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Decoupling the Design of Variable Air Volume Systems by Tuning the Tolerances of the DPs

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Abstract

An important discussion on the application of the Axiomatic Design Theory (ADT) is how to address coupled designs. Coupled designs are somewhat usual in engineering and call for solutions in the field of ADT. This paper addresses a class of designs where one or more functional requirements can be fulfilled by design parameters of the type "the higher the better". A good example of this kind of designs is one of the most widespread types of air conditioning systems for office applications: the variable air volume (VAV) system. A VAV system controls the air temperature of multiple rooms by adjusting the flow of cooled air that is supplied by the VAV box that serves each room of the office. The essential functional requirements (FRs) of any modern air conditioning system are: "to control the air temperature", and "to provide indoor air quality (IAQ)" to each served room. The drawback of the VAV systems is that the renewal of the stale air depends on the heat loading of all the rooms, which makes it a coupled design. This paper shows how this coupled design can be decoupled by using a design parameter (the outdoor airflow), which value may be set large enough to fulfil the related functional requirement (the IAQ). The VAV application serves as an example of the application of a new proposed theorem of the ADT that allows decoupling a matrix equation.

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Keywords: VAV; coupled design; tolerances.

1. Introduction

The Axiomatic Design Theory (ADT) defines the design as an interaction between the functional requirements (FR) and of design parameters (DP). The FRs are "What we want to achieve" and the DPs are "how we achieve them". According to the ADT, the number of DPs of an ideal design equals the number of FRs.

Corollary 3 of ADT [8] proposes the integration of various DPs in a single component if the existing independence of the corresponding FRs is not ruined.

Some properties of fluids, such as the temperature and the viscosity, may be design parameters of a certain design solution that cannot fulfil the corresponding FRs in an independent manner. In such a case, a coupling emerges due to the physics of the system.

2. Coupled Designs

The ADT classifies the designs as uncoupled, decoupled and coupled according to the manner the corresponding design matrices are populated. The design matrix describes the relationships between the DPs and the FRs of each design solution. The best designs are the uncoupled designs. They have diagonal design matrices that show the independence of achieving each FR by tuning one only DP (Theorem 4) [8].

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On the other hand, designs with a non-triangular matrix, with less DPs than the number of FRs are hard to handle. They are coupled designs according to Axiom 1 and to Theorem 1 of ADT.

A method for decoupling this kind of designs is proposed by Theorem 2, through the “addition of new DPs so as to make the number of FRs and DPs equal to each other, if a subset of the design matrix containing nxn elements constitutes a triangular matrix” [8].

This paper claims that the aforementioned design can be decoupled based on Corollary 2 of the ADT, giving raise to a Theorem 2A: “Coupled designs with more FRs than DPs can be decoupled by removing from the design matrix the extra FRs, if the subset of the remaining design matrix contains nxn elements being triangular or diagonal, and the existing DPs can fulfil the removed FRs by means of the “higher the better””. Notice that the design requirements remains by maintaining all FRs, which are removed from the design equation. The “higher the better” concept means that the DP greater than needed always fulfils the requirements, being a way of defining the tolerance of the DP. Therefore, the designer is able to specify an engineering value for the DP without needing to know the exact lower limit.

The next sections present an example of applying Theorem 2A using an air conditioning (HVAC) system, the Variable Air Volume (VAV) system.

3. The VAV system

VAV is an air conditioning system that modulates the heat removal by varying the flow of cooled air that is fed to each room. VAV is the typical choice in the United States (US), being widely used in office, retail and public buildings, as well as in households. On the other hand, the designers and the manufactures of Europe developed systems that provide a steady airflow at varying supply temperature. These systems usually have a dedicated outdoor air system (DOAS) that delivers a steady outdoor air (OA) flow to each room. Therefore, the DOAS independently provides the necessary OA to each room and locally removes the heat through the terminal equipment of the HVAC system [1].

Early VAV systems only offered cooling with no specific requirements regarding the indoor air quality (IAQ). In the 1970’s, many sick building syndromes appeared due to the reduction of the supplied outdoor air and the increased airtightness of the buildings. As a result, IAQ requirements were introduced in HVAC systems, but regrettably without any major improvement in the design solutions of the VAV systems. Anyhow, VAV can be very efficient in applications where the heat load depends mostly on human occupancy.

The VAV systems may have several configurations concerning the number of ducts, control of supply temperature and control of the total OA. Moreover, the terminal units may be single trolling, include induction, or be fan-powered assisted [1]. The most common VAV system is the single duct system.

Typically, the single duct VAV systems supply a variable airflow at stable temperature to each room through a single trolling terminal unit, the so-called VAV boxes. Therefore, the total airflow in the single duct is the sum of all the airflows supplied to all the served rooms.

Fig. 1 depicts the single duct VAV system with the air-handling unit (AHU) serving a set of spaces, showing space 1 and any other space n, delivering the cooled air through the VAV boxes (item 2 at Fig. 1)

The AHU allows mixing part of the return air (item RA at Fig. 1) to the OA, making the cooled supply air to have a fraction of OA, the remaining being exhausted to the outside (item EA at Fig. 1). The AHU delivers air at the supply temperature (item Ts, at Fig. 1), being the supply air a mix of OA and stale air that returns from the rooms.

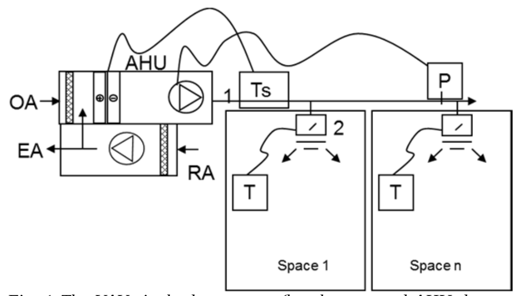

Fig. 1 The VAV single duct system (box heaters and AHU dampers not shown)

When the enthalpy at the outdoor is lower than the one of the return air, some systems are able to enter in the free-cooling mode. This is achieved by completely opening the outdoor and the exhaust air dampers, and closing the mixing damper, reducing the amount of cooling needed from the chiller and increasing to the maximum the delivery of OA.

When the airflow supplied by the AHU varies, the static pressure in the duct (item P at Fig. 1) fluctuates depending on the airflows at each room, allowing tuning the speed of the AHU fan. The system may tune the airflow supply according to the pressure in the duct or based on of a control cycle that measures the air-flow at each VAV box.

The VAV box governs the flow of cooled air supplied into the room, moving the position of the damper of the VAV box according to the set point that is required to attain the prescribed indoor temperature. A controller modulates the damper position by interfacing to a PID controller that may work independently of the duct pressure or taking into account the pressure on the duct.

When the load is zero, the throttling of a VAV box without reheat coil nullify the airflow, making the space not to receive any OA in such condition. Typically, the damper of a VAV box has a minimum position in order to supply a minimum OA rate. However, in this instance the room may be chilled out of the comfort zone. A heating water coil or electric resistance heater is a way to solve the problem of the room extra chilling. Moreover, the heater allows to heat the room in the winter season, maintaining the airflow, set by the minimum position of the damper, and adjusting the temperature of the airflow supply by the VAV box.

The VAV solution addressed in this paper is the common single duct system, with reheat at the VAV boxes, steady OA flow delivery without free-cooling, stable temperature supply around 18 ªC, and fan-speed control through the duct pressure.

3.1. The VAV ventilation air

Standard ASHRAE 62.1 [2] of the American Society of Heating, Refrigeration, and Air Conditioning Engineers, provides detailed figures to achieve an acceptable indoor air quality in buildings other than low-rise residential buildings, and generally in industries and laboratories. This standard takes into account the outdoor air quality, the systems and equipment, construction and start-up, and operation and maintenance. ASHRAE 62.1 defines two procedures to achieve the IAQ: the indoor air quality procedure that controls contaminants of concern; and the ventilation rate procedure. This paper uses the ventilation rate procedure, which prescribes the rate of 35 m3/h/person supplied to the volume of the room occupied by persons.

Fig. 2 shows an AHU serving all the spaces, and the balance of airflows and outdoor airflows. The required OA for all spaces, q0r, comes along with the primary airflow, qp. The airflow qp has an outdoor air ratio Z, and the return air an outdoor airflow content r.

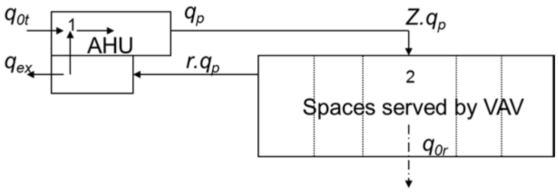

Fig. 2 The airflow balance of a system with return air

The airflow balance of the OA at the mixing box of the AHU (item 1 of Fig. 2), and at the rooms (item 2 at Fig. 2) allows defining the balance equation 1:

$$\begin{cases} r.q_r + q_{0t} = Z.q_p \\ Z.q_p - q_{0r} = r.q_p \end{cases} \quad (1)$$

Thus, the outdoor air delivered at each of those spaces are determined by the outdoor air ratio *Z* of the primary airflow q_p. The cooling load governs the primary airflow, while the number of persons and the building area determine the outdoor airflow requirements q_{0r}. ASHRAE 62.1 introduces the concept of ventilation efficiency $E_v = q_{0r} / q_{0t}$, as q_{0t} need to be greater than q_{0r}, and the ratio of required OA in the primary air $X = q_{0r} / q_p$, which allows obtaining from Eq. 1 the ratio of the total OA in the primary airflow (*Z*) . Eq. 2 shows that knowing q_p from the heat balance, and q_{or} from the requirements of the OA, for a given q_{ot} intake into the AHU it is possible to define the content Z in the primary air. Knowing the room airflow makes therefore possible to know the OA delivery at each room. This procedure is used in section 5 in the building simulation.

$$Z = (1 - E_v) + X \quad (2)$$

In design conditions, the primary air and the required OA for each room, allows obtaining the Z for each room. For a known X of the VAV system, Eq. 2 allows computing the ventilation efficiency for the room in analysis. Setting E_v as the minimum ventilation efficiency of all rooms permits the system to deliver the right OA to each room of a multi-space recirculating system. Nevertheless, the procedure cannot guarantee the OA delivery at each room for a VAV system at part-load, because the airflow varies according to the load. To solve this problem, ASHRAE 62.1 allows the OA to be met on average conditions during a time-lag period.

3.2. VAV ventilation, comfort and energy

Decreasing the supply temperature reduces the ventilation energy by reducing the amount of airflow, but in turn it increases the energy used by the chiller because of the drop of the evaporator temperature. The optimum point for the minimum energy is attaining by balancing the chiller use of energy and the energy associated with the airflow delivered by the AHU [5, 6 and 7].

In cold weather, the outdoor airflow mostly depends on the heating needs, making possible to determine the optimal ventilation rate that minimizes the energy use of the system [4]. On the ventilation side, the ventilation rate can vary according to the CO_2 content in each room, which is done by optimizing the differences of the CO_2 concentration relative to a set point, taking into consideration the heat load of each room [6].

As the ventilation rate needs to vary according to the occupancy, a control scheme can define the demanded control ventilation, which means to deliver the right amount of the hourly OA required into the building. On the other hand, as the OA delivery varies between the rooms according to the heat load, a control system can balance a weighted function of thermal comfort, IAQ and energy use, as to define the optimal supply temperature [10].

Considering the VAV system as a whole, the minimum airflow will change according to the supply temperature that allows maintaining the room thermal comfort. Thus, for a given system, it is possible to establish an opposite relationship between the minimum airflow and the discharge air temperature that allows maintaining the room thermal comfort [5].

A VAV system is ruled by inverse relationship between desired parameters as it happens with comfort and CO_2 concentration, or with comfort and energy use. Four strategies were simulated to make a comparison between the variations of those parameters, starting from a basis of constant outdoor air fraction. This strategy presents low CO_2 concentrations maintaining acceptable comfort indices. Using demand control ventilation defined by the minimum outdoor airflow it reduces the use of energy by 15%, while reaching acceptable comfort but poor CO_2 concentrations. Disabling the indoor air temperature control, the energy saving is 20% better than the reference, but the thermal comfort is poorer. Resetting the supply temperature and using an enthalpy based economizer, ruled by the difference between the outdoor and return air enthalpy, allows the energy use to lower by about 10% [11].

If most of the rooms are in heating mode, then a possible strategy for reducing the energy use is to increase the temperature of the cooled air, adjusting the minimum airflow at the same time, as to assist the VAV boxes that are operating in the cooling mode [12]. Hence, the system can adapt the minimum airflow of each VAV box according to the heating needs and to the ventilation air needs of the room.

In cooling, the use of a cooling coil in the VAV box may perform a similar option, by establishing a maximum airflow helped by the cooling capacity of the coil. Optimization algorithms can reach at any moment the optimal temperature supply and ventilation rate, maintaining the comfort conditions and IAQ [7].

4. VAV according to AD framework

In this application, the VAV single duct system with reheat has a stable supply temperature of around 18 °C, and the OA intake flow is steady and defined according to the maximum occupancy of the building.

Table 1 shows the decomposition of the FRs and DPs of the VAV single duct with reheat. The DP2 decomposition shows the FRs of concern for this evaluation, assuming independent all other FRs described at the aforementioned IAQ standard. The wording of the FRs follows the rules proposed by Thompson [9].

The process starts at FR1 "achieve the indoor thermal comfort" and FR2 "provide IAQ" [3]. In cooling mode, DP11 and DP12 allow supplying the cooled airflow to each space; in heating mode DP13 and DP14 set the minimum airflow at each space using their individual heating coil.

The AHU adjusts the temperature supply by using "DP16- AHU cooling coil system"; while "FR15- provide the total airflow supply" is attained through DP15, which allows adjusting the speed of the fan.

The "FR23- provide the building total OA" is achieved by tuning the position of the OA damper of DP23. At each room, the airflow provided for heating or cooling purposes allows to deliver the OA, making FR21 and FR22 fulfilled by DP11, DP12, DP13 and DP14.

Table 1. FRs and DPS of the VAV single duct with reheat.

FRs	DPs
FR1- Achieve indoor thermal comfort	DP1- Temperature control system
FR2- Provide IAQ	DP2- Outdoor air control system
FR11- Control space 1 cold airflow	DP11- 1's VAV box airflow
FR12- Control space n cold airflow	DP12- n's VAV box airflow
FR13- Control space 1 heating	DP13- 1's VAV box heating system
FR14- Control space n heating	DP14- n's VAV box heating system
FR15- Provide total airflow supply	DP15- AHU flow system
FR16- Adjust Ts of the AHU	DP16- AHU cooling coil system
FR21- Provide space 1 OA	
FR22- Provide space n OA	
FR23- Provide building total OA flow	DP23- AHU OA system

A design of a VAV system starts by evaluating the system in cooling mode and, later, defining the devices required to accomplish the heating needs. As to achieve a proper design, it is appropriate to evaluate the system at the mid-season, especially in what concerns to the OA flow at each room. Therefore, it is important to establish the design equations for each mode: cooling mode in all spaces; heating mode in all spaces; and heating mode in some spaces with cooling mode in others.

Eq. 3 shows the design in cooling mode, for which FR13 and FR14 do not apply. On the second level of the decomposition there are seven FR and five DP, which means that it is a coupled design.

$$\begin{bmatrix} FR1 \\ FR2 \\ FR11 \\ FR12 \\ FR15 \\ FR16 \\ FR23 \\ FR21 \\ FR22 \end{bmatrix} = \left[\begin{array}{cc|ccccc} X & & & & & & \\ X & X & & & & & \\ \hline & & X & & & X & \\ & & & X & & X & \\ & & & & X & X & \\ & & & & & X & \\ & & & & & & X \\ \hline & & X & X & & & X \\ & & X & X & & & X \end{array}\right] \cdot \begin{bmatrix} DP1 \\ DP2 \\ DP11 \\ DP12 \\ DP15 \\ DP16 \\ DP23 \end{bmatrix} \quad (3)$$

In heating mode FR11 and FR12 do not apply, and the system needs the requirements FR13 and FR14, as expressed by Eq. 4:

$$\begin{bmatrix} FR1 \\ FR2 \\ FR13 \\ FR14 \\ FR15 \\ FR16 \\ FR23 \\ FR21 \\ FR22 \end{bmatrix} = \left[\begin{array}{cc|ccccc} X & & & & & & \\ & X & & & & & \\ \hline & & X & & & X & \\ & & & X & & X & \\ & & & & X & X & \\ & & & & & X & \\ & & & & & & X \\ \hline & & X & & & & X \\ & & & X & & & X \end{array}\right] \cdot \begin{bmatrix} DP1 \\ DP2 \\ DP13 \\ DP14 \\ DP15 \\ DP16 \\ DP23 \end{bmatrix} \quad (4)$$

At last, if a space 1 is in heating mode, and space n is in cooling mode, then FR11 and FR14 apply as shown in Eq. 5:

$$\begin{bmatrix} FR1 \\ FR2 \\ FR11 \\ FR14 \\ FR15 \\ FR16 \\ FR23 \\ FR21 \\ FR22 \end{bmatrix} = \left[\begin{array}{cc|ccccc} X & & & & & & \\ X & X & & & & & \\ \hline & & X & & & X & \\ & & & X & & X & \\ & & & & X & X & \\ & & & & & X & \\ & & & & & & X \\ \hline & & X & X & & & X \\ & & X & X & & & X \end{array}\right] \cdot \begin{bmatrix} DP1 \\ DP2 \\ DP11 \\ DP14 \\ DP15 \\ DP16 \\ DP23 \end{bmatrix} \quad (5)$$

The matrixes of Eq. 3, 4 and 5 show a line separating the rows of the IAQ FRs of FR21 and FR22 from the above rows, and dotted lines separating the level of decomposition 1 to the level 2.

A HVAC design starts by knowing the cooling and heating loads at summer and winter design conditions, corresponding to the cooling and heating modes of operation.

In cooling mode, the cooling loads define the AHU airflow (DP15), based on the previously set temperature supply (DP16). DP11 and DP12 help "control the space cold airflow" according to the temperature supply, making possible to prescribe the VAV boxes. FR21 and FR22 (IAQ FRs) depend not only on the airflow of each space, but on the airflow of the remaining spaces, and on the total OA airflow supplied. Fulfilling FR21 and FR22 is a hard task in a VAV design, making the designer calculating the minimum efficiency of the system ventilation for all rooms in order to guarantee the OA at each room at design conditions.

The system in heating mode, shown at Eq. 4, have a similar design matrix, making the OA flow of each room to be defined by the minimum position of the damper at each VAV box. DP13 and DP14 are designed according to winter conditions, allowing to specify the heaters of the VAV boxes. In heating mode, normally the needs of OA define the minimum position of the damper in the VAV boxes, making FR21 and FR22 not to relate each other.

The mid-season is the typically working condition, when some rooms are in heating while others are in heating. During the mid-season the system may not fulfil the OA flow for each room, making Eq. 5 so important in terms of IAQ verification. If the OA flow is to be kept at all hours in all rooms, Eq. 5 shows that the design is hard to tune.

All design equations, Eq. 3, Eq. 4 and Eq. 5, shows that the parameters are easy to set if there are no OA requirements, making the design a decoupled design. Introducing the OA requirements, the design is coupled, raising the question if there is an OA intake in the AHU compatible to the OA needs of all rooms. A noteworthy solution of the problem is achieved by using an AHU that supplies all OA, therefore with no RA, making all primary air to be OA.

Notice that all matrixes become triangular removing the IAQ FRs from the matrix, in the case they are able to be fulfilled by DP23.

Concerning IAQ, standards define minimum values for the OA flow delivery at each room, increasing the IAQ if the OA flow increases. Therefore, the OA flow is for this application of the type "the higher the better", making possible to apply the Theorem 2A.

Therefore, the question is: In what range the OA rate might vary, consistent with the heating and cooling loads, while delivering the OA to each room?

5. Simulation and Results

The former question has not a unique answer, varying from one building to another, and on the distribution of loads in time and space on the same building. From the design equations, the damper position (DP11 and DP14), the minimum position of the damper, set at DP15 and DP16, and the DP23, the OA system intervene in the IAQ. The simulation allows defining the OA flow and the minimum position of the damper, varying the damper position according to the loads.

This paper presents the results of the simulation of a ten stores building of 6.000 sqm, 270 kW of internal cooling load, each floor with five zones, and occupancy of 570 persons. The simulation addresses a real building constructed nearby Lisbon, Portugal, ten years ago. The well-known Design Builder program interfacing with the EnergyPlus™ software package, simulate the thermal loads using a compatible Lisbon weather file. This package is an open source software, developed by the Department of Energy of the US that models dynamically the thermal behaviour of a building.

Therefore, it is possible to predict the dynamic internal loads on heating and cooling for every hours of the year. Thus, the load data of the building is post-processed in a Matlab program using, steady state conditions for each hour of the simulation. The program starts by dimensioning the VAV system, obtains the OA needs for each zone, and the primary air required for removing the maximum heat loads of the different zones at a predefined supply temperature of 18 °C. Then, it determines the mass supply and the outdoor air ratio, hour by hour, for each zone, allowing to predict when the system does not fulfil the requirement of delivering an OA flow of 35 m^3/h/person to each room.

Fig. 3 depicts the simulation of OA delivery per person, at each of the five zones during the working hours, for a winter day, with zones in heating and other in cooling mode.

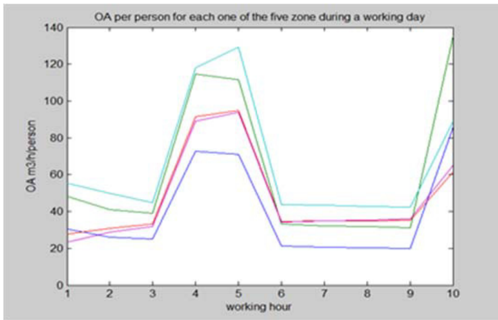

Fig. 3 Percentage of persons with low OA than required

This simulation set an OA airflow of 35 m^3/h/person as intake in the AHU and the damper minimum position at 20%. Moreover the simulation takes into account the distribution of the air in the occupied zone, using the so-called efficacy of air distribution. The efficacy set is 0.8 in heating mode, and unitary in cooling. The picture shows high volumes of OA during low occupancy hours, not only because the number of persons are smaller than at full occupancy, but because the return air is mostly OA. On the contrary, during high occupancy hours, zones with more heat loads have more OA, while the others have less than defined.

In the simulation, anytime a zone has less OA than the 35 m^3/h/person, the person-hour is assumed to be dissatisfied. Summing all person-hour dissatisfied (*phd*), allows obtaining the percentage of person-hour affected by the malfunction of the system.

Therefore, the system percentage of success depends of the person-hour (*ph*) at each hour *h* and from each zone *z*, and on the person-hour dissatisfied, according to Eq. 6:

$$P = \frac{\sum_h \sum_z (ph_{z,h} - phd_{z,h})}{\sum_h \sum_z ph_{z,h}} \qquad (6)$$

Eq. 7 allows calculating the information content *I* of the VAV system in what concerns the success of OA delivery, expressed in bits:

$$I = -\log_2(P) \tag{7}$$

Running the program for rates of OA flow per person from 25 to 75 m^3/h and for minimum damper position from 10 to 60% of the VAV maximum flow, allows obtaining a surface of the information content of the possible solutions.

Figure 4 depicts the contour-plot of the information content showing that at large OA flow rates the information is nil.

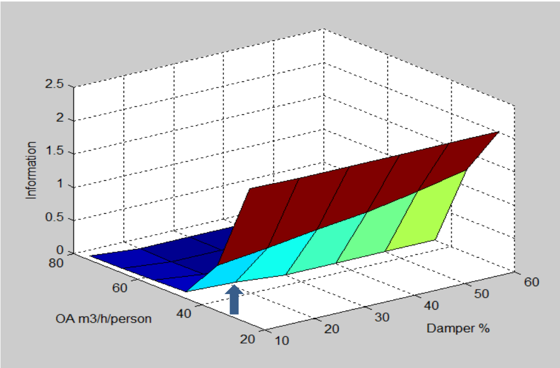

Fig.4 Information content of the simulated VAV system

For airflows close to 35 m^3/h/person, throttling the minimum airflow reduces the information as it allows distributing the scarce OA to a larger number of rooms. On the other hand, for greater OA flows, enlarging the minimum opening slightly benefits the OA distribution to all zones, as shown in Fig. 4, pointed with a bold blue arrow. As shown in the figure, the information mostly depends on the OA flow, being zero for OA flows greater than 45 m^3/h/person and minimum damper position of 30% of the maximum VAV box flow.

This is an interesting engineering result, as typical VAV designs set the minimum damper position at 20 to 30% of the VAV box airflow and the AHU usually supplies and OA flow 30% higher than the minimum needed at all rooms.

6. Conclusions

Working with coupled designs is a difficult and challenging task in engineering. This paper gives a contribution on how to handle coupled designs when there are more functional requirements (FR) than design parameters (DP). The application concerns the situation when a DP is of the type the “higher the better”. The “higher the better” is an engineering situation where it is possible to define a large enough value for a DP that fulfils the corresponding FR. Therefore, the tolerance of the DP is the range above the engineering defined value.

In this situation, a theorem is proposed, the Theorem 2A of the Axiomatic Design Theory (ADT) standing that:

“Coupled designs with more FRs than DPs can be decoupled by removing from the design matrix the extra FRs, if the subset of the remaining design matrix contains nxn elements being triangular or diagonal, and the existing DPs can fulfil the removed FRs by means of the “higher the better”.

This theorem applies to the Variable Air Volume (VAV) air conditioning system, as the VAV is a coupled design when considering the requirements of indoor air quality (IAQ) and comfort. In the VAV system, the outdoor air (OA) delivery depends on the heat loads, having no special DP to provide the OA flow at each room. Anyway, using a large enough OA flow it is possible to solve the problem of the IAQ, keeping the comfort criteria.

A 6,000 sqm building with internal cooling load of 270 kW was simulated in order to get the VAV behaviour regarding IAQ. For this building, the simulation allows saying the IAQ requirements need the OA flow intake to be greater than 45 m^3/h/person and a VAV damper minimum opening of 30%.

Finally it is important to say that these conclusions regarding the VAV system are in accordance to the good practices of the VAV designers.

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