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Experimental Validation of a Target Method for Balancing Exhaust Ventilation Duct Systems with Dampers

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This study tested the "Target Method" for adjusting ventilation systems. The Target Method is based on target hood static pressures (SPh_{target}) computed in a manner designed to take into account the estimated effects of dampers on the fan, the order of damper adjustments, and the ratio of the prebalancing branch airflows to their goals. It is aimed at achieving a desired relative distribution of airflows even if the fan output is far from ideal. The method assumes the fan output will be adjusted after the dampers are adjusted. The method is expected to produce lower fan pressure requirements than some commonly used methods. The method was tested on a working seven-branch, full-sized exhaust ventilation system in the West Virginia University Exposure Assessment Laboratory. Two radically different target distributions were tested with two replications apiece. Both target distributions of airflows were substantially different from the initial distribution, providing a high degree of challenge to the methodology. For each distribution, SPh_{target} values were computed for the first round of adjustments. Each damper was adjusted until the observed value of the hood static pressure was nearly equal to that damper's computed SPh_{target} value for that distribution. Each of the other branch dampers was adjusted similarly in turn. After the first round of adjustments, the median ratio of SPh to SPh_{target} provided the targets for the partial second round of adjustments. Twenty-point Pitot traverses were used to determine the airflow in each branch duct both before and after employing the adjustment method, providing the basis to determine the success in reaching each of the two desired distributions. The percentage of excess airflow (assuming ideal adjustment of the fan speed) was below 2.2% for all experimental trials. An unpublished study by Vivek Balasubramanian showed that excess airflow was 4.8% to 8.5% in the same experimental system after two full rounds of adjustment using the customary Target Method. Under poor measurement conditions, the greater uncertainty of pressure measurements would likely produce somewhat higher excess airflows.

Keywords balancing, dampers, ventilation

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INTRODUCTION

Industrial ventilation systems are important in protecting worker health. However, some systems have suboptimal performance due to poor airflow distribution. Whether the distribution has deteriorated due to changing conditions (e.g., by erosion, substance accumulation, or wear) or has been suboptimal from the beginning due to poor construction, the airflow at some hoods does not match current needs. A portion of the airflow can be shifted from one branch duct to another by changing the relative resistance to flow of the two pathways.[1] This can be done by strategic substitution of members (e.g., elbows with different resistances), but that can be discouragingly costly and disruptive. Ventilation system owners are more likely to take timely corrective actions if there is a nondisruptive and less expensive way to shift airflows among branches.

Although dampers can be useful in redistributing the airflows in a system, drastic changes in airflow are likely to produce excessive pressures in the system unless undersized ducts are replaced by larger ducts.[1] Some ventilation authorities argue against the use of dampers, favoring "balance by design" to achieve desired airflows. In particular, Caplan[2] stated that it was often difficult to adjust dampers properly and that the dampers themselves could encourage blockages. Other problems exist, but the widespread use of dampers suggests that ventilation system owners generally find dampers worth whatever problems they cause.

Balancing with adjustable dampers is a very common solution that need not disrupt operations and has relatively low capital costs. By judicious adjustments of all of the branch dampers, the distribution of airflows among the branches can be changed substantially without replacing any duct system components. Methods commonly used today appear to be tedious and difficult, in part, because of the interactive effects on the fan and other branches when a given branch damper is adjusted. Increasing the resistance of a branch reduces its flow and increases the flows to other branches.[1] By accounting for this shift in airflow, the Target Method[3] aims to be less tedious and difficult.

In an ideally balanced exhaust ventilation system, the airflow at each branch (Q_{br}) should equal the airflow goal for that branch ($Q_{br\text{-}goal}$). Ignoring the typically modest effects of density differences across the system, mass balance requires that the fan airflow roughly equal the sum of branch airflows (assuming no substantial leaking). Likewise, the ideal fan airflow ($Q_{fan\text{-}goal}$) must roughly equal the sum of the $Q_{br\text{-}goal}$ values. Hence, one can demonstrate by algebraic manipulation that a system with perfect distribution of airflows will have $Q_{br}/Q_{br\text{-}goal} = Q_{fan}/Q_{fan\text{-}goal}$ for each branch. If it is also true for a perfectly distributed system that if $Q_{fan} = Q_{fan\text{-}goal}$ then $Q_{br} = Q_{br\text{-}goal}$ for each branch. The latter will happen only if the fan output is ideally adjusted and if all dampers are adjusted perfectly.

Given the likelihood of imperfect damper adjustments, the minimum acceptable airflow would exist when for at least one branch $Q_{br} = Q_{br\text{-}goal}$, while for all other branches $Q_{br} \geq Q_{br-goal}$.[1] Thus the minimum acceptable final fan airflow ($Q_{fan-minimum}$) at this point can be estimated as:

$$Q_{fan\text{-}minimum} = \frac{Q_{fan}}{\text{minimum of}\left\{\frac{Q_{br}}{Q_{br\text{-}goal}}\right\}} \tag{1}$$

where Q_{fan} and Q_{br} were determined after adjusting the dampers and prior to adjusting the fan output.

For example, if the minimum value of $Q_{br}/Q_{br\text{-}goal}$ is 2, then the fan output can be reduced to one-half the value measured after adjusting the last branch damper. If $Q_{br}/Q_{br\text{-}goal}$ is 0.5, then the fan output should be doubled.

To further complicate matters, the resistance of each damper contributes to the overall resistance to flow of the entire duct system. Therefore, as each damper resistance is increased, the fan pressure increases and the fan airflow falls. The reduction in airflow and the increase in fan pressure depend on the characteristics of the fan and on the amount of change in the system resistance. The effects of dampers on system pressures depend on the balancing strategy and whether the fan airflow is initially excessive, nearly ideal, or insufficient.

Goal Method

In our experience, the great majority of ventilation practitioners adjust dampers using a very basic "Goal" Method. We have found no literature documenting such a method. It is based on anecdotal evidence, and we think it approximates the way many people who attempt to balance a ventilation system would go about the task. We present it here to illustrate the problems and difficulties associated with balancing that a good balancing strategy must address.

In the Goal Method, the first branch's damper is adjusted until its observed airflow (Q_{br}) equals its $Q_{br\text{-}goal}$. This action is consecutively repeated for the dampers on each of the other branches. Even though this method requires no calculations, the two major problems impairing its practicality and outcome are: (1) the shifting of all airflows in the system with each damper adjustment, and (2) the impossibility of predicting at the outset the effect of adjusting all dampers on the airflow produced by the fan.

The goal airflows are never achieved in one round because of the interaction between the fan, the damper insertion depths, and the airflows in each branch.[3] When a damper on one branch is pushed in, the airflow in that branch decreases, the fan airflow increases by somewhat less, while the airflows in each of the other branches increase by differing amounts depending on their location in the system. As each succeeding damper is adjusted, the airflows through those branches already adjusted become increasingly greater than their value of $Q_{br\text{-}goal}$. By the time the last damper is adjusted to achieve that branch's $Q_{br\text{-}goal}$, all but the last branch will have excess airflows, necessitating a second—and perhaps third—round of adjustments.

If this method is completed successfully, each Q_{br} will equal its $Q_{br\text{-}goal}$ without adjusting the fan output directly—assuming that the initial Q_{fan} was well above $Q_{fan\text{-}goal}$. The dampers on the branches will have produced not only the desired distribution but will have "throttled down" the total fan airflow to close to $Q_{fan\text{-}goal}$. If the fan output had been substantially excessive prior to adjusting dampers, the fan pressure will be substantially higher after adjusting dampers than the minimum possible fan pressure. On the other hand, if the fan output had been substantially low prior to adjusting dampers, it will be impossible to achieve $Q_{br} = Q_{br\text{-}goal}$ for all branches, since there would not be sufficient airflow to go around. The practitioner would have to reset the fan output to a substantially higher level then start adjusting the dampers over again.

Proportional Methods

The practitioner using a proportional method attempts to adjust a given damper until the airflow in the branch equals the desired *fraction* of the fan airflow. After all the dampers are adjusted, one adjusts the fan speed until the most deficient branch airflow equals the goal airflow ($Q_{br\text{-}goal}$). By decoupling the fan speed from the measurements, this method removes the problem of insufficient or excessive initial Q_{fan}, but the problem of shifting airflows among branches remains.

Guffey[1] described a proportional system based on the ratio of the hood static pressure (SPh) to the static pressure at the end of the branch duct. This method claims to produce the minimum possible damper insertion depths and the minimum possible duct and fan pressures. However, this method requires computations that are so complex and numerous that predictions are not feasible without specially written computer software.

ASHRAE's testing and balancing guidelines for HVAC systems[4] advocate that practitioners should balance proportionately. The fan is first adjusted to the system design airflow, and then the total fan airflow is distributed proportionately among the outlets. ASHRAE gives no directions on how to compute the airflow targets for each outlet. Their guidelines account for neither the shifting of the airflows among branches nor the reduction in total airflow at the fan during balancing.

These guidelines pertain only to supply air systems, and not exhaust ventilation.

The Sheet Metal and Air Conditioning Contractors' National Association (SMACNA)[5] describes a proportional method for supply air duct systems. The ratios of measured airflow to design airflow ($Q_{br\text{-}ratio}$) (Eq. 6) are determined for each branch, and the dampers are adjusted in sequence from the branches most deficient in airflow (lowest value of $Q_{br\text{-}ratio}$) to the least deficient (greatest value of $Q_{br\text{-}ratio}$). The damper on the most deficient branch is not adjusted. The damper of the second most deficient branch is adjusted until its $Q_{br\text{-}ratio}$ converges with $Q_{br\text{-}ratio}$ of the first branch. As the damper on the second branch is pushed in, its $Q_{br\text{-}ratio}$ drops while $Q_{br\text{-}ratio}$ of the first branch rises.

After adjusting the damper, the practitioner must measure that branch and the previous one to satisfy that their $Q_{br\text{-}ratio}$ values are equal. The remaining branch dampers are adjusted in sequence so that their value of $Q_{br\text{-}ratio}$ equals the mean value of $Q_{br\text{-}ratio}$ of the branch being adjusted and all the preceding branches. The airflows in each of the branches already adjusted should rise to nearly equal the resultant $Q_{br\text{-}ratio}$ of the branch adjusted. The target for each branch could be computed as:

$$\frac{Q_i}{Q_{goal(i)}} = \frac{\sum_{i=1}^{i} \frac{Q_{(i)}}{Q_{goal(i)}}}{i} \tag{2}$$

There are three weaknesses and inconveniences with this method. First, for branches in the same subsystem, SMACNA advises measuring both the adjusted branch and the previous branch after each damper adjustment. These measurements are in addition to measuring all branches initially. If each damper is adjusted perfectly in only one attempt, the number of measurements will be three times the number of branches minus two. If each damper is adjusted twice, the number of measurements increases to five times the number of branches minus four. A subsystem with 10 branches thus will require at absolute minimum 28 measurements, including the initial round. Even if each measurement were instantaneous, the time to move back and forth and up and down ladders would be substantial with so many measurements. Second, one must use and adjust a damper not only on each of the branches (except one) but also on submains that connect subsystems of branches. Third, although the method is apparently widely used, we have been unable to find published, experimental determinations of its effectiveness.

It is important to note that $Q_{br\text{-}ratio}$ for the most deficient branch is by definition the lowest ratio. The minimum necessary ratio for a perfectly balanced system would be:

$$\frac{Q_{br}}{Q_{br\text{-}goal}} = \frac{Q_{fan}}{Q_{fan\text{-}goal}} \tag{3}$$

One would expect the value of $Q_{fan\text{-}final}/Q_{fan\text{-}goal}$ to fall somewhere near the median value of $Q_{br}/Q_{br\text{-}goal}$, which is necessarily higher than the minimum value. Thus, using the SMACNA method, extra dampers on the submains are inserted than would have been necessary in an ideal method. As a result, duct and fan pressures would be higher than necessary.

The Target Method[3] tested in this study is a proportional method designed to address the problems of inappropriate fan speed and shifting airflow among branches. Because the relative distribution of airflows among branches will change very little even if the fan airflow changes a great deal,[6,7] the Target Method is designed to allow adjustment of dampers to achieve branch airflow ratios equal to $Q_{fan\text{-}final}/Q_{fan\text{-}goal}$ (Eq. 3) but does not use that ratio as a direct target. Instead, it uses target values that account for the problems of both inappropriate fan speed and shifting airflows among branches.[3] The desired levels of airflow are then achieved by adjusting the fan output after all dampers are adjusted. That is, like other proportionality methods, the Target Method does not aim to attain a specific airflow level in each branch but instead seeks to obtain a fraction of total airflow.

The proposed equations are designed to anticipate the effects of adjusting dampers on the final fan airflow and on the shifts in airflow from the last adjusted branch to all other branches as they are adjusted. The equations determine the airflow one would use as targets when actually adjusting each branch. Instead of attempting to adjust dampers to achieve either a goal airflow or specific ratio of Q_{br} to $Q_{br\text{-}goal}$, the method employs "target" values of airflow, hood static pressure (SPh), or centerline velocity pressure (VPcl). These targets are temporary goals (i.e., targets) whose values are deliberately not proportional to the desired final values and are used in adjusting each damper only during the first round of adjustments. To demonstrate what happens if the goal ratios were used as the targets, we now propose a simple, obvious alternate proportionality method wherein one simply adjusts each branch to a target airflow that is computed by:

$$Q_{target} = Q_{goal} \times \frac{Q_{fan\text{-}goal}}{Q_{fan\text{-}open}} \tag{4}$$

where the goal airflow is multiplied by the ratio of the airflow at the fan divided by the airflow at the fan measured when all dampers are fully open. Those $Q_{targets}$ would work poorly because: (1) they do not take into account the shift in airflows from branch to branch during balancing, and (2) it is not likely that the fan airflow after adjusting dampers will just happen to equal $Q_{fan\text{-}goal}$. Therefore the target values should not be proportional to goal values since values of Q, VPcl, and SPh will (1) change as each subsequent damper is adjusted (i.e., each value is adjustment order-dependent), and (2) they will change again when the fan output is adjusted at the end.

APPARATUS

The study was carried out on a full-sized exhaust ventilation system at the West Virginia University Ventilation and Exposure Assessment Laboratory. The system had seven branches designed to have diverse resistances to flow due to their different duct lengths, number of elbows, and types of hood transition (Figure 1, Table I). The 20-gauge, galvanized

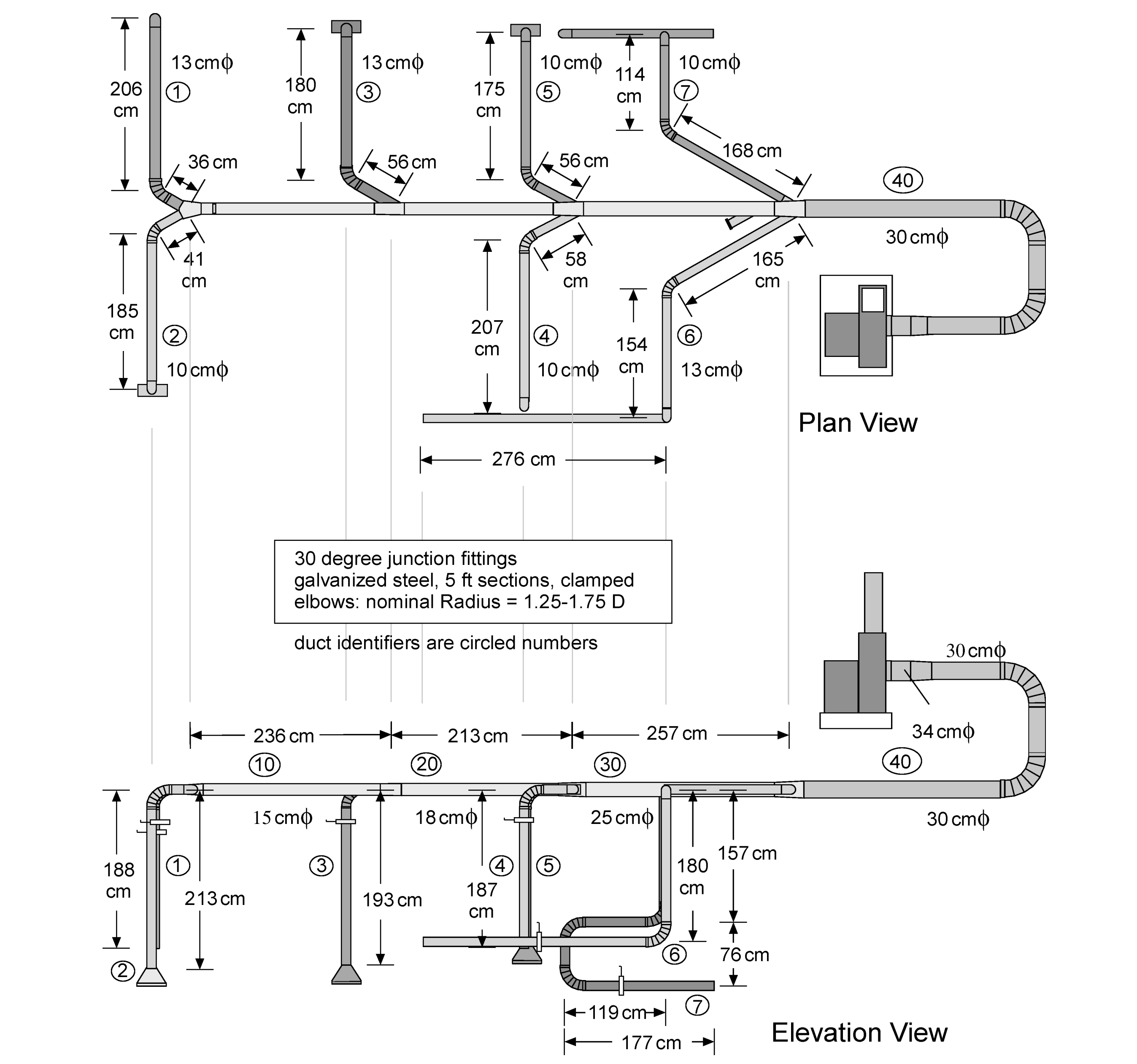

FIGURE 1. Schematic of the experimental ventilation duct system

steel ductwork was manufactured and donated by Nordfab Inc. (Thomasville, N.C.). For this study, the clamped joints were sealed with caulking to eliminate air leakage and leak tested. Airflow was provided by an Aerovent (Minneapolis, Minn.) fan (No. 315BI-SWCB-3435-3 Type SWCB Ser. 8708562-001), which was run at least 30 min prior to taking measurements. The temperature in the room varied little during testing.

A TSI (Shoreview, Minn.) DP-Calc digital manometer (model 8702) was used in conjunction with a standard 0.32 cm (1/8″) stem Pitot tube (Dwyer Instruments Inc, Michigan City, Ind.) for all static pressure and velocity pressure readings. The digital manometer was calibrated using a Dwyer hook gage (model 1425). After leaving the manometer on for at least 30 min to stabilize, the digital manometer was calibrated each day against water gauge levels of 0.635, 1.270, 1.905, 2.540, 3.175, 5.080, 7.620, 10.160, 12.700, and 15.240 cm (0.25, 0.50, 0.75, 1.00, 1.25, 2.00, 3.00, 4.00, 5.00, and 6.00 inches) immediately before measurements were taken. The time average was set at 1 sec to measure velocity pressure and at 5 sec to measure static pressure. The Pitot tube was held in place at correct insertion depths using a custom-made device[8] with interchangeable scales that were premarked to the insertion depths for each duct diameter.

TABLE I. Specifications of the Ventilation System Used in the Study

Run	Run Type	Inner Diameter	60° Elbows, 12.7 cm (5″) Radius	60° Elbows, 17.8 cm (7″) Radius	60° Elbows, 12.7 cm (5″) Radius	60° Elbows, 17.8 cm (7″) Radius	90° Elbows, 20.3 cm (8″) Radius	Nipples	Abutments Between Tubes	Run Length (cm)	Length from SPh to SPend (cm)	Hood Type
1	Branch	12.3 cm (5″)		1			1	1	6	429.26	294.64	Naked
2	Branch	9.8 cm (4″)	1			1		1	8	439.42	346.71	30.5 cm × 5.2 cm (1 2″ × 6″) opening, 22.9 cm (9″) deep
3	Branch	12.3 cm (5″)		1			1	1	7	429.26	261.62	30.5 cm × 15.2 cm (12″ × 6″) opening, 22.9 cm (9″) deep
4	Branch	9.8 cm (4″)	1			1		1	7	450.85	373.38	Naked
5	Branch	9.8 cm (4″)	1			1		1	7	419.1	337.82	30.5 cm × 15.2 cm (12″ × 6″) opening, 22.9 cm (9″) deep
6	Branch	12.3 cm (5″)	1		2			3	11	748.03	694.69	Naked
7	Branch	9.8 cm (4″)	1		2	2		5	17	811.53	728.98	Naked
10	Submain	14.9 cm (6″)							3	236.22		
20	Submain	17.5 cm (7″)							2	213.36		
30	Submain	25.4 cm (10″)							3	256.54		
40	Main	30.48 cm (12″)							1	111.76		

PROCEDURE

Barometric pressures, air temperatures, and relative humidity were measured using standard laboratory apparatus. Static pressures and velocity pressures were measured as described in the "Industrial Ventilation Manual"[9] using a Pitot tube and a digital manometer. Static pressures were measured at the duct centerline roughly 4 duct diameters (4D) downstream of each hood (SPh) and 4D upstream of each junction fitting for all branches and submains. Two perpendicular velocity pressure traverses were performed for each branch duct at least 8D downstream of disturbances (i.e., a hood or elbow) and at least 4D upstream of other disturbances (e.g., elbow or junction fitting).

Dampers were adjusted by pushing or pulling on the slide-gate handles until the measured SPh equaled the target value for that branch. Once the target was reached, the next damper in order was adjusted. After completion of the first round of damper adjustment, a second round of adjustments was done to achieve a different set of target SPh values. The second round did not adjust all of the dampers, but only those on the three branches whose share of SPh digressed most from their target share.

For this study, two sets of goal airflows for each branch (Distribution A and Distribution B, Table II) were used to diversify the changes between the distributions and strongly challenge the method. Each distribution was arbitrarily chosen to be radically different from the initial airflows and from each other. $Q_{fan\text{-}goal}$ was 1.2 m^3/s for both distributions. The dampers were adjusted to achieve each distribution twice. The order in which the distributions and their replications were tested was randomized. All dampers were pulled completely open before beginning the balancing procedure for a given replication.

The methodology for the Target Method used in this study is based on that published by Guffey.[3] The determination of target values and the order of adjustments methodology for this study followed the Target Method[3] except for the adjustment of the fan after balancing the dampers. As specified by the method, the existing airflows with all dampers completely open first were determined from initial measurements. The goal distribution of airflows was chosen and the targets to meet them were determined. Two rounds of damper adjustments were carried out with measurements taken after each round to evaluate success. The significance of the treatment (choice of target airflow distribution) was analyzed using Datadesk statistical software (v.6). The confidence interval for the system excess airflow for each distribution was computed using the Student-T distribution.

The complete methodology followed in this study follows with explanations:

1. After determining the desired airflow ($Q_{br\text{-}goal}$) for each hood, compute $Q_{fan\text{-}goal}$ from:

$$Q_{fan\text{-}goal} = \left(\frac{1}{df_{fan}}\right)\sum_{i=1}^{n} df_i Q_{br\text{-}goal_i} \quad \textbf{(5)}$$

where i = ith branch duct
n = total number of branch ducts in the system
df = ratio of actual density to standard density
$Q_{fan\text{-}goal}$ = airflow goal for the fan

TABLE II. Damper Open, Goal, and Target Values for Round 1

Branch	$Q_{br\text{-}goal}$	$Q_{br\text{-}open}$	SPh_{open}	Q_{open}/Q_{goal}	FanFactor	Order	k	SPh_{goal}	Q_{target}	$SPh_{target1}$
Distribution A										
1	0.165	0.191	0.231	1.156		4	0.98	0.173	0.145	0.133
2	0.170	0.132	0.199	0.776		6	0.99	0.331	0.151	0.262
3	0.189	0.227	0.243	1.204		3	0.96	0.168	0.163	0.125
4	0.189	0.145	0.298	0.769		7	1.00	0.505	0.169	0.406
5	0.179	0.154	0.279	0.857		5	0.99	0.379	0.159	0.296
6	0.137	0.188	0.226	1.371		1	0.92	0.120	0.113	0.081
7	0.085	0.105	0.163	1.241		2	0.95	0.106	0.072	0.076
Fan	1.114	1.142		1.025	0.897					
Distribution B										
1	0.236	0.191	0.231	0.809		7	1.00	0.353	0.207	0.284
2	0.118	0.132	0.199	1.117		2	0.95	0.159	0.098	0.115
3	0.245	0.227	0.243	0.926		4	0.98	0.284	0.210	0.217
4	0.106	0.145	0.298	1.367		1	0.92	0.160	0.086	0.108
5	0.156	0.154	0.279	0.987		3	0.96	0.286	0.132	0.214
6	0.212	0.188	0.226	0.883		5	0.99	0.290	0.184	0.226
7	0.130	0.105	0.163	0.812		6	0.99	0.247	0.113	0.196
Fan	1.203	1.142		0.949	0.879					

Note: Airflows in m^3/s, hood static pressures in kPa.

2. Open all dampers, taking care to protect the fan motor, since the power it uses may increase substantially.
3. Using standard methods[9] do Pitot traverses on each branch duct and measure VPcl or SPh for each branch duct. This study used SPh. If one decides to use VPcl, measure VPcl while doing the Pitot traverse. One may also measure and record the amperage for the fan motor, the SP across the air cleaner, and other values for later use.
4. Use the traverse results to compute the "open" damper value of airflow ($Q_{br\text{-}open}$) for each branch using standard computations.[5]
5. Compute $\%Q_{br\text{-}ratio}$ for each hood from:

$$Q_{br\text{-}ratio} = \left(\frac{Q_{br\text{-}open}}{Q_{br\text{-}goal}}\right) \times 100 \tag{6}$$

Set $\%\min Q_{br\text{-}goal}$ equal to the minimum value of $\%Q_{br\text{-}goal}$.

6. Compute the initial fan airflow ($Q_{fan\text{-}open}$) from the sum of the observed airflows using:

$$Q_{fan\text{-}open} = \left(\frac{1}{df_{fan}}\right)\sum_{i=1}^{n} df_i Q_{br,\,i} \tag{7a}$$

Or, if the range of densities is small, then the density factors can be ignored, as was done in this study:

$$Q_{fan\text{-}open} = \sum_{i=1}^{n} Q_{br,\,i} \tag{7b}$$

7. Compute the FanFactor from:

$$\text{FanFactor} = \frac{\left(\frac{Q_{fan\text{-}open}}{Q_{fan\text{-}goal}}\right) + \min\%Q_{br\text{-}goal}}{2} \tag{8}$$

The FanFactor is intended to correct for the change in fan airflow due to adjusting dampers to their correct settings. The FanFactor term was derived[3] based on some assumptions about the relationship between the maximum change in airflow for any branch and Q_{fan}. Note that the $Q_{fan\text{-}open}/Q_{fan\text{-}goal}$ term increases the target value if the initial fan airflow ($Q_{fan\text{-}open}$) is excessive and reduces the target when $Q_{fan\text{-}open}$ is insufficient. Hence, it "corrects" for excessive or insufficient fan output in an attempt to remove initial fan output as an issue. The $\min(Q_{br\text{-}goal})$ term tends to increase the target value substantially if even one branch has much less than the fraction of fan airflow it should have. As an example, if initially $Q_{fan\text{-}open} = Q_{fan\text{-}goal}$ and the lowest ratio of Q_{br} to $Q_{br\text{-}goal}$ is one-half, then the target airflow would fall by 25%. This is reasonable because the dampers will have to create a great deal of resistance to increase the duct pressures to the point that Q_{br} could double. That resistance would reduce the fan airflow to a level well below $Q_{br\text{-}goal}$. Hence, it would be impossible to achieve $Q_{br} = Q_{br\text{-}goal}$ for all branches. Instead, the target value is lower than $Q_{br\text{-}goal}$.

8. Rank order and number the branches based on their $Q_{br\text{-}ratio}$ values. Compute an order factor (k) value for each branch duct based on its rank order number (n) using:

$$k = (n/N)^{0.0445} \tag{9}$$

where k = factor less than one based on the order of damper adjustment
n = sequence number for adjustment of the damper
N = total number of branch ducts

The k value computed in Eq. 9 and employed in Eqs. 11a, 11b, and 11c is intended to "correct" for the effects of the interactions among branch airflows as dampers are adjusted[3] by forcing the practitioner to adjust to a value below the goal value. The method begins with all dampers open and adjusts the branches in sequence from those requiring the highest fraction of airflow to the lowest. Each damper adjustment reduces that branch's airflow and raises the other branches' airflows. The earlier in the sequence the branch is adjusted, the smaller the k value is to account for that branch's airflow increase incurred by the adjustment of the following branches. Values of k are computed from an equation developed by trial and error using simulated duct systems and "curve-fit" equations to model fans that fit those systems. The equation is of unknown efficacy for other systems and fans. For those who prefer to use a table instead of Eq. 9, Table III suggests values of k for ranges of n/N.

9. Compute the values of SPh_{goal} or $VPcl_{goal}$ from the initial values of Q_{br}, SPh, and VPcl for each branch from:

$$VPcl_{goal} = VPcl_{open}\left(\frac{Q_{br\text{-}goal}}{Q_{br\text{-}open}}\right)^2 \tag{10a}$$

$$SPh_{goal} = SPh_{open}\left(\frac{Q_{br\text{-}goal}}{Q_{br\text{-}open}}\right)^2 \tag{10b}$$

This study used SPh_{goal} as computed per Eq. 10b. The method calls for determining $VPcl_{open}$ and $Q_{br\text{-}open}$ for each duct just prior to balancing, then using both values in Eq. 10a. Based on our experience, there is little evidence that the relationship between the two changes during balancing unless the damper is very close to the measurement location. We specify that they should be

TABLE III. k Values for Damper Adjustment

n/N	k	n/N	k
0.00–0.10	0.90	0.51–0.60	0.98
0.11–0.20	0.93	0.61–0.70	0.98
0.21–0.30	0.95	0.71–0.80	0.99
0.31–0.40	0.96	0.81–0.90	1.00
0.41–0.50	0.97	0.91–1.00	1.00

well separated. Hence, whatever effects dents, elbows, debris, etc. have on the relationship between VPcl, VPavg, and Q for that section are accounted for by the procedure. The utility of Eq. 10a is unaffected by conditions at the VP traverse location as long as no changes occur there between the time open conditions are measured and the balancing is done.

10. Compute the values of Q_{target}, $VPcl_{target}$, and SPh_{target}:

$$Q_{target} = k \times FanFactor \times Q_{br\text{-}goal} \quad \textbf{(11a)}$$

$$VPcl_{target} = \left[k \times FanFactor \times \left(\frac{Q_{br\text{-}goal}}{Q_{br\text{-}open}}\right)\right]^2 \times VPcl_{open} \quad \textbf{(11b)}$$

$$SPh_{target} = \left[k \times FanFactor \times \left(\frac{Q_{br\text{-}goal}}{Q_{br\text{-}open}}\right)\right]^2 \times SPh_{open} \quad \textbf{(11c)}$$

Eqs. 11a, 11b, and 11c are derived elsewhere[3] but are discussed here briefly.

Note that no "pipe factor" (i.e., ratio of the average velocity to the centerline velocity) is employed in Eq. 11b. It is assumed only that the pipe factor for a given location does not change appreciably as dampers are adjusted. We were unable to find justification for that assumption in the published literature. Furthermore, constancy of pipe factors would be a poor assumption if the damper were upstream of the VPcl measurement point, so it is important that VPcl be measured well upstream of the damper. In any case, for this study SPh was employed instead of VPcl values.

The practitioner may use observed values of Q_{br}, SPh, or VPcl as the basis for comparison to their corresponding target values. The choice is up to the individual, but it is not likely that many will wish to take full Pitot traverses for each tweak of the damper. Because measuring VPcl or SPh is much faster than completing full Pitot traverses and computing Q_{br}, it is more likely that practitioners will chose to adjust a given damper while comparing VPcl to $VPcl_{target}$ or SPh to SPh_{target}. For some branches VPcl may be more convenient to employ than SPh and *vice versa* for other branches.

11. Beginning with the branch with the lowest value of $Q_{br\text{-}ratio}$ and continuing through to the next to highest, adjust each damper in turn until the measured parameter equals the target parameter value for that branch (e.g., $SPh = SPh_{target}$). Leave the branch with $n = N$ completely open.
12. After the first round is complete, measure SPh for each branch again.
13. Compute $SP_{ratio} = SPh/SPh_{goal}$ for each branch and determine the median value of the ratios, $med(SPh_{ratio})$.
14. Compute a new set of target hood static pressures from:

$$SPh = SPh_{goal} \times med(SPh_{ratio}) \quad \textbf{(12)}$$

The two rounds are different because of the different way to choose the targets. Round 2 is different from Round 1 because the methods to choose the target hood static pressures and the order of adjustment are different. Unlike Round 1, which begins with all dampers open, Round 2 fine-tunes the distribution already established in Round 1. Since each SPh is now equal to or deviates above or below SPh_{goal}, Round 2 will not change total system resistance and shifting of airflows does not need to be accounted for.

15. Adjust each branch damper so that its measured hood static pressure equals its corresponding $SPh_{target\ 2}$ value. Begin adjusting dampers for the second round with the duct whose SPh_{ratio} value is the greatest, followed by the least and alternate between next highest and next lowest until roughly one-half of dampers have been adjusted a second time. If necessary, adjust all dampers. This study readjusted only three of the seven branches in the second round.
16. Do a Pitot traverse for each branch duct to determine the final observed airflows and $Q_{br\text{-}ratio}$ values. Select the new $\%Q_{br\text{-}goal}$ ($\%minQ_{br\text{-}goal}$).
17. Using the $\%minQ_{br\text{-}goal}$ value determined above, adjust the fan speed from the original rotation rate (ω_1) to:

$$\omega_2 \geq \frac{\omega_1}{\%\min Q_{br\text{-}goal}} \quad \textbf{(13)}$$

Note that it may be prudent to set the fan airflow to 5% above the minimum rotation rate above as a safety factor.

RESULTS

The steps of the procedure are listed along with the results:

1. The $Q_{br\text{-}goal}$ values are shown in Table II for each distribution.
2. All the branch dampers were completely opened.
3. The initial SPh values were measured in each duct.
4. The $Q_{br\text{-}open}$ and SPh_{open} values computed from the Pitot traverses are shown in Table II.
5. The initial branch airflows deviated from the goal airflows by −22% to +37% for Distribution A and by −36% to +37% for Distribution B (Table II and Figure 2). As can be determined from the values listed in Table II, $\%minQ_{br\text{-}goal}$ was 76.9% for Distribution A and 80.9% for Distribution B.
6. The value of $Q_{fan\text{-}open}$ was 1.142 m^3/s (Table II).
7. The FanFactor values were computed:

For Distribution A: FanFactor

$$= \frac{\left(\frac{1.142 m^3/s}{1.114 m^3/s}\right) + 0.769}{2} = 0.897$$

For Distribution B: FanFactor

$$= \frac{\left(\frac{1.142 m^3/s}{1.203 m^3/s}\right) + 0.809}{2} = 0.879$$

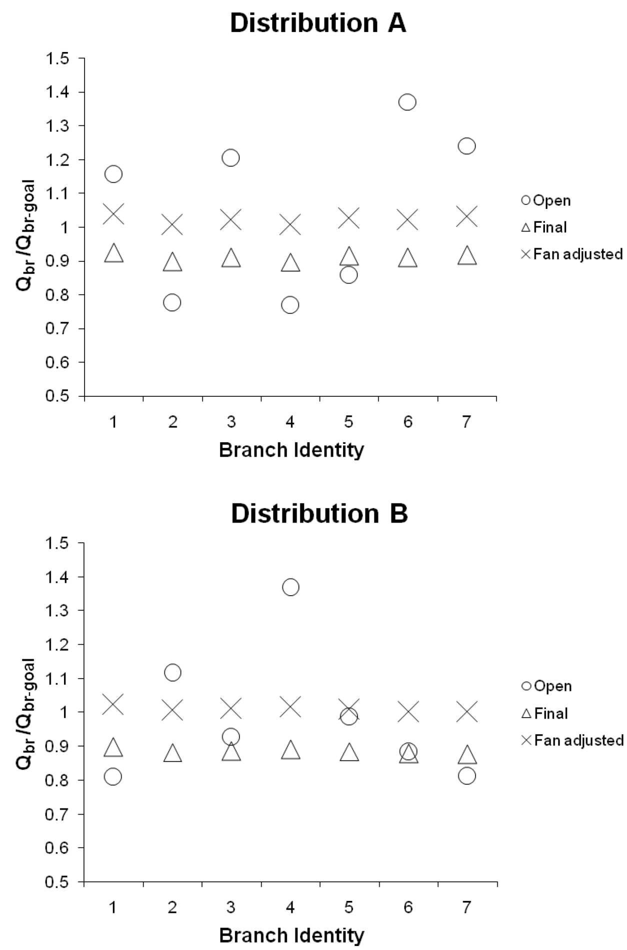

FIGURE 2. Airflow results before and after balancing with calculated airflows after fan adjustment

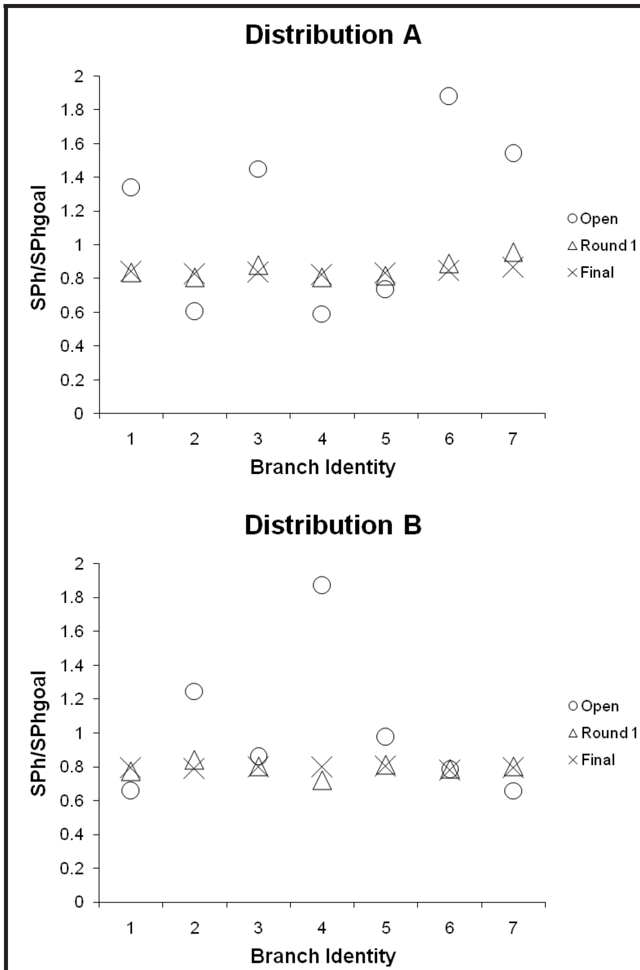

FIGURE 3. Hood static pressures before, during and after balancing

8. As seen in Table III, the values of k increase with increasing order for each distribution. This means that the earlier in the sequence the branch is adjusted, the less the value of k and the more Eq. 11c reduces its SPh_{target} below its SPh_{goal} to account for the SPh increases with each subsequent damper insertion. The last branch in the sequence for both distributions has a k value of 1 because no more branches are adjusted after it.
9. The SPh_{goal} results are shown in Table II. For example, for Branch 1:

   For Distribution A:

$$SPh_{goal} = 0.231\ \text{kPa}\left(\frac{0.165\ \text{m}^3/\text{s}}{0.191\ \text{m}^3/\text{s}}\right)^2 = 0.173\ \text{kPa}$$

   For Distribution B:

$$SPh_{goal} = 0.231\ \text{kPa}\left(\frac{0.236\ \text{m}^3/\text{s}}{0.191\ \text{m}^3/\text{s}}\right)^2 = 0.353\ \text{kPa}$$

   Note in Figure 3 that the initial SPh values were substantially different from the goals for both distributions.

10. The results for SPh_{target} are shown in Table II. For example, for Branch 1 and Distribution A, the values are:

$$Q_{target} = k \times \text{FanFactor} \times Q_{br\text{-}goal} = 0.98 \times 0.897 \times 0.165 = 0.145\ \text{m}^3/\text{s}$$

$$SPh_{target} = \left[0.98 \times 0.897 \times \left(\frac{0.165\ \text{m}^3/\text{s}}{0.191\ \text{m}^3/\text{s}}\right)\right]^2 = 0.133\ \text{kPa}$$

11. The first round of damper adjustments was completed.
12. The SPh results are shown in Table IV and Figure 3. Note that although the measured second round SPh values all deviate substantially from SPh_{goal}, the ratios of SPh to SPh_{goal} are now mostly about the same at about 81% of goal SPh values. However, Branches 6 and 7 in Distribution A deviated somewhat from the 81% ratio. Distribution B ratios were all about 80% of the goal SPh values, but Branch 4 deviated somewhat from that ratio. Because some branches deviate substantially from the common value, a second round of damper adjustments was done.

TABLE IV. Results After Round 1 and Targets for Round 2

Distribution A						Distribution B					
Branch	SPh round 1	SPh goal	SPh1/SPh$_{goal}$	med SPh ratio	SPh target 2	Branch	SPh round 1	SPh goal	SPh1/SPh$_{goal}$	med SPh ratio	SPh target 2
		Replication 1						Replication 1			
1	0.14	0.17	0.83	0.83	0.14	1	0.27	0.35	0.77		0.28
2	0.27	0.33	0.81		0.27	2	0.13	0.16	0.83		0.13
3	0.15	0.17	0.87		0.14	3	0.23	0.28	0.80		0.23
4	0.41	0.50	0.80		0.42	4	0.12	0.16	0.73		0.13
5	0.31	0.38	0.81		0.31	5	0.23	0.29	0.81		0.23
6	0.11	0.12	0.89		0.10	6	0.23	0.29	0.78		0.23
7	0.10	0.11	0.95		0.09	7	0.20	0.25	0.79	0.79	0.20
		Replication 2						Replication 2			
1	0.15	0.17	0.84	0.84	0.15	1	0.27	0.35	0.78		0.28
2	0.27	0.33	0.80		0.28	2	0.14	0.16	0.85		0.13
3	0.15	0.17	0.88		0.14	3	0.23	0.28	0.81		0.23
4	0.41	0.50	0.81		0.42	4	0.11	0.16	0.71		0.13
5	0.31	0.38	0.82		0.32	5	0.23	0.29	0.81		0.23
6	0.11	0.12	0.89		0.10	6	0.23	0.29	0.79		0.23
7	0.10	0.11	0.96		0.09	7	0.20	0.25	0.80	0.80	0.20

Note: Static pressures in kPa.

13. The SP_{ratio} values at the end of Round 1 are shown in Table IV.
14. A new set of target hood static pressures were computed for the second round. For example, for Branch 1 in Distribution A:

$$\begin{aligned} \text{SPhtarget}_2 &= \text{SPh}_{goal} \times \text{med}(\text{SPh}_{ratio}) \\ &= 0.173 \text{ kPa} \times 0.823 = 0.143 \text{ kPa} \end{aligned}$$

15. Only three of the seven branches were readjusted in the second round. The branch dampers on those branches that digressed the most from med(SPh_{ratio}) were adjusted so that their measured hood static pressures equaled their corresponding $SPh_{target\ 2}$ value.
16. The "final" SPh ratios (i.e., at the end of Round 2) were all nearly the same amount for both distributions (Table V). For Distribution A all of the branch airflows were now 89% to 92% of their respective goals (Table V and Figure 2). Hence, the relative distribution of airflows was very close to desired levels. Likewise, the branch airflows for Distribution B all fell between 87% and 91% of their respective goals, a very tight range (Table V and Figure 2). As can be determined from the data in Table V, the value of $\%minQ_{br\text{-}goal}$ for Distribution A was 0.89 and for Distribution B the value of $\%minQ_{br\text{-}goal}$ was 0.88 for one replication and 0.87 for the other.

DISCUSSION

Note the last column of Table V (i.e., "$\%Q_{adj}/Q_{br\text{-}goal}$") shows the percentage deviation from $Q_{br\text{-}goal}$ and $Q_{fan\text{-}goal}$ after the fan airflow was mathematically adjusted so that no branch had insufficient airflow (i.e., the lowest ratio, $\%Q_{adj}/Q_{br\text{-}goal} = 1$). As shown in Table V and Figure 2, the greatest percentage deviation from the ideal airflow for any branch for Distribution A was 3.9% and for Distribution B was 1.9% and 4.6%. Hence, in 28 damper adjustments, not one produced a deviation greater than 5%.

Because adjusting the speed of the fan during the experiment was difficult, we used a measure of effectiveness (Eq. 14) for this study as an equivalent to adjusting the fan at the end of balancing. According to the fan laws,[7] the proportional distribution of airflows among the branches of a system cannot change simply by changing the fan speed. Guffey and Spann[7] demonstrated that the airflow distribution does not change on changing fan airflow when all other conditions remain constant. Therefore, for the purposes of validating the Target Method, final adjustment of the fan was unnecessary.

Instead, we computed what the excess airflows and pressures would have been for each replication of each distribution if the fan were adjusted using the fan laws (Eq. 14).[9] The unlikelihood of achieving a perfect distribution makes such a measure of damper adjustment effectiveness useful.

$$\text{ExcessQ}_{fan} = 100 \times \left(\frac{100}{\%\ \text{minQ}_{br\text{-}goal}} \times \frac{Q_{fan}}{Q_{fan\text{-}goal}} - 1 \right) \quad \textbf{(14)}$$

The results are shown in Table V under the columns headed by "$Q_{afterfanadj}$." The column entitled "$\%Q_{adj}/Q_{br\text{-}goal}$" shows the

TABLE V. Final Results with Values after Fan Adjustment

Distribution A							Distribution B						
Branch	SPh_{round2}	SPh_2/SPh_{goal}	Q_{round2}	Q_2/Q_{goal}	$Q_{afterfanadj}$	$\%Q_{adj}/Q_{br\text{-}goal}$	Branch	SPh_{round2}	SPh_2/SPh_{goal}	Q_{round2}	Q_2/Q_{goal}	$Q_{afterfanadj}$	$\%Q_{adj}/Q_{br\text{-}goal}$
			Replication 1							Replication 1			
1	0.143	0.83	0.153	0.92	0.172	3.9%	1	0.278	0.79	0.208	0.88	0.237	0.3%
2	0.277	0.84	0.151	0.89	0.170	0.0%	2	0.125	0.78	0.104	0.88	0.118	0.4%
3	0.138	0.82	0.171	0.90	0.192	1.6%	3	0.226	0.80	0.216	0.88	0.245	0.0%
4	0.416	0.83	0.170	0.90	0.191	1.4%	4	0.127	0.80	0.095	0.90	0.108	1.9%
5	0.316	0.83	0.165	0.92	0.185	3.3%	5	0.230	0.81	0.137	0.88	0.156	0.0%
6	0.100	0.83	0.124	0.91	0.140	2.0%	6	0.225	0.78	0.187	0.88	0.213	0.2%
7	0.091	0.86	0.078	0.92	0.088	3.2%	7	0.196	0.80	0.114	0.88	0.130	0.0%
Fan			1.011	0.89	1.137	2.1%	Fan			1.061	0.95	1.207	0.3%
			Replication 2							Replication 2			
1	0.148	0.86	0.153	0.93	0.171	3.8%	1	0.283	0.80	0.216	0.91	0.247	4.6%
2	0.270	0.82	0.154	0.91	0.173	1.6%	2	0.126	0.79	0.104	0.88	0.119	0.9%
3	0.142	0.85	0.173	0.92	0.194	2.9%	3	0.225	0.79	0.219	0.89	0.251	2.2%
4	0.414	0.82	0.168	0.89	0.189	0.0%	4	0.127	0.79	0.094	0.89	0.108	1.5%
5	0.313	0.82	0.163	0.91	0.183	2.1%	5	0.228	0.80	0.139	0.89	0.159	1.9%
6	0.104	0.86	0.125	0.91	0.140	2.4%	6	0.227	0.78	0.186	0.87	0.212	0.0%
7	0.092	0.87	0.078	0.92	0.087	2.8%	7	0.194	0.78	0.114	0.88	0.130	0.2%
Fan			1.015	0.89	1.138	2.1%	Fan			1.072	0.89	1.225	1.8%

Note: Airflows in m^3/s and static pressures in kPa.

percentage excess airflow that would be in each branch after the fan is adjusted so that the minimum $\%Q_{br\text{-}goal}$ value is unity. For example, the excess airflow through Branch 1, Replication 1, Distribution A is:

$$\%\text{ExcessQ} = 100 \times \left(\frac{Q_{fan\_adj}}{Q_{br\text{-}goal}} - 1\right) = 100 \times \left(\frac{0.1717}{0.1652} - 1\right) = 3.9$$

The excess airflows for the entire system (%ExcessQ) were very low. As shown in Table VI, the values for both replications of Distribution A were 2.1%, and Distribution B was 0.3% and 1.8%. The excess airflow through individual branch ducts is of much less concern than the total excess through the entire system. As shown in Table V ("Fan" row for columns headed "$\%Q_{adj}/Q_{br-goal}$") and in Table VI, the percentage excess airflow for the two replications of Distribution A were both 2.1%, and the percentage excess airflows through the fan for Distribution B were 0.3% and 1.8%. The geometric mean over both distributions was 1.6%, with a 95% confidence interval of 0.3% to 5.7%. These are very low values by any reckoning, especially given the very poor beginning distributions. There were too few data to determine the probability that the results for Distribution A were significantly different from Distribution B.

Even if the SMACNA proportional balancing method[5] were to perform just as well on our seven-branch experimental system as the Target Method, it would still be more time-consuming because the number of measurements needed would have been 19 at absolute minimum compared with 16 in this study. Measuring the branch one is adjusting is convenient as long as one does not have to measure other locations between adjustments. Having to move back and forth to different locations in the duct system is time-consuming and can be disruptive to workers. Hence, it would be ideal if a method did not require measuring other ducts while adjusting the current one. Likewise, it would be ideal to minimize the required number of rounds of measurement to initial, the adjustment round, and final to confirm success.

We could not find any previously published experimental studies of balancing methods. Using the Goal Method on the same duct system and goal airflow distributions studied here, Vivek Balasubramanian found that the excess airflow was 4.8% to 8.5% after two full rounds of adjustments (unpublished data). These results were comparable to those found in another experimental investigation of the Hood Static Pressure Ratio Method[3] in our laboratory. It is possible that the errors would have been different if centerline velocity pressures (VPcl) had been used instead of hood static pressures. We could find no evidence in the literature that could suggest whether the errors would have been higher or lower. Nevertheless, proportional methods, if done successfully, should produce much lower fan pressures, since the fan output is adjusted as a separate step rather than using solely the resistance of the branch dampers to reduce the fan output.

TABLE VI. Airflow Excesses after Balancing and Fan Adjustment

Distribution	Replication	% Excess Airflow
A	1	2.1%
	2	2.1%
	Mean	2.1%
B	1	0.3%
	2	1.8%
	Mean	1.1%

CONCLUSIONS

The Target Method proved to be very effective for this system. All deviations in branch airflows were 4% or less and total wasted airflows for the whole system were 2.1% or less, (Table VI). In practical terms, there was little room for further improvement, since random measurement errors would produce some degree of error in adjusting dampers and in measuring airflows before and after adjusting. These low observed errors are even more noteworthy given that less than two full rounds of adjustments were done and the initial distribution deviated greatly from the desired distribution. Because the distribution after one round was so close to the goal, a practitioner could reasonably choose to stop before beginning the second round.

The Target Method requires substantially more computations and steps than the Goal Method, limiting the number of practitioners who would be willing and able to do the necessary computations. An important caveat is that the test system was in a ventilation laboratory. The length of straight duct upstream of measurement points was always at least 7 duct diameters long, and the duct system was completely clean. The adjustment errors using the Target Method in working systems with much less ideal measurement conditions may be significantly higher.

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