A review of common human errors in design, installation, and operation of multiple-zone VAV AHU systems

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Abstract. Faults in air-based heating, ventilation, and air conditioning (HVAC) systems lead to energy waste and discomfort. While the emphasis of fault detection and diagnostic (FDD) research has been on hard faults in actuators, sensors, and equipment, faults arising from human errors account for a significant portion of faults occurring in HVAC systems. In this paper, human errors occurring in air handling units (AHUs) and variable air volume (VAV) thermal zones during design, construction, and operation phases are identified through a review of the literature. Then, the faults are divided into six main categories. Based on case studies investigating these faults, the impact of each fault category on occupant comfort, energy consumption, and equipment life is discussed. The authors provide recommendations to minimize human errors in AHUs and VAV zones throughout the building life cycle.

1. Introduction

Heating, ventilation, and air conditioning (HVAC) systems are one of the major consumers of energy in commercial buildings. The purpose of an HVAC system is to respond to changes in building thermal, ventilation, and internal loads by adding or subtracting heat, moisture, and properly filtered air [1]. While modern buildings have added capabilities such as building automation systems (BASs), the added complexity can increase the probability of faults [2]. Faults can develop during the design, construction, and operation of building HVAC systems and result in excessive energy waste [3], [4]. Such faults not only affect thermal comfort and indoor air quality but also increase the energy consumption of the system and may lessen the lifespan of HVAC equipment. Therefore, fault detection and diagnostic (FDD) methods are a vital and effective tool for timely detection of faults – reducing the effect of faults in building HVAC system applications [5]. There are many types of faults, e.g., design faults, manufacturing faults, assembly faults, normal operation faults, wrong operation faults, maintenance faults, hardware faults, software faults, and operator's faults; some faults that are directly caused by humans may be called errors [6]. In general, faults occurring in the service life of a building are divided into two main categories: hard faults and soft faults [7]. Hard faults include sensors, actuators, and mechanical equipment failures such as stuck/broken/leaking valves or dampers, fouled heating/cooling coils, and failure of supply/return fans or sensors [3], [8], [9]. Soft faults include controller tuning errors, programming mistakes, improper design, poor installation, non-optimal commissioning, and poor preventive maintenance. A significant number of previous research projects or papers on FDD for buildings HVAC systems have addressed hard faults, while soft faults or, in general, human errors account for a considerable portion of faults. This paper conducts a critical review of the literature to identify and categorize common human-induced errors made by technical professionals of the building...
industry such as engineers, contractors, and operators in multiple-zone VAV AHU systems.

1.1. Previous literature review
FDD for building HVAC systems has been an active area of study for more than 20 years [10]. Researchers have developed methods to automatically detect, diagnose and evaluate faults in air-based HVAC systems. For this article, we performed a manual search of the literature via Google Scholar and other related databases. There are several published review articles on FDD for HVAC systems. Katipamula and Brambley [11] published a two-part review in 2005 on fault detection, diagnostics, and prognostics methods for building systems. They classified FDD methods as qualitative (i.e., expert rules), quantitative (i.e., physics-based models), and process history-based (i.e., black- and grey-box models) and identified the weakness and strength of each method. They also reviewed FDD research in HVAC & R field such as refrigerators, heat pumps, air handling units, and chillers. Yu et al. [3] presented a review of existing FDD methods for AHUs with firstly providing a background of AHU systems, and summarizing typical faults investigated in the existing literature. Then they proposed a new categorization method and divided FDDs into three main categories: analytical-based methods, knowledge-based methods, and data-driven methods and they assessed examples of the FDDs in each category to understand the pros and cons of each method. Ken et al. [10] reviewed and analyzed currently in use FDD techniques to show how automated FDD can aid the commissioning of AHUs. They outlined various available FDD tools to see which one has the most potential for energy saving. Then they listed the issues that have inhibited the adoption of existing FDD tools for AHUs and recommended areas for future research to overcome the impediments to the adoption of automated AFDD tools in AHUs. Kim and Katipamula [12] reviewed published FDD studies in commercial buildings since 2004 and categorized them in three methods that were adapted from Katipamula and Brambley earlier in 2005. A few FDD methods in each category with their strengths and weaknesses were selectively reviewed by them. They proposed the distribution of studies based on the FDD method and HVAC system and offered their paper as a guideline to researchers for selecting an appropriate FDD method. Shi and O’Brien [13] reviewed over 250 papers published in the last 20 years on building FDD. First, they provided introductions to the fault detection and diagnostics fundamentals and also to the building AFDD. Then, they discussed feature generation by listing the characteristics that process models used for building AFDD should have and dividing the process model types into the white-box, black-box, and grey-box models. They discussed fault detection methods and possible symptoms generated from their results and also fault diagnostic methods, and ways to improve their performance.

Some guidelines such as ASHRAE Guideline 11 provides some instruction for testing and inspection of HVAC controls components during commissioning, and ASHRAE Guideline 36, which is the outcome of the ASHRAE research project 1455-RP, develops standardized sequences of operation to achieve more effective use of existing controls [14]. However, none of the previous FDD review articles focused on human errors. Human errors in HVAC systems consist of a wide range of errors that may occur during the design, construction, or operation phase of a building. To address some of the gaps identified in the reviewed literature, the authors of this paper focus on the possible human errors in a building's multi-zone AHU from conception to completion and later on in operation.

1.2. Scope of paper and paper organization
Human intervention errors in a building may occur in three phases (as shown in Table 1): design or preconstruction phase, construction phase, and operation or post-occupancy phase. The authors have divided human errors into six categories based on three major life-cycle phases and two categories of human errors for each. Design phase errors by engineers/designers of consulting engineering firms are divided into two groups: improper design and incorrect sequence of operation. Construction phase errors by contractors/subcontractors or BAS operators are divided into two categories: poor installation and programming errors. Finally, the operation phase errors are divided into non-optimal commissioning and poor preventive maintenance. The most common human errors in each phase and category and the impact of each error on energy consumption, indoor air quality, occupant comfort, and equipment life are listed in Table 1. Then the authors define each category and provide some industry examples for the common errors related to each category. Lastly, recommendations to lessen human errors in commercial buildings are provided.
| Phase          | Fault category                   | Fault description                                                                 | Fault impact |
|---------------|----------------------------------|------------------------------------------------------------------------------------|--------------|
|               |                                  | Energy consumption | Indoor air quality | Occupant thermal comfort | Equipment life |
| Design phase  | Incorrect control sequence of operation | Incorrect temperature of hot/cold water supply or return to or from heating/cooling coil [15] | ✓ | ✓ |         |
|               |                                  | Zone temperature setpoint too high [16] | ✓ | ✓ | ✓        |
|               |                                  | Scheduling errors [4], [17] | ✓ |         | ✓        |
|               |                                  | Improper supply air temperature setpoint reset [18] | ✓ |         |         |
|               |                                  | Improper duct static pressure setpoint reset [18] | ✓ |         |         |
|               | Improper design                  | Incorrect heating/cooling coils and perimeter heating systems sizing [7], [8], [16] | ✓ | ✓ |         |
|               |                                  | Maximum VAV airflow setpoint too low/high [16], [19] | ✓ | ✓ | ✓        |
|               |                                  | Minimum VAV airflow setpoint too low/high [16], [29] | ✓ | ✓ |         |
|               |                                  | Wrong VAV terminal unit or diffuser selection [15] | ✓ |         | ✓        |
|               |                                  | Undersized supply air duct or undersized /oversized supply fan [16] | ✓ | ✓ | ✓        |
|               |                                  | Poor thermostat location [6], [7] | ✓ | ✓ | ✓        |
|               |                                  | Adjacent placement of supply diffuser and return grille [7], [15] | ✓ |         |         |
|               |                                  | Inaccurate location of sensors and valves [8], [20] | ✓ |         |         |
|               |                                  | Improper zoning (e.g., one AHU serves both east and west exposures) [21] | ✓ | ✓ | ✓        |
| Construction phase | Programming errors | Simultaneous mechanical cooling and economizing [16] | ✓ |         |         |
|               |                                  | Simultaneous heating and cooling [8], [21] | ✓ |         | ✓        |
|               |                                  | Simultaneous heating and economizing [22] | ✓ |         | ✓        |
|               |                                  | Frequent changes in AHU's mode of operations [8] | ✓ |         |         |
|               |                                  | Inappropriate economizer program [22], [8] | ✓ | ✓ | ✓        |
| Operation phase | Non-optimal commissioning | Not supplying insulation for ductwork or pipes | ✓ | ✓ |         |
|               |                                  | Slipping supply/return fan drive belt | ✓ |         | ✓        |
|               |                                  | Not providing required clearance for AHUs | ✓ |         | ✓        |
|               |                                  | Inadequate ductwork installation or duct leakage [9], [15] | ✓ | ✓ | ✓        |
|               |                                  | VAV access panel in the ceiling is not accessible [6] | ✓ | ✓ |         |
|               |                                  | Not providing drain pan for condensation in cooling coil [15] | ✓ |         | ✓        |
|               |                                  | Insufficient testing, adjusting, and balancing of HVAC system [23] | ✓ | ✓ |         |
|               |                                  | No coordination between subcontractors | ✓ | ✓ | ✓        |
|               | Poor preventive maintenance      | Commissioning is not performed [24] | ✓ |         |         |
|               |                                  | Initial commissioning is rushed due to delays in other phases [24] | ✓ | ✓ |         |
|               |                                  | Commissioning is not performed at the proper time [24] | ✓ |         | ✓        |
|               |                                  | Poorly developed or inadequate O&M manual [25] | ✓ |         | ✓        |
|               |                                  | Incorrect frequency of maintenance intervals [26] | ✓ |         | ✓        |
|               |                                  | Completing maintenance prior or past due dates [26] | ✓ |         | ✓        |
2. Design phase

2.1. Improper design

HVAC design is a vital part of a construction project and a comfortable, healthy and efficient indoor environment is obtained by a high-quality design of HVAC system [27]. The use of building information modelling (BIM) in the design phase of a building has helped architects/designers to detect design issues and interference between multiple disciplines [28], which helps prevent design changes in the construction phase and saves time and money. However, improper design such as over-/under-sizing HVAC equipment or misplacing HVAC components results in defects in the operation phase that require costly maintenance. For example, oversizing leads to huge bills both at the handover and over years of operation, and under-sizing results in not providing adequate heating or cooling [1]. Hence the design experts should consider the effects of their decisions on the cost of maintenance in the first place [15]. For instance, the wrong selection of diffuser's throw leads to direct hot/cold air [15] or inadequate placement of supply diffuser and return grille that results in short-circuiting [7] causes uncomfortable zone temperature and occupant discomfort. Another example is the poor thermostat location, such as being positioned too close to supply air diffuser [21], on the exterior wall, under the direct sunlight [8], or near the main door on the HVAC drawings causes inaccurate reading and subsequently energy waste. Finally, providing cooling for IT rooms from the same AHU that feeds other zone spaces is not a good practice in the design phase as the AHU needs to be operational even when it is unoccupied.

2.2. Incorrect sequence of operation

A sequence of operations (SOOs) is an overall specification of the control strategy for the HVAC system [29]. Establishing a successful SOO is one of the most important design aspects of any HVAC system [30]. The control sequences and logic of HVAC systems are expressed through schematic diagrams and textual descriptions called SOOs in the final construction documents/drawings [4]. Various information such as setpoints, control parameters, control logic, sequences, and time schedules are described in SOOs to specify the relation between HVAC components, sensors, actuators, controllers, and their behaviour. Missing set points or insufficient descriptions cause ambiguity and results in inaccurate interpretation by the BAS operators and, eventually, faults in the system [4]. Incomplete or poorly written SOOs cause BAS operators/facility managers to implement SOOs in the BAS without a complete understanding of the design intent [31]. Even if inappropriate set points or operating schedules may not cause occupant discomfort; however, it may waste a large amount of energy. For instance, defining a constant low supply air temperature setpoint for AHUs causes the excessive use of baseboard heaters or VAV reheat coils to meet the zone temperature setpoint. Defining improper operating modes such as leaving the AHU operational while the building is unoccupied (scheduling error), assuming a constant and conservative period for warm up/cool down mode, and wrong logic for setup/ setback mode are incorrect operation modes defining by engineers. Another common error made by HVAC engineers is defining an improper economizer behaviour. The type of the economizer either if it is a dry bulb temperature, or an enthalpy based, and the description of economizer cycle strategy need to be provided in detail.

3. Construction phase

3.1. Programming errors

The sequence of operations written by design engineers on the control schematic drawings is used by system controls integrators to implement the HVAC controls into BAS [29]. Based on the level of detail the engineer provides, the system integrator technician applies his judgment in defining how the equipment will be controlled [29]. However, practical implementations of BAS often fail to meet the design intent [17]. This happens either because of incomplete or poorly written SOOs by design engineers or the BAS operators make tuning control loops mistakes or wrong interpretation of sequencing logics. A survey in 2004 found that more than 50% of the buildings in the United States with BAS do not operate as per their design intent [24]. Additionally, up to 30% of heating energy savings can be achieved in an office building by implementing properly configured BAS [25]. Although ASHRAE Standard 90.1 has requirements to prevent simultaneous heating with either free cooling or mechanical cooling (except for dehumidification); one of the most common programming faults by BAS operators are simultaneous heating and cooling, simultaneous economizing and heating, and
simultaneous economizing (between minimum and 100% position) and mechanical cooling. Another common programming error that also has overlap with incorrect SOOs is the inappropriate supply air temperature (SAT), and duct static pressure (DSP) setpoint reset. SAT setpoint is usually reset based on outside air temperature; therefore, it is lower in the summer to achieve better dehumidification and higher in the winter to prevent drafts. Resetting the DSP setpoint adjust the setpoint in real-time based on the percentage of the opening of the VAV dampers instead of maintaining constant DSP. Defining constant SAT or DSP setpoint or implementing wrong reset programs will result in energy waste [18].

3.2. Poor installation

Contractors are the performers of the designed HVAC systems. To ensure the new HVAC system performs in the best possible way, care must be taken during installation to avoid errors that directly reduce the system's performance [32]. In the building industry, a general contractor usually takes responsibility for the completion of a project and hires and supervises subcontractors and suppliers. Coordination between control, HVAC, electrical, or other subcontractors is a vital factor that results in on-time delivery of the project and lessens deficiencies. For example, the exact location of an AHU and its intake and exhaust opening must be coordinated between the involved subcontractors. For this purpose, the general contractor should always be on-site and communicate between the subcontractors and designers if any questions arise. One of the most common installation errors during the construction phase is inadequate ductwork which restricts delivered airflow to the zones. Not providing enough inlet/outlet direct duct to/from a VAV terminal unit that creates noise and affects the airflow delivered to the zone; installing unnecessary or bad transitions/fittings that increase the pressure loss in the ductwork; changing the duct routing, which impacts the supply fan size, and not providing turning vanes in a 90-degree turn that can eliminate some of the equivalent lengths and reduce pressure drop are all examples of insufficient ductwork installation. Testing, adjusting, and balancing (TAB) air and hydronic systems is the last step of the construction phase when the system is prepared for operation [23]. Regardless of how good an HVAC system is designed, installed, and controlled, it still has to be balanced by a qualified contractor to provide comfort and efficiency. Errors in performing TAB such as improper supervision and technical incompetence result in delivering unbalanced air or hydronic flow to the zones.

4. Operation phase

4.1. Non-optimal commissioning

Building commissioning has become known as the ideal model to verify and document that the building systems and equipment are installed and operating to provide the performance intended by the designer and owner [25]. The commissioning of a new building and an existing building that was not previously commissioned is called initial commissioning and retro-commissioning, respectively [10]. To maintain, improve and optimize performance, commissioning should be undertaken throughout a building lifecycle which is called ongoing commissioning [10]. Studies have shown ongoing commissioning of building systems for peak efficiency can save an average of over 20% of total energy cost [33]. Automated ongoing commissioning which reduces the operating costs and increases energy efficiency and comfort, has been an area of interest for researchers in recent years and some model-based approaches have been represented [9]. Commissioning agents also work towards improving energy performance and decreasing operation and maintenance costs. Since initial commissioning is the last step before delivery of a new building and if a project is already behind schedule due to construction delays, it is usually done in a hurry. Therefore, tests are not completed, reports are not finalized, and equipment does not operate perfectly [24]. Moreover, employing commissioning in the late stages of a new building can cause operational problems. Commissioning should be applied across the pre-design, design, construction, and post-occupancy phases of a new building and the ongoing life of an existing building [23]. Engaging commissioning in the early stages can identify potential design issues and, later on, installation errors, so by checking design and construction documents, the building will be set up for a lifetime success [24].

4.2. Poor preventive maintenance

Maintenance is understood as an action taken to retain a system in its designed operating condition or bring it back to the design condition. It extends the useful life of systems, ensures the optimum availability of installed equipment or equipment for emergency use [7]. Preventive or scheduled
maintenance starts with inspection and incorporates actions such as cleaning, adjustment, lubrication, and replacement of small parts before they fail at predetermined intervals [7]. Unplanned maintenance is completed in emergencies to avoid immediate shutdowns or for safety purposes [7]. FDD techniques were also extended to preventive maintenance by developing smart or optimal maintenance scheduling tools [24]. Optimal commissioning is expected to influence building operation and maintenance (O&M) positively. Poorly developed or incomplete O&M manuals, which consist of as-built drawings, manufacturer instructions, guarantees, and warranties, etc., make it difficult for the maintenance staff to keep the building running efficiently [25]. The required training for O&M staff also needs to be provided by the maintenance contractor. Completing preventative maintenance before or after the due date will result in unpredicted failures. Incorrect interval frequency in preventive maintenance is also another mistake [26]. The frequency should be based on the useful life of the component, not the mean time between failures [26].

5. Recommendations and future work
In this section, the authors provide some recommendations to minimize human errors in the different phases of a building. One of the observed gaps is the lack of communication to lessen human errors. Clients need to understand design intent, and the designers need to understand the client's expectations fully. Lack of communication between the owner and designers can result in inaccurate assumptions such as the use of each space and the number of people inside it, IT equipment load, etc. Hence, owners need to be engaged throughout the design process proactively. Moreover, the exchange of information about control logic between design engineer, BAS operator, maintenance contractor, commissioning agent, and energy consultant over the life cycle of BAS is necessary to minimize programming errors [17], [29]. An effective solution for passing information can be done by a computer processible representation of BAS from specification through design to operation and maintenance [17]. Sharing access to the control logic is also very important because owners, facility managers, and commissioning agents can review and discuss the control logic that is programmed and implemented in the BAS; so they may find errors, diagnose potential issues and provide recommendations to fix the problems which save time and energy [17]. Education and training is another vital factor in lessening human errors, especially in construction and operation phases. The contractors should consider the importance of hands-on training and provide it to their workers. The building owners should also see the value of training and demand it for building operators, facility managers, commissioning agents, energy auditors, and operation and maintenance staff. Lastly, lessons learned from the mistakes in each phase of a building should be shared with all the team members and transferred to the new members to prevent reoccurring the defects and consequently cost increase and energy waste.

Human error throughout the life cycle of a building is a broad topic that cannot be fully addressed in one paper. Future work should expand the list of errors and provide more industry examples by investigating and inspecting several commercial buildings followed by interviews with building operations staff to explain the identified issues. A worthwhile discussion is also the extent to which we can remove human error through better design.

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