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Design Optimization of Air distribution Systems in Non-Residential Buildings

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Abstract

In most HVAC installations, the ductwork layout, i.e., the network structure of the ducts, as well as the number and locations of the fans, is an important determinant of the installation's cost and performance. Nevertheless, the layout is not explicitly taken into account in existing duct design methods. All existing methods assume the layout of the air distribution system to be predetermined and focus solely on the sizing of each fan and duct in the system. The overarching aim of this research is to extend previous research by developing a design method that is able to calculate the optimal air distribution system configuration, i.e., the optimal ductwork layout and duct and fan sizes, taking into account constraints imposed by the building structure, customer requirements, etc. One of the prerequisites of such a design method, and the subject of this paper, is an efficient simulation model that is able to quickly quantify the cost, performance and feasibility of a given air distribution system configuration. The simulation model proposed in this paper is developed in EES (Engineering Equation Solver), and can simulate large air distribution systems with an arbitrary layout. Last the significance of the ductwork layout to the design of an air distribution system is investigated by means of a test case. The design method itself, however, is outside the scope of this paper.

Keywords – air distribution systems, duct design method, ductwork layout, simulation model, optimization, Engineering Equation Solver (EES)

1. Introduction

One of the most energy-consuming and cost expensive (up to 35% in Belgium) parts of an HVAC system in non-residential buildings is the air duct system. Duct systems are designed to properly distribute the air throughout the building and satisfy the airflow rates specified for each terminal unit in the different rooms to be conditioned. The energy needed to distribute the air and overcome all the pressure losses of the various components in the ductwork (e.g. fittings and silencers), is delivered by one or more fans. Duct systems that are not well designed result in discomfort, high energy costs, bad air quality, increased noise levels and (possible) excessive ductwork material [6].

Starting from a floor plan where all terminal units in the building with corresponding air flow rates are indicated, the duct design process can generally be subdivided in three different phases. First the ductwork's layout needs to be determined, i.e. the number and location of each fan and duct in the building. Second all duct and fan types, i.e. size and material, are selected. Last, dampers for the different branches in the system are calculated to balance the system and ensure that every demand point receives the correct airflow.

2. Problem formulation

Since the 1960s, much research has been dedicated to the simulation and optimization of air duct systems [4], [5], [7] and numerous design methods have been developed such as the equal friction, static regain and T-method [1],[2],[3]. These methods support the design engineer in the second phase of the process, namely the duct sizing and/or fan selection, starting from a given ductwork layout. The layout itself, however, depends on the design engineer in charge. It is determined using rules of thumbs, which results in different designs that are workable, but not necessarily optimal. Since the ductwork layout and duct and fan sizing are interrelated decisions, the HVAC sector could benefit from a method that incorporates both decisions and generates potential ductwork layouts with corresponding duct and fan sizes automatically. The overarching aim of this research is to develop such a method and examine its added value compared to traditional methods and software packages. Besides the quality of the design, the method's feasibility to respond on external design changes in the conceptual phase (e.g. due to the client or the building structure) will be investigated. One of the prerequisites of such a design method, and the subject of this paper, is an efficient simulation model that is able to quickly quantify the cost, performance and feasibility of a given air distribution system configuration. In this paper, the simulation model is used to examine the extent to which the layout influences the cost, pressure drops and pressure balance of an air duct system, as this is new compared to existing duct design methods. Paragraph 3 describes the simulation model, whereas paragraph 4 discusses a test case. The design method itself, however, is outside the scope of this paper.

3. Simulation Model

The simulation model, described in this paper, will be addressed during the optimization phase of the design method to calculate the cost, performance and feasibility of a given air distribution system. Since the simulation model will be called multiple times, it is important that the simulation model is quick, efficient and simplified. Simplified in the sense that the number of equations and corresponding variables should be limited to the number that complies with the desired accuracy of the model and the equations should be comprehensible for the user. The proposed simulation model is written in EES (Engineering Equation Solver). This modeling tool allows an equation-based approach: each component is modeled by a set of directly executable equations which describe the main physical characteristics inherent to the component. Therefore the modeling can be made fully transparent and easy to adapt to specific requirements of any user. For each model, the distinction is made between the input and output variables and the parameters which the user can "manipulate". Due to the modular approach, the inter-connection between the different models is very straightforward: the outputs of one model equal the inputs of another model.

3.1 General properties

The simulation model is a steady-state model, i.e., the model does not store mass or energy. The thermophysical properties, i.e. the temperature T (°C), relative humidity RH (/), air density (kg/m³) and viscosity (kg/m-s), are assumed to be constant in the whole air distribution system. EES can deliver the density and viscosity as function of the air temperature and pressure in the respective ducts. Since the pressure drops are small compared to the absolute pressure, the atmospheric pressure is used to determine the density and viscosity in the system. The temperature and relative humidity can be adapted by the user. In this stage the simulation model is able to calculate, for an arbitrary supply duct system, the static and total pressure of the fan, the pressures at the end units, the total cost of the ductwork and the total amount of ductwork material. The first two results give a good first impression of the system's energy usage.

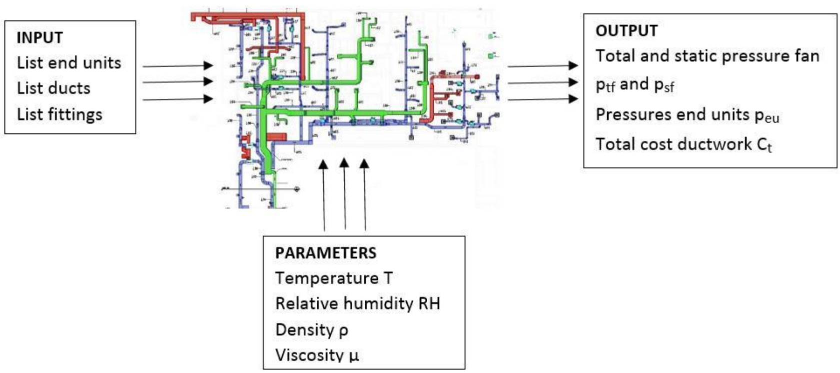


Fig. 1 Schematic representation general model

3.2 Ducts

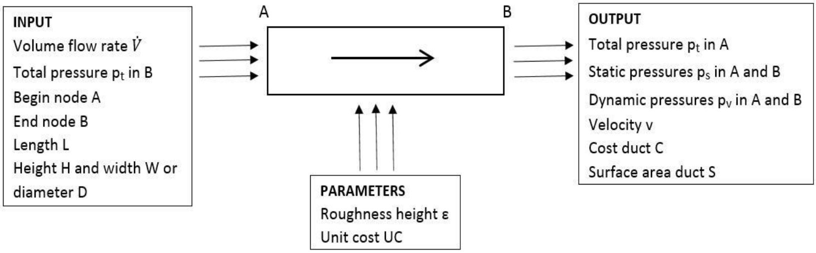


Fig. 2 Schematic representation duct model
(in EES the inputs and outpust are exchangeble)

The head losses Δp (Pa) caused by friction in a straight constant-area duct are calculated with the Darcy-Weisbach equation:

$$\Delta p = f * \frac{L}{D_h} * \frac{\rho v^2}{2} \tag{1}$$

where f is the friction factor (/), L the duct length (m), Dh the hydraulic diameter (m), ρ the density (kg/m³) and v the average velocity (m/s). The last grouping of terms in (1) is also called the dynamic or velocity pressure. The friction factor depends on the Reynolds number Re (/) and in case of ducts with rough walls (e.g. sheet metal ducts) also on the relative roughness, which is the ratio of the height of the roughness elements ε (m) to the hydraulic diameter Dh (m). When the Reynolds number is smaller than 10^6, the relation for the friction factor for rough walls is given by (2).

$$f^{-0,5} = 1{,}14 + 2\log\left(\frac{D_h}{\varepsilon}\right) - 2log\left(1 + \frac{9{,}3}{Re\left(\frac{\varepsilon}{D_h}\right) f^{0,5}}\right) \tag{2}$$

where:

$$Re = \frac{4\dot{m}}{WP\mu} \tag{3}$$

In (3) $\dot{m}$ is the mass flow rate (kg/s), WP the wetted perimeter (m) and μ the air viscosity (kg/m-s). The head losses in a constant-area duct can also be expressed by a second relation:

$$\Delta p = p_{t,A} - p_{t,B} \tag{4}$$

where:

$$p_{t,A} = p_{s,A} + p_{v,A} = p_{s,A} + \frac{\rho v^2}{2} \tag{5}$$

and:

$$p_{t,B} = p_{s,B} + p_{v,B} = p_{s,B} + \frac{\rho v^2}{2} \quad (6)$$

In these equations, $p_{t,A}$ and $p_{t,B}$ are the total pressures (Pa) in respectively point A and B, $p_{s,A}$ and $p_{s,B}$ the static pressures (Pa) and $p_{v,A}$ and $p_{v,B}$ the dynamic pressures. The velocity v in the equations is calculated with (7).

$$\dot{V} = A_c v \quad (7)$$

$\dot{V}$ is the volume flow rate (m^3/h) and A_c the duct flow area (m^2). The duct surface area S (m^2) is given by (8), whereas the duct cost C (€) is given by (9) for rectangular ducts and (10) for round ducts.

$$S = WP * L \quad (8)$$

$$C = S * UC \quad (9)$$

$$C = L * UC \quad (10)$$

where L equals the duct length (m) and UC the unit cost per square meter for rectangular ducts (€/m^2) and per meter for round ducts (€/m).

3.3 Fittings

The total pressure losses due to duct fittings (e.g. bends) are calculated by means of (11).

$$\Delta p = C \frac{\rho v^2}{2} = C p_v \quad (11)$$

where C is a loss coefficient that depends on the type of fitting. The C-values are dimensionless and are retrieved from tables [1], p_v (Pa) is the velocity pressure at the referenced cross section. For converging and diverging flow junctions, total pressure losses Δp_s (Pa) through the straight (main) section are calculated with (12), whereas the total pressure losses Δp_b (Pa) through the branch section are calculated with (13).

$$\Delta p_s = C_s p_{v,c} \quad (12)$$

$$\Delta p_b = C_b p_{v,c} \quad (13)$$

C_s and C_b are dimensionless loss coefficients for respectively the straight and branch flow paths and $p_{v,c}$ is the velocity pressure at the common section (i.e.

the inlet of the junction). Moreover, in every junction, the sum of the incoming volume flow rates (m³/s) equals the sum of the outgoing flow rates (m³/s):

$$\sum \dot{V}_{in} = \sum \dot{V}_{out} \tag{14}$$

3.4 End units

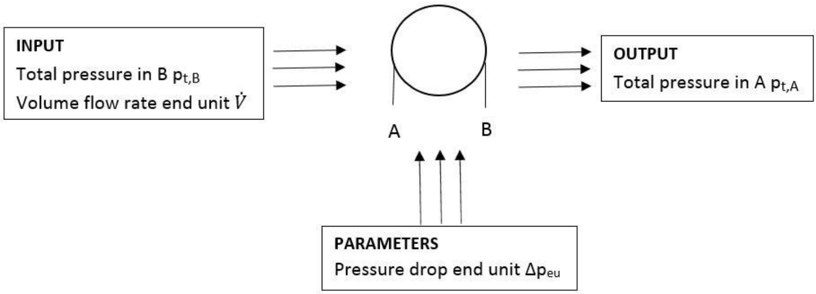


Fig. 3 Schematic representation end unit model

The pressure drops Δp_{eu} (Pa) due to the air outlets can be obtained from the supplier's catalogue. This pressure drop is the difference between the pressure at the inlet ($p_{t,A}$) and the outlet of the end unit ($p_{t,B}$) and can be 'modified' by the user. Additionally to entering a value for the pressure drop in the model, the user has to set the pressure $p_{t,B}$ in one end unit equal to the desired relative room pressure. The simulation model is now able to calculate automatically the fan pressure and the end pressures at all the other air outlets in the system. If it appears that the resulting end pressure in one of the air outlets is lower than the room pressure set by the user, the simulation will be repeated but this time the outlet with the lowest pressure will be set equal to the room pressure.

3.5 Fans

The fan model proposed in this paper is a simplified model, yet accurate enough in this stage of the research. The model is able to calculate the system's required total and static fan pressures $p_{t,f}$ (Pa) and $p_{s,f}$ (Pa) by means of (15) and (16).

$$p_{t,f} = p_{t,f,out} - p_{t,f,in} \tag{15}$$

and

$$p_{s,f} = p_{t,f,out} - p_{t,f,in} - p_{v,f,out} \tag{16}$$

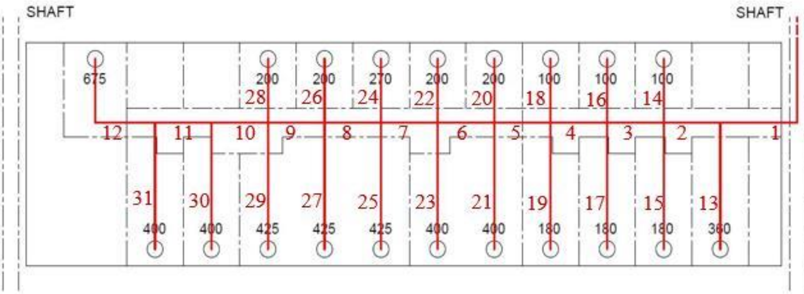
where $p_{t,f,in}$ (Pa) and $p_{t,f,out}$ (Pa) are the total pressures at respectively the in- and outlet of the fan. The total pressure at the outlet is assumed to be equal to the inlet pressure of the duct ($p_{t,A}$) that is connected with the fan. The same applies to the dynamic pressure at the outlet of the fan $p_{v,f,out}$ (Pa).

4. Test Case

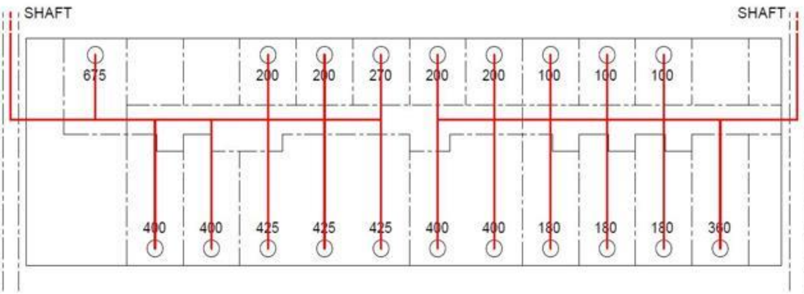
A simplified yet real-life test case is described in this paper to investigate the importance of the ductwork layout in the duct design process. Figures 1 to 3 display the floor plan of the seventh floor in a multistory university building in Belgium. The building accommodates among others class rooms, research laboratories and offices. The air handling units are located on the top floor from where the air is guided into the ductwork. Multiple shafts are present in the building enabling the ducts to reach all floors. The numbers indicated on the floor plan are the required air flow rates expressed in cubic meters per hour (m^3/h). As stated in paragraph 2, each building can have multiple potential ductwork layouts depending on the design engineer in charge, architectural building characteristics (e.g. height of the false ceiling, dimensions and location(s) of the shaft(s)), aesthetic preferences, acoustic requirements etc. Three of these potential layouts are displayed in figures 1 to 3. For an objective comparison the three layouts are all supply ductwork layouts with one fan located in the air handling unit on the top floor of the building. The ducts' dimensions have been determined using the equal friction method, considering a unit frictional loss of one pascal per meter and a velocity constraint. The maximum velocity was set to six meters per second in corridors and three meters per second in occupied spaces. As an example the duct specifications of layout one are summarized in table 1. The dimensions of layout two and three are calculated analogous. The simulation model described in paragraph 3 is used to compare the three layouts in terms of material cost, fan pressure and pressure balance, taking into account the following conditions:

- A supply temperature and relative humidity equal to 12°C and 90% respectively
- A room pressure of 50Pa above atmospheric pressure
- Turbulent air flow
- Galvanized sheet metal ducts
- Fittings from the ASHRAE data base

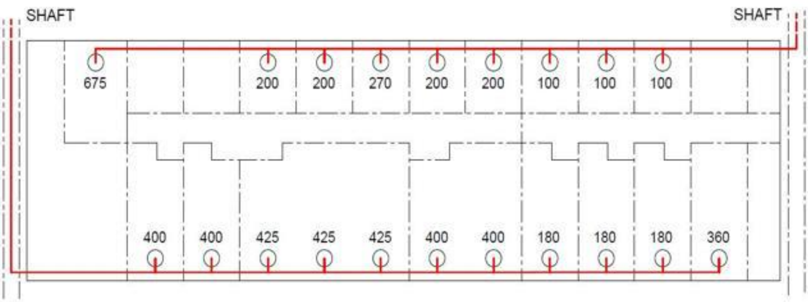
The results of the simulation model are presented in table 2.



Layout 1



Layout 2



Layout 3

Fig. 4 One floor plan with three different ductwork layouts

Table 1. Duct specifications layout 1

Duct section	Diameter (m)	Length (m)
1	0,630	31,5
2	0,630	3,6
3,4,5	0,560	3,6
6	0,500	3,6
7,8	0,450	3,6
9	0,400	3,6
10	0,355	3,6
11	0,315	3,6
12,13,21,23,25, 27,29,30,31	0,250	8,5
14,16,18	0,125	4,5
15,17,19	0,160	8,5
20,22,26,28	0,160	4,5
24	0,200	4,5

Table 2. Different layouts

	Layout 1	Layout 2	Layout 3
Tot. air flow (m^3/h)	5820	5820	5820
Duct surface (m^2)	208	200	187,1
Cost ductwork (€)*	5258,2	4676,5	5029
Tot. fan pressure (Pa)	257	223	86

*Cost fittings and fan not included

According to the results listed in table 2 the layout of the air distribution system has a considerable influence on the system's cost. Additionally substantial differences are calculated in terms of fan pressure and pressure balance. From an economical point of view layout two tends to be the best solution of the cases studied, whereas layout three scores better in terms of fan pressure and pressure balance.

5. Conclusions and future research points

Although only three relatively small test cases have been studied, it is shown that the layout has an economical and qualitative impact on the design of air distribution systems. It is expected that higher savings can be achieved in larger air distribution networks. Further research is advisable to examine the added value of a design method that supports the engineer in both the duct and fan sizing and the layout. Extended research includes a more detailed simulation model, the impact of the layout on variable flow systems and the automatic generation of feasible layouts, which includes the location of the supply devices.

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