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Research Article

Building Systems and Components

A simulation-based method for air loop balancing and fan sizing using uncertainty and sensitivity analysis

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Abstract

Two main tasks of commissioning an air-side HVAC system are to verify the fan capacity and to balance the air loop. Simulations can be of assistance to these two tasks. However, the models used in the simulation will inevitably have some uncertainties, especially for the models of the pressure loss components. This paper proposes to use uncertainty analysis to obtain the adjustment instructions for tuning the dampers and the fan pressure value for sizing the fan on a virtual testbed implemented in Modelica. An air-side system with eight terminals, ten dampers and seven junctions is taken as the use case. 24 correction factors for the pressure loss coefficients (PLC) (10 for the dampers, 14 for the junctions) are taken as the inputs for the uncertainty analysis. 1000 samples of the correction factors are generated by using the Latin Hypercube Sampling method. The proportional balancing method is adopted to determine the positions of the damper so that the designed terminal flow rates could be met. The fan pressure value is also determined accordingly. The distributions of the dampers' positions and fan pressure can be used to guide the balancing work and fan sizing in practice. In addition, the sensitivity analysis reveals that the position adjustments and fan pressure results are more sensitive to the uncertainties of the dampers' PLCs. When the uncertainty level of the dampers' PLC is reduced from ±40% to ±10%, the ranges of the damper's positions will be significantly narrowed down to less than 15%, and the 95th percentiles of the fan pressure will drop from 116Pa to 38Pa, which shows the practicality and benefit of the proposed method.

Keywords

commissioning,
air loop balancing,
fan sizing,
uncertainty analysis,
sensitivity analysis,
Modelica modeling

Article History

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1 Introduction

Commissioning process "is a quality-oriented process for achieving, verifying, and documenting that the performance of facilities, systems, and assemblies meets defined objectives and criteria" (ASHRAE 2005), which is essential for an HVAC system to achieve a good performance of thermal comfort and energy efficiency. Specifically, for the air-side HVAC systems, the work of testing, adjusting, and balancing (TAB) is the key to guarantee that the total airflow is distributed to each one of the terminals as designed. On one hand, the practitioners need to validate whether the designed capacity of the fan is sufficient to generate the designed total flow rate given the resistance of the duct system as a prerequisite of TAB. On the other hand, the required fan capacity will also alter accordingly since the resistance property of the duct system will be changed by adjusting the balancing dampers during the TAB process. Therefore, the works of fan sizing and TAB are inherently coupled together.

However, fan sizing and TAB are conventionally separated and accomplished by different parties. Sizing the fan is usually done by the designers. After finishing the design of the duct system, the designers can calculate the total pressure loss of the system and select the fan. Unfortunately, the reliability of the system pressure loss herein may be impacted by several underlying facts, such as the unknown position of the balancing dampers, the inaccuracy of fitting data (i.e. pressure loss coefficient, PLC), the unavailability of data

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for certain fittings, and the effects of close-coupled fittings (ASHRAE 2009). Therefore, the designers usually multiply the preliminary system pressure loss by a safety factor (larger than one) to manage the aforementioned impacts in order to avoid the risk that the system is undersized and cannot meet the requirement under all potential scenarios. However, implementing the safety factor often leads to oversizing in practice. For some cases, the fan is oversized as much as three times the necessary size (Crozier 2000). The oversized equipment would be inevitably working in the low efficiency region for most of the time, which leads to energy waste.

Separated from the fan sizing in design phases, the TAB is usually accomplished by the mechanical contractors or by the dedicated professional commissioning providers. Two basic air loop balancing procedures are well documented in (NEBB 2015), which are the proportional method and stepwise method. These two methods are both iterative methods, which means the practitioner may need to follow the procedure for certain rounds so that the airflow distribution can meet the design condition. As for the basic iterative TAB procedures, the quality of the work highly depends on the experience of the practitioners, and much on-site work is required. Other than that, Pedranzini et al. (2013) proposed a non-iterative method for TAB, called "progressive flow method". This method uses an additional feedback control to adjust the fan speed in order to maintain the design flow rate through the furthest terminal while keeping the other dampers shut. With the help of the feedback control, all the other dampers can be directly adjusted to their final position one by one without repeating. Although the non-iterative method does have certain advantages over the basic methods, it requires additional feedback control for the fan, and sometimes, if the nominal fan flow rate is way larger than the design flow rate of the furthest terminal, it is not practical to reduce the fan speed to obtain the flow rate only for that terminal.

With the development of modeling techniques, simulation can assist in providing precedent knowledge for decision making and serve as a guidance for actual work. The reliability of a simulation-based method depends on the accuracy of the models (Sun et al. 2014; Allard et al. 2018). In this case, the simulations can be performed immediately after the final HVAC plan drawings are available and before the in-situ commissioning work.

To build the system model, we must make full use of the information from the system layouts and the duct components' PLC data. In terms of the accuracy of the layout information, the emerging Building Information Modelling (BIM) technique can assist in closing the gap between the layout and real situation because the risk of pipeline collision could be significantly reduced with the help of 3D modeling and visualization. Therefore, the information of the structure and the length of the duct system is adoptable and can be precisely extracted from the layouts.

However, on the other hand, the components' PLC data can hardly eliminate some inherent uncertainties. Since we want to calculate the airflow allocation within the duct system and the flow condition is coupled with the pressure distribution, the differential pressure models of the components in the duct system become important. A typical air-side system is usually composed of fans, straight ducts, fittings, dampers, etc. For the ducts and fittings, the practitioners usually refer to ASHRAE handbook fundamental (ASHRAE 2009) or other counterparts like Idelchik et al. (1994), to look up the PLC data. For the fans and dampers, the data in the products' leaflets are often referenced because the resistance property may differ from product to product. All the referenced data is mostly from experimental tests. The users have to bear in mind the fact that the target component usually has a pair of relatively long upstream and downstream straight ducts during the test (ASHRAE 2017) which is probably different from the scenario in a real system. The components in a real system are usually coupled with each other, and the duct in between is not long enough for the flow inside to be fully-developed. Therefore, the total resistance for two closely coupled components does not equal to the summation of their individual resistances (Gan and Riffat 1995; Mumma et al. 1997; Atkin and Shao 2000; Sami and Cui 2004; Mylaram and Idem 2005; Ai and Mak 2013; Li et al. 2014; Salehi et al. 2017). Because there could be enormous coupling scenarios, it would be difficult to make a comprehensive conclusion to solve this problem. Thus, when the referenced PLC data is used, there are always some uncertainties with it.

Some researchers tried to use the measured data to calibrate the model for avoiding those uncertainties. Small (2002) developed a simple quadratic model for the duct system and used it to adjust the balancing dampers. To identify the resistance parameters, the flow rates through each terminal are measured. Compared to Small's work, Chen et al. (2016) adopted the more detailed models, such as Darcy-Weisbach equation for the duct friction, to improve the accuracy of the model and conducted more measurements for each terminal to reduce the measurement error. Although these simulation-based approaches both plausibly offer the non-iterative and efficient solution for air loop balancing, they have the additional precedent measurement involved and cannot eliminate the uncertainties within the measurement.

Although we cannot cast off the uncertainties, uncertainty analysis method can be used to address them for obtaining a more robust result. In the HVAC field specifically, researchers often perform uncertainty analysis to identify the variation range of the dependent variables, due to the pre-defined probability distribution of the independent variables. After that, sensitivity analysis is often performed to identify the most influencing source within the independent variables. Sun et al. (2014) considered 25 input parameters related to the calculation of the cooling and heating load and plotted the cumulative probability function curve to visualize the variation of the peak cooling/heating load. This method was adopted for HVAC system sizing and could provide a quantitative risk when choosing the system capacity, which could be informative for the stakeholders to make decisions. Then they revealed several independent variables by sensitivity analysis, to which the cooling/heating loads are most sensitive. By doing this, they identified the most effective way to reduce the uncertainty in the cooling/heating loads so that the size of the system can be reduced with the same level of risk. Some other applications of uncertainty and sensitivity analysis are more related to control performance evaluation. Shan et al. (2013) studied the uncertainty of the control performance for several demand-controlled ventilation strategies under the uncertainty of measurement. They identified the most critical sensors and demonstrated the improvement of control performance after reducing the uncertainty of those sensor measurements.

In this paper, we focus on the uncertainty of using the existing PLCs data and perform the uncertainty analysis to investigate the uncertainty in the position adjustments of the balancing dampers and the corresponding pressure capacity of the fan. The proposed approach can provide a guidance with quantitative confidence for the work of fan sizing and air loop balancing, which will improve the quality and reduce the on-site work. In addition, we will analyse the sensitivities of the dampers' positions and fan pressure in order to reduce the uncertainty effectively. At last, we will demonstrate the practicality and the benefits of the proposed simulation-based method for the efficient air loop balancing and proper fan sizing.

2 Methodology

2.1 System modeling and virtual balancing

In this study, we use Modelica (Fritzson 1998), an equation-based modeling language, to build the air-side system and run the simulations on Dymola (www.dynasim.se), a commercial Modelica environment. The Modelica Buildings Library (Wetter et al. 2014) developed by LBNL contains the models of most common equipments and components in a building mechanical system so that users can adopt it to model typical system topologies. However, the application of the proposed method is not necessarily limited to the platform of Modelica or Dymola. As long as the software to be used could support dynamic simulation and the models are precise enough, the proposed method could be implemented on those platforms as well.

Considering the implementation of this application, we need to use the models of fans, ducts, junctions, dampers, flow meters, etc. Most of the models are available in the Buildings Library version 4.0.0. For the pressure loss models specifically, the authors assume that the original duct ("PressureDrop") and damper ("Exponential") models are accurate enough to describe the pressure loss characteristics of themselves if not considering the effect of close connection. For detailed equations of these two models, please refer to the documentations of Buildings Library v4.0.0 (LBNL 2017). However, the default junction model in Modelica Buildings Library has the fixed PLC, which is found to be too simple for the application in this paper. Wang et al. (2018) reported that the dynamics of the airflow distribution within a duct system could be considerably different if one used the simplified junction model with the fixed PLC. They suggested that one should at least use the model with the variable PLCs defined as a polynomial function of the ratio of downstream velocity to upstream velocity so that the correct dynamics could be captured. More details of the models we use will be elaborated in Section 3.1.

Figure 1 shows the structure of a junction model with the variable PLCs built in Modelica. Three velocity meters are used to measure the velocity in each branch, which requires the user to input the cross-sectional area. The resistance module on the branch from port_1, i.e. res1, can be used to model the upstream duct friction. The other two on the branch to port_2 and port_3, i.e. res2 and res3, will read the measured velocity, then calculate the velocity ratio and the corresponding PLC, and finally calculate the pressure loss for each branch. The references of the modules used for building the new junction model are listed in Table 1, in which the reference starting with "Modelica" is the Modelica Standard Library (Modelica Association 2008) and the

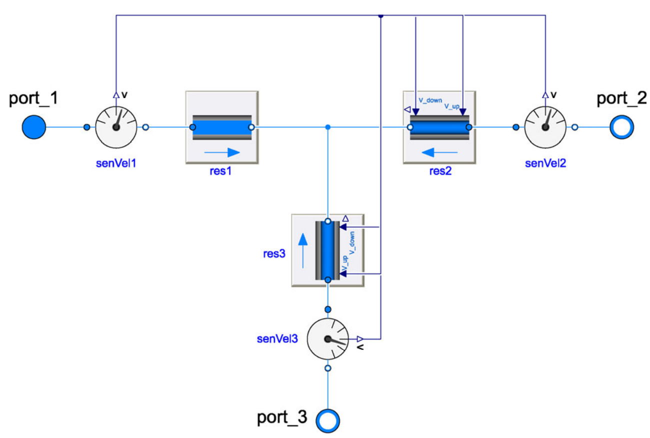

Fig. 1 Junction model with variable PLCs

Table 1 References of the module used for building the new junction model

Modules	References
port_1	"Modelica.Fluid.Interfaces.FluidPort_a"
port_2, port_3	"Modelica.Fluid.Interfaces.FluidPort_b"
res1	"Buildings.Fluid.FixedResistances.PressureDrop"
res2, res3	Modified based on "Buildings.Fluid.FixedResistances. PressureDrop"
senVel1–sen Vel3	"Buildings.Fluid.Sensors.Velocity"

reference starting with "Buildings" is the Modelica Buildings Library (Wetter et al. 2014).

Equations (1) to (3) define how the velocity ratio, PLC, and the pressure loss are calculated. Both the PLCs of the straight and vertical branch will be calculated accordingly.

$$R = \frac{V_{\text{downstream}}}{V_{\text{upstream}}} \tag{1}$$

$$\text{PLC} = a_0 + a_1 \times R + a_2 \times R^2 + a_3 \times R^3 \cdots \tag{2}$$

$$\Delta P = \text{PLC} \times \text{DP}_{\text{upstream}} \tag{3}$$

where R is the velocity ratio, $V_{\text{downstream}}$, V_{upstream} are the downstream/upstream velocities (m/s) in the cross section, a_0, a_1, a_2, ... are the polynomial coefficients, ΔP is the pressure loss of the junction, and $\text{DP}_{\text{upstream}}$ is the dynamic pressure in the upstream branch. The order of the polynomial function in Eq. (2) could be user-defined and the values of the coefficients could be referenced from existing literature (ASHRAE 2009; Wang et al. 2018). While for those pressure loss components whose coefficients are not available, it may need to perform the pressure loss measurement or CFD simulation to generate the corresponding coefficient values, as the work done by Wang et al. (2018).

Having finished modeling the air-side system, we will need to perform the virtual air loop balancing on it. The balancing procedure chosen in this paper is the proportional method. The principle of the proportional method has been introduced in the introduction. Here we elaborate the detailed steps for balancing the air loop with multiple branches and multiple terminals on each branch, as described in the NEBB's procedural standard for TAB (NEBB 2015):

a. Verify all balancing dampers are wide open;
b. Adjust the fan to approximately 110% of design airflow or as necessary;
c. Measure the airflow of all terminals;
d. Calculate the ratio of measured branch flow to design branch flow;
e. Keep the damper serving the branch with lowest flow ratio wide open;
f. Adjust the damper serving the branch with the second lowest flow ratio until these two branches have the same branch flow ratio, which means they are balanced;
g. Adjust the damper serving the branch with the third lowest flow ratio until all three branches are balanced;
h. Repeat Step g until all branches are balanced;
i. Re-adjust the fan to approximately 110% of design airflow or necessary;
j. Balance the terminal dampers on each branch following the similar procedure as in the balancing process for branch dampers;
k. Adjust the fan speed to set all terminal flow rates at the design values within ±10% biases.

We implement the proportional procedure using Python. The Modelica model reads the positions of the balancing dampers from an external text file. The Python script will modify the position values in the text file for specific dampers, call Dymola to run the model, receive the flow ratio results, and decide whether to iterate the adjustment until the loop is balanced.

Since we are performing the virtual balancing using simulation, we can use the ideal fan model to simplify the process by skipping the steps of adjusting the fan speed. The ideal fan model can generate a user-defined flow rate and calculate the corresponding fan pressure needed for the given ductwork. Therefore, the design total system airflow is always guaranteed. This feature can also avoid the risk of numerical problems during the simulation because the prechosen fan capacity may not be sufficient to deliver the design total system airflow after adjusting several balancing dampers, and the solver may not find a physically meaningful solution. In addition, it actually provides the capability for sizing the fan because the calculated fan pressure will always match the resistance of the ductwork precisely.

2.2 Uncertainty quantification

As aforementioned, the uncertainty we address in this study is the potential difference of the fittings' PLC data between its referenced value and its true value under the circumstances where the fittings are closely connected with each other in a real system. We use a multiplier as a correction factor on the original referenced PLC data to represent the impact of the closely-coupled effect. By assuming that the correction factor is uniformly distributed within a certain range, we only have to identify the variation range of the fitting data under the closely-connected situation. Table 2 lists the results from literature review about the variation range of the fittings' PLC caused by the closely-coupled effect. We can see that the range of the percentage difference varies considerably with respect to different fitting types and connecting arrangements. In fact, the connection scenarios in a real system can exceed far beyond the scope of existing research, such as a damper closely installed near

Table 2 Difference in PLCs impacted by closely-coupled effect

Studies	Fitting types	Connecting arrangements	Difference from the non-coupled value
Gan and Riffat (1995)	Bend elbow	U-shape	−10% to 0
Mumma et al. (1997)	Pyramidal transition, 2 types of bend elbows	Customized connection	0 to +27%
Atkin and Shao (2000)	Bend elbow	U-shape S-shape	−5.4% to +8.1%
Sami and Cui (2004)	Bend elbow	U-shape S-shape T-shape Z-shape	−35% to 0
Mylaram and Idem (2005)	6 types of bend elbows	S-shape	−4.8% to +37.4%
Lakshmiraju and Cui (2006)	Bend elbow	U-shape S-shape T-shape Z-shape	−18% to 0
Ai and Mak (2013)	Damper-like fitting	Straight connection	−36.8% to −2.0%
Salehi et al. (2017)	Bend elbow	U-shape Z-shape	−24.35% to +11.74%

a bend elbow or junction. Therefore, it is difficult to illustrate all possible scenarios to draw a comprehensive conclusion on the impact of the closely-coupled effect. In this study, we take the widest range, i.e. −40% to +40%, as the uncertainty range of PLCs for the subsequent uncertainty analysis and assume the error follows a uniform distribution within this range.

2.3 Sampling method

Since an air-side system usually consists of multiple terminals and local components, we have multiple uncertain inputs, i.e. the inaccurate PLCs, in our study. Say there are p uncertain inputs to be analysed, then we have a p-dimensional space. For each dimension, the uncertainty is quantified by a uniform distribution with the identified upper/lower limit, i.e. ±40% as aforementioned. Then we need to generate a certain number of samples, i.e. the combinations of the p parameters and feed them into the model to calculate the corresponding outputs. A good sampling method can assist in revealing the relationship between the inputs and outputs with a relatively small sample size (Hyun et al. 2007; Sun et al. 2014; Prada et al. 2018). Hereby, we use the Latin Hypercube Sampling (LHS) method instead of the random sampling. LHS is one of the stratified sampling methods. Each dimension is divided into N disjoint intervals in which a single sample is randomly drawn from the predefined distribution. This method has been widely adopted in many uncertainty analysis studies in the HVAC field.

2.4 Uncertainty analysis

The purpose of uncertainty analysis is to investigate how the outputs are affected by the input uncertainties. The distribution of the outputs will be identified according to the probability distribution of the inputs. In this study, the outputs are the position adjustment results of each damper and the corresponding fan pressure. The frequency distribution and cumulative frequency distribution are used to visualize the variation range of the outputs over all the combinations of inputs, as illustrated in Fig. 2. The wider the outputs distribute, the more uncertain they are. In addition, we can identify the variation range of the outputs and determine the value with the highest probability from the distribution. To perform the interval estimation of the outputs, we use the 5th and 95th percentile. The 5th/95th percentiles mean that there are 5%/95% of the observations whose values are smaller than it, respectively. For example, by identifying the 5th/95th percentile of a damper's position adjustment result, we can say that the position of this damper will be within this range by the chance of 90%. Similarly, by identifying the 95th percentile of the fan pressure, we can say that the required fan pressure will have to be greater than this value to guarantee 95% chance of being sufficient.

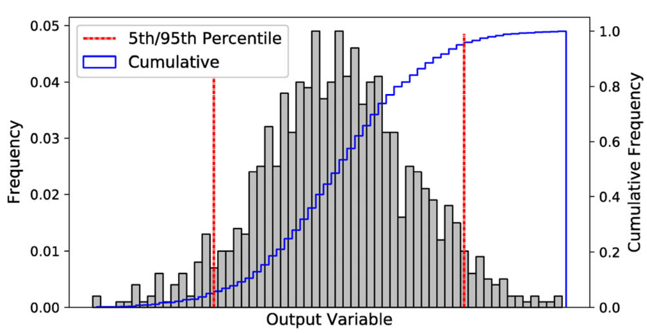

Fig. 2 Illustration of uncertainty analysis results

In addition, the percentile could be user-defined in this framework according to the desire of the stakeholders for risk management. For example, if the building owner puts more emphasis on the initial investment, they can use a lower percentile to size the fan, like 90th percentile, which will lead to a smaller fan capacity but a higher risk of under-sizing at the same time. Therefore, we can see that this framework of uncertainty analysis can assist the stakeholders to make a more informative and flexible decision.

2.5 Sensitivity analysis

Sensitivity analysis provides a way to find which factors are the most influencing ones resulting in the variation of the outputs and gives a direction on how to moderate the impact from the uncertainties. The Pearson correlation coefficient (PCC), and the Spearman rank order correlation coefficient (SRCC) are usually used to estimate the correlation between two variables. PCC only measures the strength of the linear relationship, while SRCC is the non-parametric measurement of rank order correlation (whether linear or not) (Vořechovský 2012). Therefore, we use SRCC as the sensitivity indicator in the study. Since there are no identical data pairs in this application, the SRCC can be calculated by the following formula:

$$\mathrm{SRCC} = 1 - \frac{6\sum d_i^2}{n\left(n^2-1\right)} \tag{4}$$

where d_i is the difference between the two ranks of the variables in the i-th observation. The "rank" is the ordering label, like "first", "second", etc, to different observations of a particular variable. n is the number of observations.

Sometimes the input parameters can be categorized into several groups. Specifically, in this study, we have the PLCs of the dampers, the straight branch of the junction, and the vertical branch of the junction. We can group the sensitivity indicators together (Sun et al. 2014), i.e. the SRCCs in this case, by summing up the SRCC of each parameter in the same group to estimate the correlation between this input group and the output variable. Since the SRCC takes the values between −1 and 1, we take the absolute value of each SRCC before summation to avoid the offset from summing up the positive and negative values.

3 Case study

3.1 Case description

We choose a case of an air-side system with a typical branched topology, as shown in Fig. 3. This illustrative air-side system has a supply fan serving eight terminals in total, which are marked as "T". The design airflow rate for each terminal is 300 m^3/h, which makes the system total flow rate 2,400 m^3/h. The ductwork system has seven T-junctions, marked as "J", and ten balancing dampers, marked as "D". The straight ducts between the fan and Junction #3 or each pair of two adjacent junctions are all set as one-meter long for the purpose of simplicity. The ducts are sized according to the recommended maximum velocity range from engineering experiences, i.e. 6 – 8 m/s for the main ducts and 3 – 6 m/s for the branch ducts.

Figure 4 presents the model implementation for the case study. Table 3 lists the references of all the modules in Fig. 4. The models of the fan, dampers, and junctions are connected as shown in Fig. 3 and configured as the aforementioned settings. The straight ducts are modelled within the junction models, as resistance "res1" as shown in Fig. 1. The polynomial models of the PLCs for junctions are regressed using the data from the reference (Wang et al. 2018). In this case study specifically, we select the cubic polynomial model. As in Eq. (2), the coefficients of a_0 to a_4 for the straight branch equal to 0.4526, −0.9833, 0.2801, 0.2785 sequentially while for the vertical branch the coefficients equal to 0.6014, −1.1521, 1.1244, −0.0537.

As mentioned at the end of Section 2.1, an ideal fan model is adopted which can always generate the design system airflow rate. The model of "MassFlowSource_T" from the Modelica Buildings Library is adopted to represent

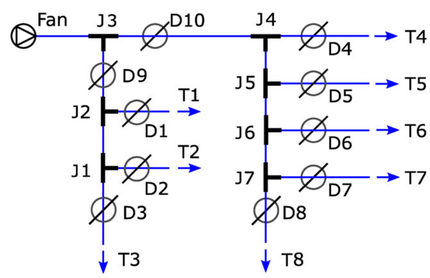

Fig. 3 Schematic of the air-side system for case study

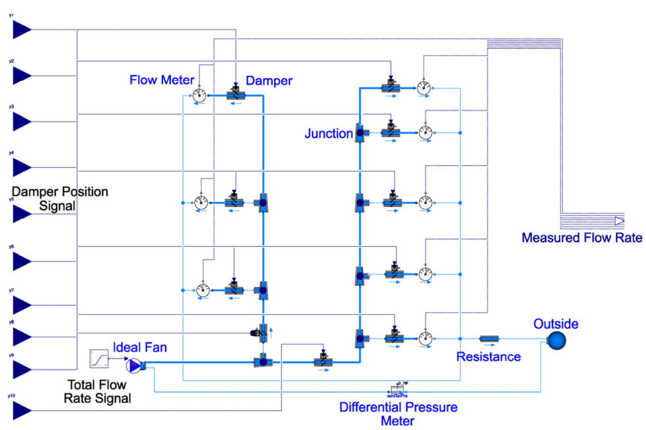

Fig. 4 Modelica model for the case study

Table 3 References of the modules used for building the case system

Modules	References
Damper position signal	"Modelica.Blocks.Interfaces.RealInput"
Total flow rate signal	"Modelica.Blocks.Sources.Ramp"
Ideal fan	"Buildings.Fluid.Sources.MassFlowSource_T"
Flow meter	"Buildings.Fluid.Sensors.MassFlowRate"
Damper	Modified based on "Buildings.Fluid.Actuators. Dampers.Exponential"
Junction	New junction model built as in Fig. 1
Differential pressure meter	"Buildings.Fluid.Sensors.RelativePressure"
Resistance	"Buildings.Fluid.FixedResistances.PressureDrop"
Outside	"Buildings.Fluid.Sources.Boundary_pT"
Measured flow rate	"Modelica.Blocks.Interfaces.RealOutput"

the fan. The pressure value at the outlet port of the "MassFlowSource_T" model will be calculated according to the downstream pressure drops. The pressure needed is measured by a differential pressure meter located between the fan and the outside boundary, which calculates the value of total pressure difference. The pressure of the outside boundary is set as the default value, i.e. 101,325Pa. To model the pressure loss of the supply inlets and the differential pressure between inside and outside, we adopt a resistance module whose nominal pressure loss is 20Pa at the design airflow rate. In addition, eight flow meters are used to measure the airflows through each terminal for the calculation of airflow ratio as required in the balancing procedure.

To introduce the PLC uncertainties into the models of junctions and dampers, we multiply the referenced value of PLC, which is calculated by the models, by a correction factor (CF) generated by the LHS method. Since we have ten balancing dampers and seven junctions, and for the junctions, there are two PLCs for the straight branch and vertical branch respectively, there are a total of 24 correction factors as the inputs for the uncertainty analysis. Table 4 lists the input variables, the distribution they follow and the output variables to be analysed in this case study. As for the implementation, the Modelica model will read an external txt file, which restores the correction factors of all junctions and dampers, and update the correction factors correspondingly at the beginning of running a new case.

Table 4 The input and output variables considered in the case study

Inputs		Outputs
Name	Distribution	
CF for the PLC of straight branch of junction ("js1" – "js7")	Uniform	Damper positions
CF for the PLC of vertical branch of junction ("jv1" – "jv7")	Uniform	Flow rate ratios
CF for damper's PLC ("d1" – "d10")	Uniform	Fan pressure

As presented in Section 2.2, the correction factors are ranging from 0.6 to 1.4, i.e. ±40% around the original PLC value. We set it up as Scenario A, which has the widest uncertainty range for the PLCs of both junctions and dampers. In addition, we also set up another two scenarios of reduced uncertainty levels as shown in Table 5 in order to investigate how the outputs would alter if the uncertainty of the damper models were reduced. The reason why we only narrow down the uncertainty range of dampers is based on the results of sensitivity analysis from Scenario A, which will be expatiated in Section 3.3. For each scenario, we use the LHS method to generate 1000 samples of the correction factors and perform the virtual air loop balancing by simulation. The number of the samples is well above the minimum required value (Hyun et al. 2007). The minimum number of the samples could be calculated by $4k/3$, where k is the number of inputs and equals to 24 in this case. Therefore, 32 cases are required at least. In addition, in order to avoid the influence of the sampling size on the output results, a convergence test using 2000 samples is performed as well. The distributions of the outputs using 2000 samples are identical to the results of using 1000 samples, which guarantees the convergence.

Table 5 Scenarios of different uncertainty ranges for PLCs of junctions and dampers

Scenario #	Correction factors for junctions' PLCs	Correction factors for dampers' PLCs
A	0.6 – 1.4	0.6 – 1.4
B	0.6 – 1.4	0.8 – 1.2
C	0.6 – 1.4	0.9 – 1.1

3.2 Uncertainty analysis for Scenario A

The uncertainty analysis is performed based on the histograms of the output variables. Since the number of bins would affect the shape of the distributions, we select the number of bins as the smallest value which can generate the converged shape of distribution. Firstly, Fig. 5 shows the flow ratio result of each terminal under Scenario A. Each sub-figure is a frequency histogram of the flow ratio of certain terminal. The bars in green mean the position values which are between the 5th and 95th percentile. We can see that after the virtual balancing, the final airflow through each terminal satisfies the required ±10% tolerance. The proportional method works very well for the studied air loop as expected.

Secondly, Fig. 6 shows the position adjustment results of each damper under Scenario A. We can clearly see

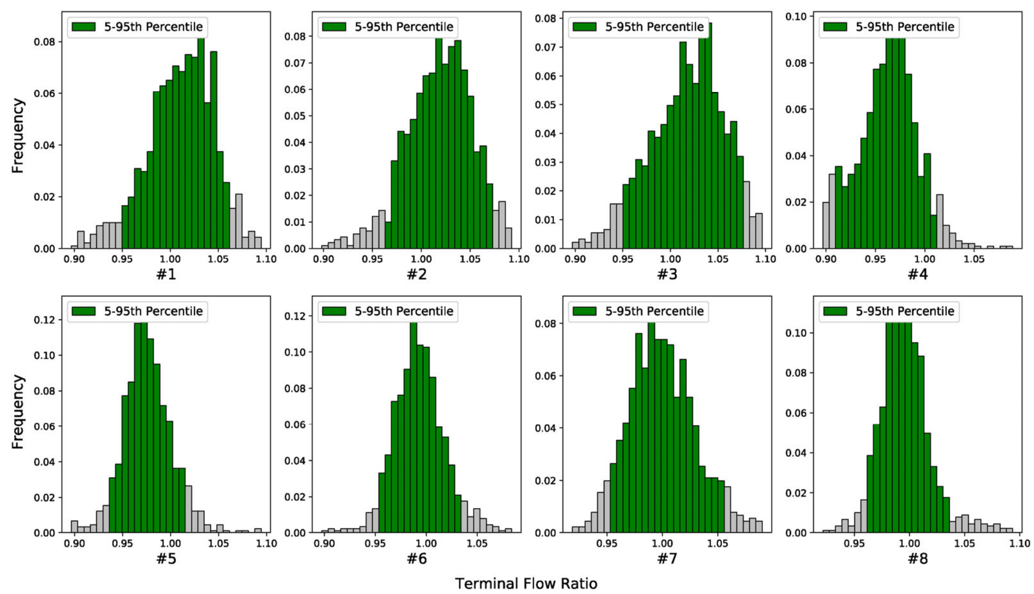

Fig. 5 Terminal flow ratio results under Scenario A

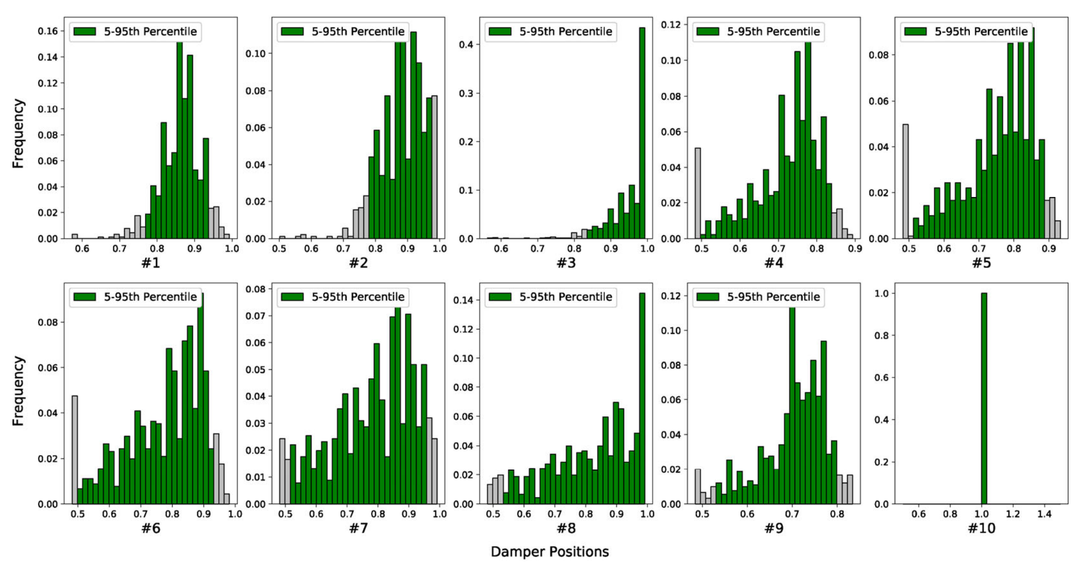

Fig. 6 Position adjustment results of each damper under Scenario A

that adjusted positions for most dampers distribute over a considerably wide range. For example, the adjusted positions for damper #6, #7, and #8 are ranging from 0.5 to 1. The interval of 5th – 95th percentile is similarly wide as well. However, it is good to see that the most disadvantaged branch remains stable no matter how the PLCs alter. Because the branch balancing damper #10 is always kept 100% open, the branch with the five terminals is always the more disadvantaged one. If we compare the variation range of the positions for the dampers on different branches, i.e. dampers #1 – #3 versus damper #4 – #8, it is apparent that the positions for damper #4 – #8 spread over a wider range, which means the dampers on the most disadvantaged branch are more sensitive to the uncertainty of the PLCs.

3.3 Sensitivity analysis for Scenario A

From the results of preliminary uncertainty analysis for Scenario A, unfortunately, we have to admit that the variation ranges of position adjustment results are quite large given the uncertainty level of PLCs. This result cannot provide any meaningful guidance for in-situ work of TAB. Thus, we need to reduce the uncertainty of the PLCs of the junction and damper models so that the simulation results could be practically applicable. Therefore, we have to perform sensitivity analysis in order to focus on the most important sources of uncertainty.

Figure 7 shows the SRCCs for all the significant PLC inputs with respect to the position adjustment result of

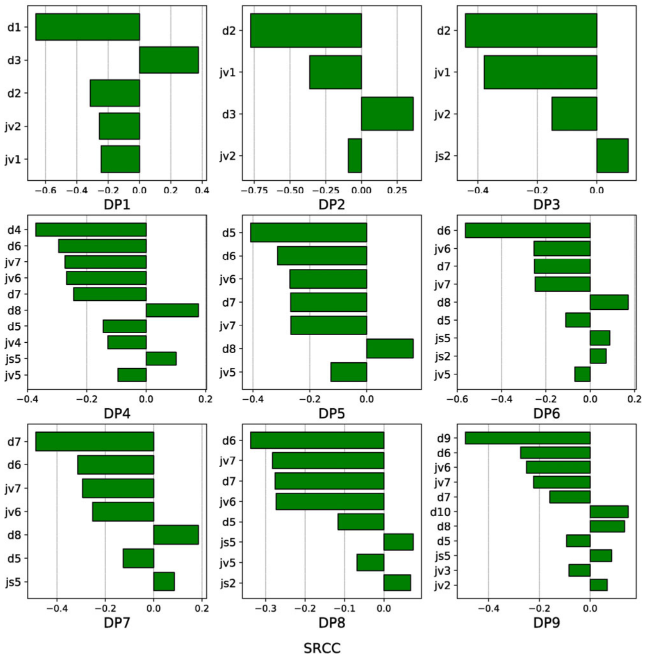

Fig. 7 SRCC for position adjustment result of each damper

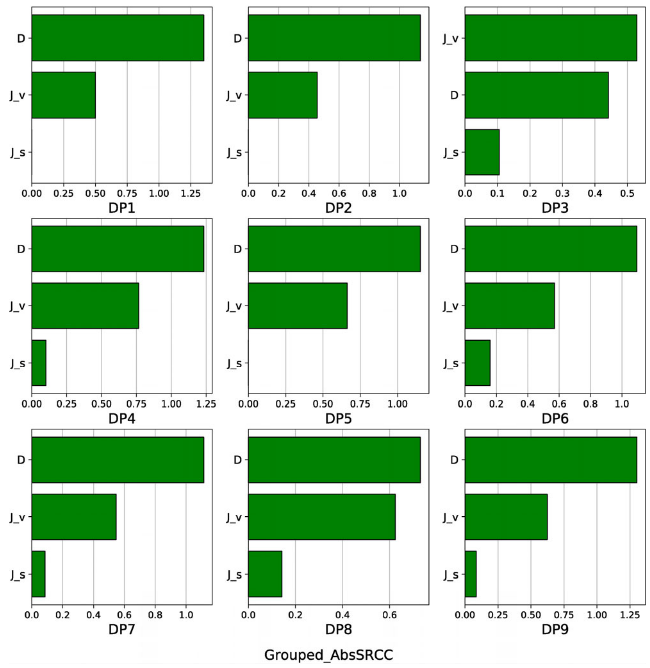

Fig. 8 Grouped absolute SRCC for position adjustment result of each damper

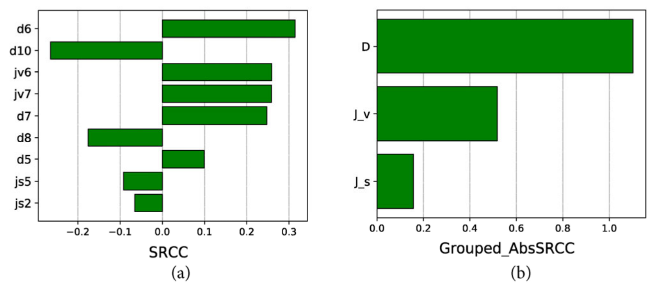

Fig. 9 Sensitivity analysis result of fan pressure

each damper. Hereby, the word "significant" means that the P-values of the SRCCs for these uncertainty sources are smaller than 0.05. In each sub-figure, the *x*-axis label indicates which damper the result belongs to. For example, "DP1" means the position of damper #1. The *y*-tick labels represent the locations where the PLC correction factors are implemented in. For example, "d1" means damper #1, "jv1" means the vertical branch of junction #1, and "js2" means the straight branch of junction #2. Since damper #10 is always 100% open, which means the position of it is insensitive to any of the input parameters, we only present the SRCC results for dampers #1 – #9. As we can see from the figure, the damper positions are most sensitive to the PLCs of themselves or the adjacent dampers and junctions. For example, the first-ranking source for DP1 is the PLC of damper #1, and the first-ranking source of DP3 is the PLC of the adjacent damper to it, i.e. damper #2. In addition, from the number of the bars in each sub-figure, we can see that the dampers on the most disadvantaged branch, i.e. dampers #4 – #8 are sensitive to more sources, so does the branch balancing damper for the other branch, damper #9.

Then we present the grouped absolute SRCC results in Fig. 8 from which we can clearly see that the position adjustment results are more sensitive to the PLCs of the dampers. Eight out of nine damper positions (except for damper #3) take the dampers' PLC as the first-ranking sensitivity source. Figure 9 shows the similar sensitivity analysis result of the other output variable, i.e. fan pressure, from which we can draw the same conclusion that the fan pressure is also more sensitive to the uncertainty of dampers' PLC models.

3.4 Comparison among Scenarios A, B, & C

From the sensitivity analysis results, we identify the most influencing uncertainty sources, i.e. the dampers' PLCs, to the outputs of the position adjustments and fan pressure. Since the community of duct fittings has already realized the necessity of addressing the effect of closely connection as mentioned in introduction, the uncertainty from the dampers' PLC model can be expected to be reduced by more dedicated researches in the future. Therefore, we design the Scenarios B and C, under which the uncertainty ranges for the dampers' PLCs are reduced to ±20% and ±10%, respectively. Then we can evaluate the ultimate potential of such framework by comparing the results of the three scenarios. Figure 10 shows the comparison results among Scenarios A, B, and C. On the left side are the overview results of the position adjustments for each damper under Scenarios A, B, and C. On the right side are the results of the fan total pressure correspondingly. The flow ratio results of

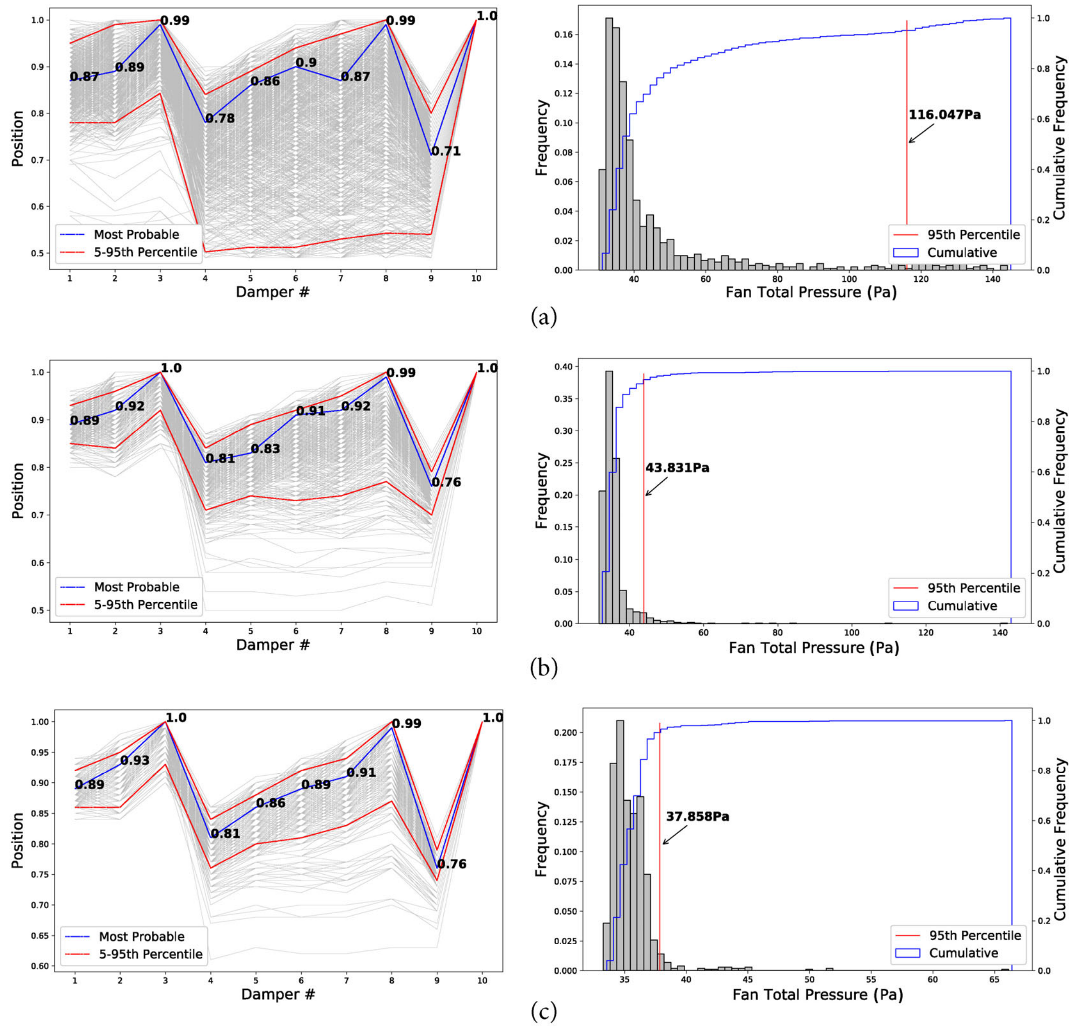

Fig. 10 Uncertainty analysis results of the damper positions and fan pressure under Scenarios A (a), B (b), and C (c)

three scenarios are not shown to avoid redundancy, because the flow ratios of all terminals are within the required range of ±10% bias after the balancing.

In the figures of position adjustment results, each grey line represents the result from one single time of simulation based on one sample of PLC correction factors. The dashed lines in red and blue represent the value of 5th/95th percentiles and the value with the highest probability, respectively. The most probable position for each damper is annotated with its value. The gap between the two red lines covers 90% of the results, which can be used as a guideline for the on-site damper tuning. When the practitioners are balancing the air loop on-site, they can try the most probable position first. Then if the flow ratios are not satisfying, they can adjust the dampers within the gap between the 5th and 95th percentiles for fine-tuning. From the comparison among the three scenarios, the gap becomes narrower as the uncertainty level of dampers' PLC decreases. In Scenario B, the biggest gap appears at damper #8, which is around 0.23, while in Scenario C the gap is furtherly reduced to less than 0.15.

In the figures of fan pressure results, the grey bars represent the distribution of fan pressure values. The blue line is the cumulative frequency curve. Since we only have to estimate the lower boundary of the fan pressure for the purpose of sizing, we annotate the 95th percentile in the figure. We can see the potential benefit of reducing the uncertainty of the dampers' PLC. From Scenario A to B, the 95th percentile is reduced from 116.05 Pa to 43.83 Pa by 62.23%, while the reduction from Scenario B to C is not that huge as before but still by 13.62%. The required fan pressure determined through this framework can be reduced furtherly when we use the more accurate PLC models. The initial investment of the fan can be reduced accordingly. In addition, a higher operational efficiency of the fan can be expected since the fan pressure is closer to its required value.

Another bonus benefit of this framework comes from the fact that the air loop cannot be balanced within 10 iterations of performing the proportional procedure for some of the combinations of PLC correction factors in Scenario A. There are only 906 (out of 1000) valid results for Scenario A, while all the cases under Scenarios B & C succeed in being balanced. The designed structure for the air duct system may have the risk of having difficulties in being balanced given the uncertainty level of Scenario A. In this case, the probability is nearly 10%.

Therefore, the proposed method can firstly guide the on-site tuning of the balancing dampers with both the most probable damper position values and the practical variation ranges. Secondly, the building owners can have the flexibility for fan sizing acquainted with the quantitative risk of under-sizing. If the building owners want to reduce the initial investment, they can use the relatively lower percentiles to choose a lower fan pressure but with a higher risk of under-sizing. This natural request can be easily supported by the proposed framework but not by the traditional sizing method. Thirdly, by going through this frame of work, a reminder can also be provided for the designers to double check whether the current structure of the duct system is appropriate or not for the subsequent balancing.

4 Conclusion

This paper proposes a simulation-based uncertainty analysis method to provide a quantitative guideline for the work of on-site air loop balancing and fan sizing, in which the uncertainty of using the referenced PLC data of dampers and junctions is addressed. The correction factors are assigned to the PLCs and are sampled using LHS method. Then the proportional method is adopted to obtain the positions of the balancing dampers so that the terminal flow rates are close to the designed values. After performing the simulations for all samples of the correction factors, the distributions of the dampers' positions and fan pressure needed could be determined. The 5th/95th percentiles and the most probable value could be identified from the histograms. The gap between the 5th/95th percentiles and the most probable value of the position adjustment results can provide a guidance for the balancing work in practice. On the other hand, the 95th percentile of the fan pressure can be used to size the fan properly.

The sensitivity analysis reveals the priority order for the work of model improvement in the future. It is necessary to obtain the more accurate models of the damper's PLC to reduce the uncertainty so that the proposed framework could provide a more accurate guidance for the on-site damper tuning. When the uncertainty level of the damper's PLC model is reduced to ±20%, the ranges of the damper position results are significantly narrowed down, and the required fan pressure also decreases considerably.

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