	3000.0 m^3/h	500ø	4.2 m/s	-	5000	-	0.36 Pa/m	1.9 Pa	2.6 Pa
	Fittings	3000.0 m^3/h	-	4.2 m/s	10.8 Pa	-	0	-	0.0 Pa	
IL	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	1.9 Pa	7.6 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	1.18	-	5.7 Pa	
HI	Duct	1000.0 m^3/h	355ø	2.8 m/s	-	5000	-	0.26 Pa/m	1.2 Pa	12.7 Pa
	Fittings	1000.0 m^3/h	-	2.8 m/s	4.7 Pa	-	2.43	-	11.5 Pa	
BH	Duct	1500.0 m^3/h	355ø	4.2 m/s	-	5000	-	0.54 Pa/m	2.3 Pa	15.3 Pa
	Fittings	1500.0 m^3/h	-	4.2 m/s	10.7 Pa	-	1.21	-	13.0 Pa	
HK	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	1.9 Pa	2.2 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	0.06	-	0.3 Pa	
IJ	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	1.9 Pa	2.2 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	0.06	-	0.3 Pa	
DE	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	1.9 Pa	2.2 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	0.06	-	0.3 Pa	
CD	Duct	1000.0 m^3/h	355ø	2.8 m/s	-	5000	-	0.26 Pa/m	1.3 Pa	1.9 Pa
	Fittings	1000.0 m^3/h	-	2.8 m/s	4.7 Pa	-	0.13	-	0.6 Pa	
BC	Duct	1500.0 m^3/h	355ø	4.2 m/s	-	5000	-	0.54 Pa/m	2.5 Pa	3.1 Pa
	Fittings	1500.0 m^3/h	-	4.2 m/s	10.7 Pa	-	0.059	-	0.6 Pa	
CF	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	2.0 Pa	14.0 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	2.48	-	12.0 Pa	
DG	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	2.0 Pa	7.7 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	1.18	-	5.7 Pa	

A.3. Design configuration outputs while considering fittings at an early design stage

Section	Element	Flow	Size	Velocity	Velocity Pressure	Length	Loss Coefficient	Friction	Total Pressure Loss	Section Pressure Loss
AB	Duct	3000.0 m^3/h	500ø	4.2 m/s	-	5000	-	0.36 Pa/m	1.8 Pa	1.8 Pa
	Fittings	3000.0 m^3/h	-	4.2 m/s	10.8 Pa	-	0.0	-	0.0 Pa	
IL	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	2 Pa	7.7 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	1.18	-	5.7 Pa	
HI	Duct	1000.0 m^3/h	355ø	2.8 m/s	-	5000	-	0.26 Pa/m	1.3 Pa	5.2 Pa
	Fittings	1000.0 m^3/h	-	2.8 m/s	4.7 Pa	-	0.82	-	3.9 Pa	
BH	Duct	1500.0 m^3/h	500ø	2.1 m/s	-	5000	-	0.10 Pa/m	0.5 Pa	11.6 Pa
	Fittings	1500.0 m^3/h	-	2.1 m/s	2.7 Pa	-	4.1	-	11.1 Pa	
HK	Duct	500.0 m^3/h	200ø	4.4 m/s	-	5000	-	1.19 Pa/m	5.95 Pa	6.65 Pa
	Fittings	500.0 m^3/h	-	4.4 m/s	11.8 Pa	-	0.061	-	0.7 Pa	
IJ	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	2.0 Pa	2.3 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	0.06	-	0.3 Pa	
DE	Duct	500.0 m^3/h	200ø	4.4 m/s	-	5000	-	1.19 Pa/m	5.5 Pa	6.0 Pa
	Fittings	500.0 m^3/h	-	4.4 m/s	11.8 Pa	-	0.043	-	0.5 Pa	
CD	Duct	1000.0 m^3/h	250ø	5.7 m/s	-	5000	-	1.39 Pa/m	6.95 Pa	8.15 Pa
	Fittings	1000.0 m^3/h	-	5.7 m/s	19.3 Pa	-	0.06	-	1.2 Pa	
BC	Duct	1500.0 m^3/h	400ø	3.3 m/s	-	5000	-	0.30 Pa/m	1.5 Pa	1.8 Pa
	Fittings	1500.0 m^3/h	-	3.3 m/s	6.6 Pa	-	0.043	-	0.3 Pa	
CF	Duct	500.0 m^3/h	200ø	4.4 m/s	-	5000	-	1.19 Pa/m	5.95 Pa	16.25 Pa
	Fittings	500.0 m^3/h	-	4.4 m/s	11.8 Pa	-	0.87	-	10.3 Pa	
DG	Duct	500.0 m^3/h	250ø	2.8 m/s	-	5000	-	0.41 Pa/m	2.0 Pa	10.8 Pa
	Fittings	500.0 m^3/h	-	2.8 m/s	4.8 Pa	-	1.82	-	8.8 Pa	

B. Appendix - Ductwork material and installation costs

Galvanized steel ducts	
Diameter 80 mm	20.00 €/m
Diameter 100 mm	25.00 €/m
Diameter 125 mm	31.50 €/m
Diameter 160 mm	35.00 €/m
Diameter 200 mm	40.00 €/m
Diameter 250 mm	50.00 €/m
Diameter 315 mm	55.00 €/m
Diameter 355 mm	60.00 €/m
Diameter 400 mm	75.00 €/m
Diameter 450 mm	80.00 €/m
Diameter 500 mm	90.00 €/m