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Sensor Impacts Evaluation and Verification: Expert Interview Responses

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OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE US DEPARTMENT OF ENERGY

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Energy and Transportation Science Division

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1. INTRODUCTION

The sensor configuration/deployment method has critical impacts on energy efficient building control and thermal comfort. However, traditional sensor techniques for building operation and fault detection and diagnostics (FDD) are not necessarily optimal in terms of energy efficiency and thermal comfort, and their global effects are not thoroughly investigated. In an effort to address and overcome this limitation, a multilaboratory and multiyear project, "Sensor Impact Evaluation and Verification," was proposed. Its purpose is to develop a framework to investigate the impacts of sensor deployment and configuration on building energy optimization, FDD, occupant thermal comfort, and potentially grid efficiency.

The first project task was a literature review to establish a solid knowledge of and a background related to sensor technologies and placement. To accomplish this task, an extensive review of previous research literature was performed. A series of expert interviews were conducted to augment the findings of the literature review.

This report summarizes the interview design and interview results and findings. The interview was designed and performed to (1) investigate the current status and limitations of sensor configuration, (2) identify the research gaps and expectations for potential improvements in sensor configuration and deployment, and (3) integrate expert (e.g., researcher, building operation practitioner) knowledge and experience to develop use-case scenarios (see Section 5).

2. EXPERT INTERVIEWS

The interview questionnaires contained items with multiple-choice and scale-rank types of questions. After the questions were designed, interviews were conducted with experts in the sensors and control area, including those in academia and industry and at US national labs. The interview consisted of six sections: background of the study, purpose of the interview, area of expertise, current sensor configuration practice, how to improve building performance with sensor systems, and use-case evaluation (including both control and FDD-related use-cases). The most common type of question was multiple-choice, and the interviewees were asked to select one or more options from a list of predefined answers. If an interviewee's answer did not fit into the list of choices, or the interviewee wanted to provide their own custom response, they could specify the "other" section. Scale-rank type questions were used to evaluate use-cases identified from previous literature reviews. The experts were asked to evaluate each use-case on a numeric scale from 1 to 5, with 1 meaning least impact and 5 meaning highest impact. The complete interview form is attached as Appendix A.

A total of 31 interview responses were collected from academia (6 individuals), industry (11 individuals), and national labs (14 individuals). Figure 1. Areas of expertise shows the areas of expertise of the interviewees. Interviewees could choose multiple areas of expertise, and their experience included heating, ventilation and air-conditioning (HVAC) systems, building operation, indoor environment, building systems, and policy. Most of the interviewees responded that they had expertise in HVAC systems and building operation, and more than half of the interviewees answered that they had expertise in building systems (e.g., building envelope, construction, building retrofit).

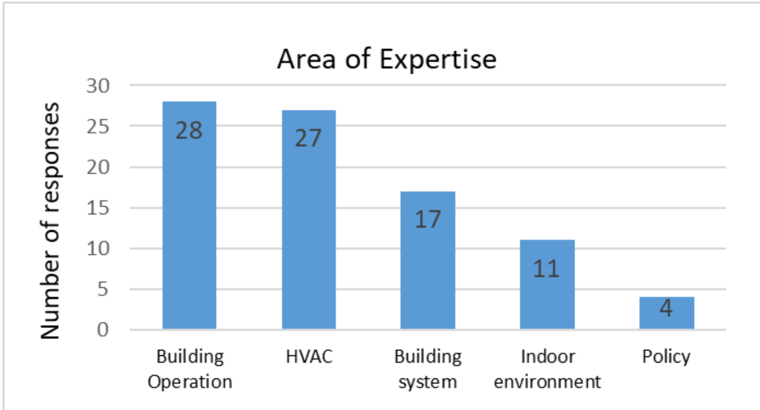


Figure 1. Areas of expertise of interviewees.

3. ANALYSIS OF CURRENT SENSOR CONFIGURATION PRACTICE

To identify current sensor configuration practice, experts were asked three questions: What is your purpose of using sensor system for building performance/maintenance? What are the most significant factors for selecting the sensor set? and What are the current issues of sensor performance? The interviewees selected from one to three choices, and the selection percentages were calculated by dividing the sum of selections for each purpose/factor/issue by the total number of interviewees (31).

Figure 2 shows that for the question regarding the purpose of using sensor systems, responses of energy/power consumption and system efficiency ranked the highest. They were followed by thermal comfort and fault detection: e.g. FDD performance. Other purposes of using sensor systems were benchmarking and real estate utilization, optimization, code compliance, and transactive energy. One researcher also included regulatory reporting as a possible purpose for using sensor systems in the context of building operations. Some other less commonly specified application areas of interest included freeze protection, indoor air quality management, and staging/scheduling.

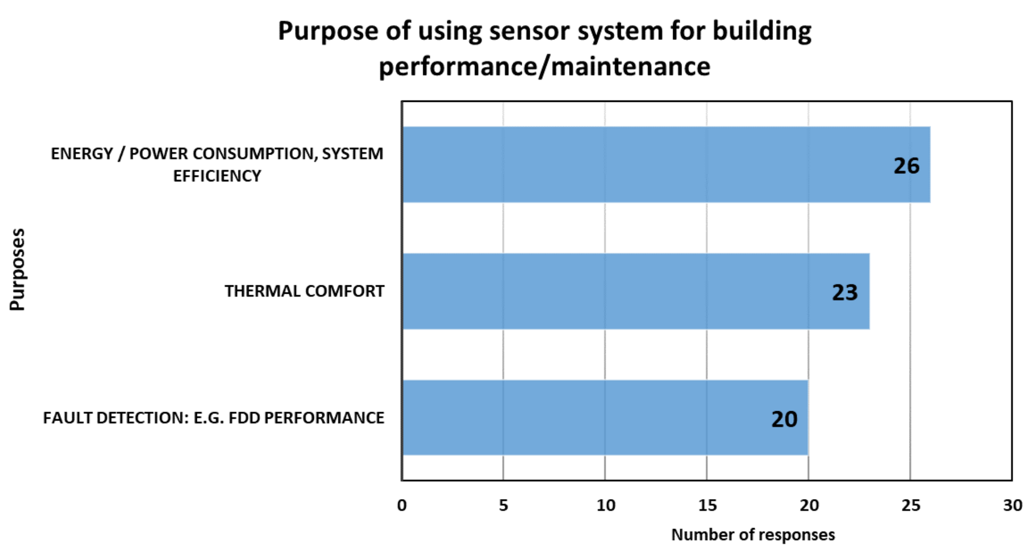


Figure 2. Summary of purposes of using sensor system for building performance/maintenance.

In terms of the significant factors for selecting the sensor set, three factors—initial cost, reliability, and accuracy—held a significant lead over other factors, meaning that most interviewees valued these elements in selecting a sensor set appropriate to their purpose of using a sensor system (Figure 3).

Initial cost, including both equipment and installation costs, was rated the most important and significant factor in sensor selection and sensor performance. Accuracy was chosen as a significant factor in selecting sensors by many experts; however, accuracy was not as highly regarded by some other researchers because they consider high accuracy to be required for only some of the applications for which they used sensors.

Some researchers noted that the significance of factors could differ according to the sensor type, which in turn is dependent on the application domain. For example, reliability and lifespan may be the important factors for selecting lighting sensor systems, for which accuracy is not a major concern. However, accuracy is a highly important factor for air quality monitoring and therefore would be a priority in considering choices for indoor air quality sensor systems.

Besides the factors listed in the interviews, some interviewees mentioned that easy installation, less sensor drift over time, longer lifespan, data handling, management, and accessibility were also key factors for selecting a sensor set. One researcher highlighted that sometimes it may be more viable (both economically and logistically) to use local sensors for ease of deployment. Some interviewees also noted that answers to the aforementioned questions pertaining to current sensor practice are contingent on the background of the interviewee and their specific sub-area expertise.

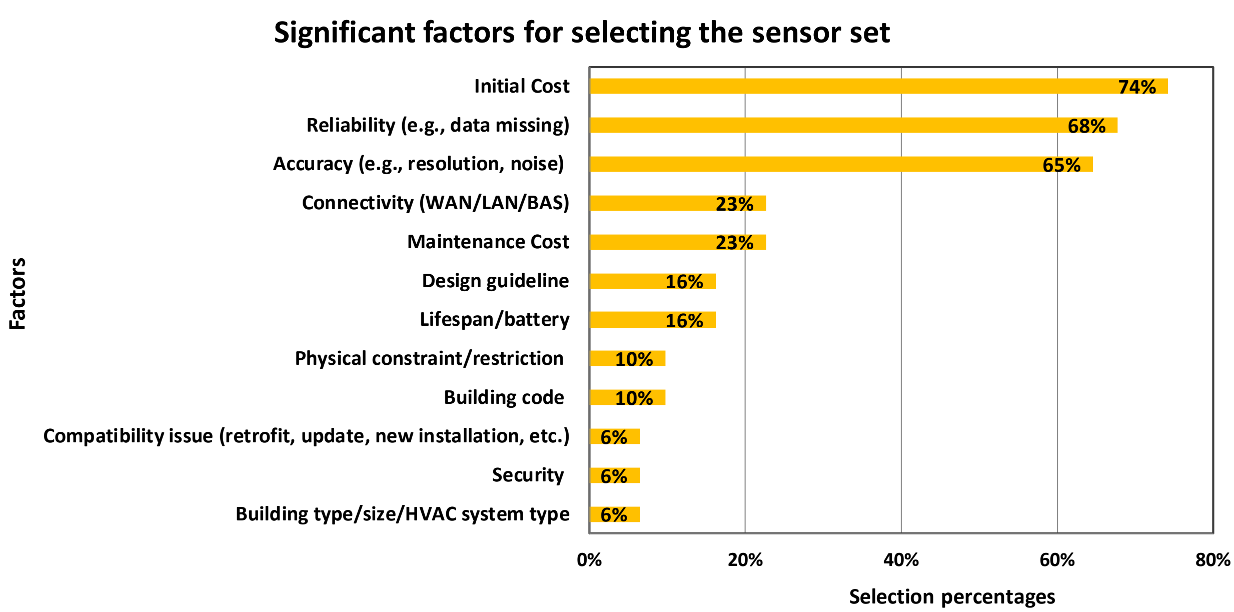


Figure 3. Summary of significant factors for selecting the sensor set.

Figure 4 shows the interview results for current issues in sensor system design, deployment, and operation. Interviewees chose reliability, initial cost, accuracy, and maintenance cost as the most common issues for current sensor systems. The same list of issues (a total of 12) were chosen as significant factors in selecting a sensor system (see Figure 3).

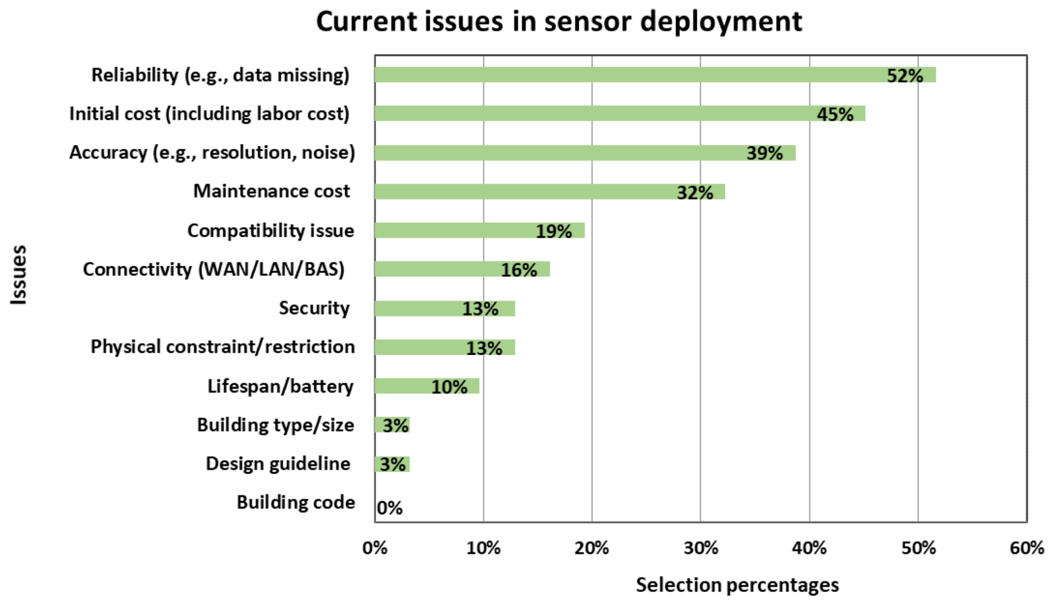


Figure 4. Summary of current issues in sensor deployment.

The important issues for sensor system could differ according to building type and sensor type. Two interviewees stated that in old buildings, there are more obstacles and issues related to regulations and safety for sensor installation and maintenance, whereas the issues could be different for new buildings. New buildings can more easily accommodate more advanced sensors because there are fewer physical constraints. Lighting and occupancy (room-layer) sensors are easily replaced, but sensors in HVAC systems are not. One interviewee noted that the issues do not involve the location limitations and selection of the sensors themselves, but the physical limitations of HVAC systems, i.e., the actuation side.

In addition to the issues presented in Figure 4, the following issues were reported from multiple interviewees: difficulties in deploying sensors, inaccuracy due to sensor location, stability of sensor communication links, difficulties of auto-calibration of sensors (especially CO_2 sensors and entropy sensors), long-term accuracy against sensor drift and bias, and inaccuracy due to indoor contaminants.

Another issue was related to increased demand for the use of sensors and the limitations of wireless sensors. In considering trade-offs between sensor cost and resulted benefits, one potential solution is to install wireless sensors. However, one expert suggested a battery-operated system (i.e., wireless sensors) is not desirable for existing buildings because of the physical limitations of sensor location (e.g., ceiling height). Considering that most sensors are installed in ceilings, and the ceilings of existing buildings are difficult to access, wireless sensors are not desirable for calibration or maintenance work. Another interviewee stated that wireless sensors are limited with regard to reliability and battery life, so it is important to choose sensors with lower power consumption and longer lifespans.

4. ANALYSIS OF BUILDING PERFORMANCE IMPROVEMENT WITH SENSOR SYSTEMS

To identify the most influential sensor system and corresponding building performance improvement method, experts were asked two questions: What are the most important sensor systems in terms of building energy/thermal comfort performance and FDD? How would you improve on current sensor performance for new building or existing building design? The selection percentages were calculated by dividing the number of interviewees who chose each sensor system/method of improvement by the total number of interviewees.

The interviewees made at least one selection in each category (room layer and HVAC layer) for the first question. In the room-layer category, sensors for thermal comfort, indoor air quality, occupancy, and lighting/daylighting were the choices. Sensors for control, efficiency, and fault detection were the choices for the HVAC-layer category.

Interviewees identified sensors measuring temperature, humidity, air velocity, and globe temperature in the presence of radiation heat sources among the thermal comfort sensors, and CO_2 sensors and volatile organic compounds sensor in among indoor air quality sensors. Supply air/return air temperature sensors and airflow and static pressure sensors were specified among control sensors. Some researchers noted that the choice of the most important sensors among the HVAC categories might be guided by other categorial/numerical factors such as system size and weather.

Figure 5 shows that thermal comfort sensors were identified as the most important sensor systems in terms of building energy/thermal comfort performance and FDD, followed by control sensors, indoor air quality sensors, and occupancy sensors. It is worth noting that thermal comfort sensors, indoor air quality sensors, occupancy sensors, and lighting/daylighting sensors belong to the room category; and control sensors, efficiency sensors, and fault detection sensors are in the HVAC category.

Besides the important sensor systems listed in Figure 5, other important sensor systems were also proposed by multiple interviewees: mean–radiant-temperature sensors; energy meters; refrigerant leakage sensors, which are important for fault detection but quite expensive; and sensors for critical temperature and flow measurements, such as mixed air temperature.

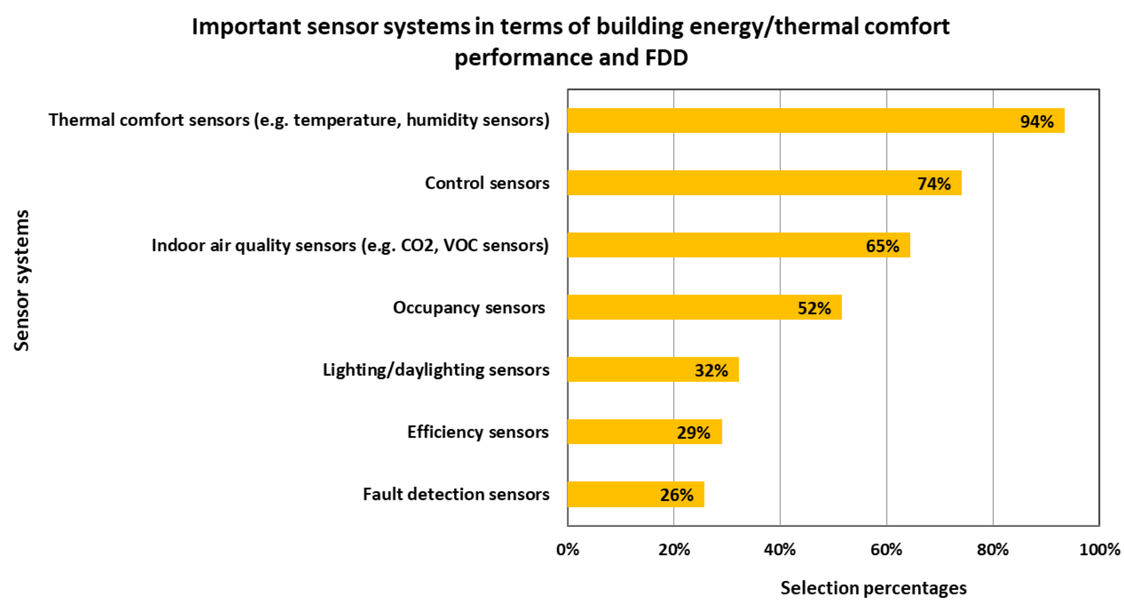


Figure 5. Summary of important sensor systems in terms of building energy/thermal comfort performance and FDD.

Figure 6 shows the results for building performance improvement methods. Interviewees were asked to choose one of the proposed methods and to specify a detailed description of the method. The most common selections among all the proposed methods were improve the current practice of sensor configuration/design, install additional sensor sets, and install advanced sensor system(s). Detailed descriptions of methods of improving current sensor performance suggested by interviewees are summarized in the following paragraphs.

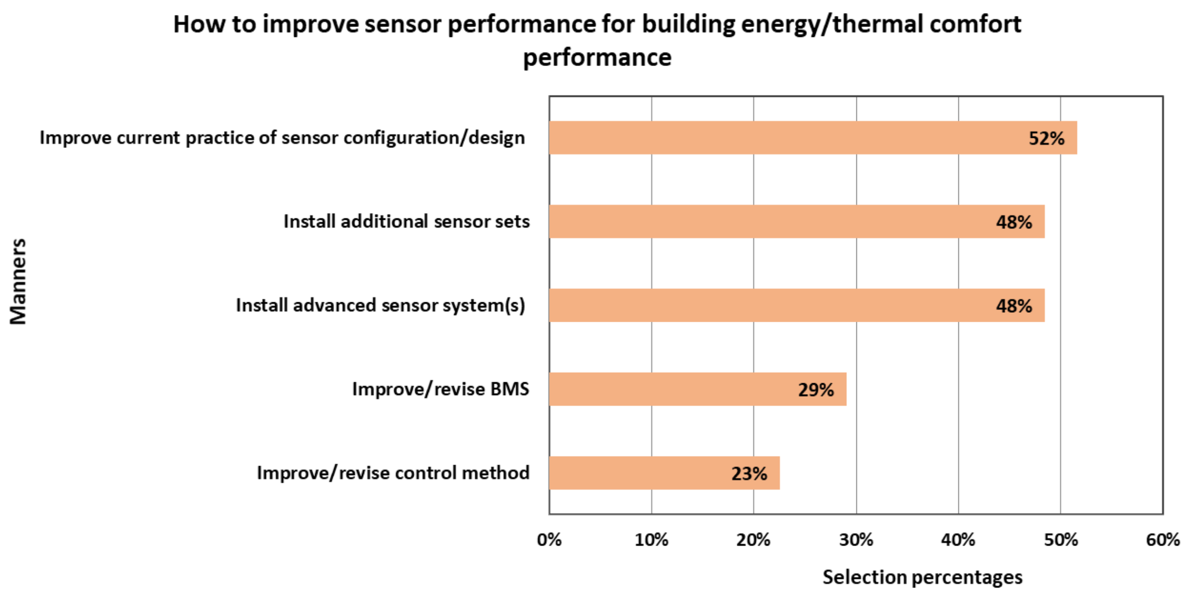


Figure 6. Summary of ways to improve sensor performance for building energy/thermal comfort performance.

Development of new and advanced sensors: One researcher recommended advanced sensors. Advanced sensors can have open formats, and the data they produce can be used by any kind of software for analysis. Improved new sensor technologies such as local thermal imaging and advanced imaging sensors are suggested. Enhanced sensor systems (e.g., lighting, occupancy, daylight, air flow meters, combined with CO_2 sensing for retrofits) are recommended for installation in office buildings as well. Electrical submetering of key equipment, natural gas interval metering, hot/chilled water flow submetering, room-level sensing (as opposed to only zone-level sensing), direct air flow measurement (instead of estimation from indirect measurement) are suggested. Advanced occupancy sensors that detect not only occupancy but also the number of occupants are suggested. Some interviewees also proposed the use of advanced state-of-the-art sensors as well (such as Internet of Things, water flow rate, and refrigerant leak sensors), noting, however, that their cost might be prohibitive. One researcher also identified the use of advanced data-driven analytics to enhance sensor system performance by generating more actionable (rather than passive) data.

Improvement of current practice of sensor configuration and design: One researcher suggested improving sensor placement to ensure accuracy, requiring actuator feedback sensors (e.g., damper/valve position) and occupancy sensors, and measuring air temperatures and flow rates at all air terminal devices. Another researcher suggested ensuring that sensors are labeled with the correct names and calibrated regularly. Another stated that most sensors are limited by their need of wires for power and communication. Even wireless sensors still need power; that need severely limits where they can be installed, often resulting in sensors installed in completely inappropriate locations.

One researcher suggested adding auxiliary sensors to improve reliability and to perform self-calibration. A researcher highlighted that it may be better to focus on end-use and understand how sensor data can be used to cater to that end-use before designing the sensor configuration. Such approaches might render simpler and improved configurations. Additionally, there were suggestions to (1) include zone occupancy sensors integrated with a building automation system (BAS) for airflow and thermostat resets, (2) include more zone-level CO_2 sensors for flexible airflow control, (3) include more water flow and supply/return temperature monitoring systems to calculate and trend energy output on each piece of equipment, and (4) ensure better connectivity of sensors to the BAS, especially for zone-level information such as occupancy and lighting.

Installation of additional sensor sets: Installation of additional sensor sets was recommended to sufficiently cover the space to be monitored. Wireless sensors were suggested for their simplicity and cost-effectiveness, so that they can be installed without continuous monitoring of sensor data. One researcher suggested adding CO_2 occupancy sensors and adding sensors to monitor various duct and pipe statuses. A researcher also suggested including more self-commissioning and self-configuring sensor systems. A caveat to that recommendation is that adding sensors must be economically viable to attain those self-adaptive goals. In addition to the methods listed in Figure 6, other others were proposed from multiple interviewees: improve data collection/trend logging and communication infrastructure; choose sensors that are simple to understand and easy to implement; use proven technologies rather than state-of-the-art sensors (which could create more issues); integrate sensors into a building management system (BMS); develop a consistent taxonomy and sensor naming scheme to allow more effective and time-efficient configuration of the building energy management system; improve building performance with sensor systems in the building commissioning and building retro-commissioning process; implement plug-and-play and wireless sensors; provide guidance and codes on including valuable sensors that are often left out; use FDD techniques to validate that sensors are installed and calibrated properly; allow more sensor measurement trending and more reliable data acquisition (reduce missing data). Some researchers also suggested determining failed or out-of-range sensors as a potential case study. One researcher pointed out the need for improved inference mechanisms for sensor data to improve current practices.

5. ANALYSIS OF USE-CASE EVALUATIONS

This section analyzes an evaluation of use-cases by interviewees. The analysis of sensor impacts on building control is introduced in Section 5.1 and impacts on FDD are introduced in Section 5.2. Each interviewee was asked to evaluate each use-case on a scale of 1 to 5 for least impact to highest impact. Based on a literature review conducted beforehand, the most suitable four building control use-cases and six FDD uses-cases were selected. These use-cases are worth investigating because of their high impact on building operation performance. The selected use-cases are shown in Table 1.

Table 1. Selected use-cases for control and FDD.

Control use-cases	
1	Thermostat performance evaluation by thermostat location, number, and sensor characteristics for energy and thermal comfort (e.g., optimal thermostat locations)
2	Sub-zoning variable-air-volume (VAV) system (e.g., one thermostat for multiple zones to individual thermostats in the zone)
3	Occupancy sensor impacts on energy use and comfort
4	Sensor requirements for advanced control strategies (e.g., model-predictive control [MPC], adaptive control)
FDD use-cases	
1	Inappropriate set points/schedule or biased thermostat/sensor malfunction
2	Air flow duct leakage
3	Insufficient evaporator or condenser airflow (condenser fan degradation)
4	Economizer damper/sensor issue (e.g., stuck damper, biased sensor)
5	Heating/cooling coil fault (leaking or stuck heating/cooling coil valve, fouled or blocked heating/cooling coil)
6	Leaking or stuck VAV reheat coil valve or VAV damper

The rationales for the evaluations in terms of research potential and research limitations are also provided. There were four selections for research potential—energy savings, comfort, grid-interactivity, and economic/cost potential, and five selections for research limitation—already investigated in active academic research, already optimal, practically not feasible, no cost benefit, or code restriction.

In addition to the detailed use-cases (pertaining to controls and FDD), researchers suggested newer cases, such as use of sensors to control plug and process loads, that might benefit from inclusion in this project. One researcher mentioned that sensor redundancy is another important use-case that could benefit from a study like this. Another mentioned as a potential use-case identifying the most important sensor technology needs and their benefits aggregated across the identified benefits (e.g., thermal comfort, energy efficiency, and others).

5.1 SENSOR IMPACTS ON BUILDING CONTROLS

The weighted average values of control use-cases are shown in Figure 7. The weighted average value of each use-case was calculated by dividing the sum of all the scales by the total number of interviewees who made selections (e.g., 25 interviewees made selections for control use-case occupancy sensor impacts on energy use and comfort, and 24 made selections for control use-case sensor requirements for advanced control strategies.)

It can be seen that three control use-cases have similar weighted average values, whereas thermostat performance evaluation by thermostat location, number, and sensor characteristics for energy and thermal comfort (the bottom bar) has a significantly lower value.

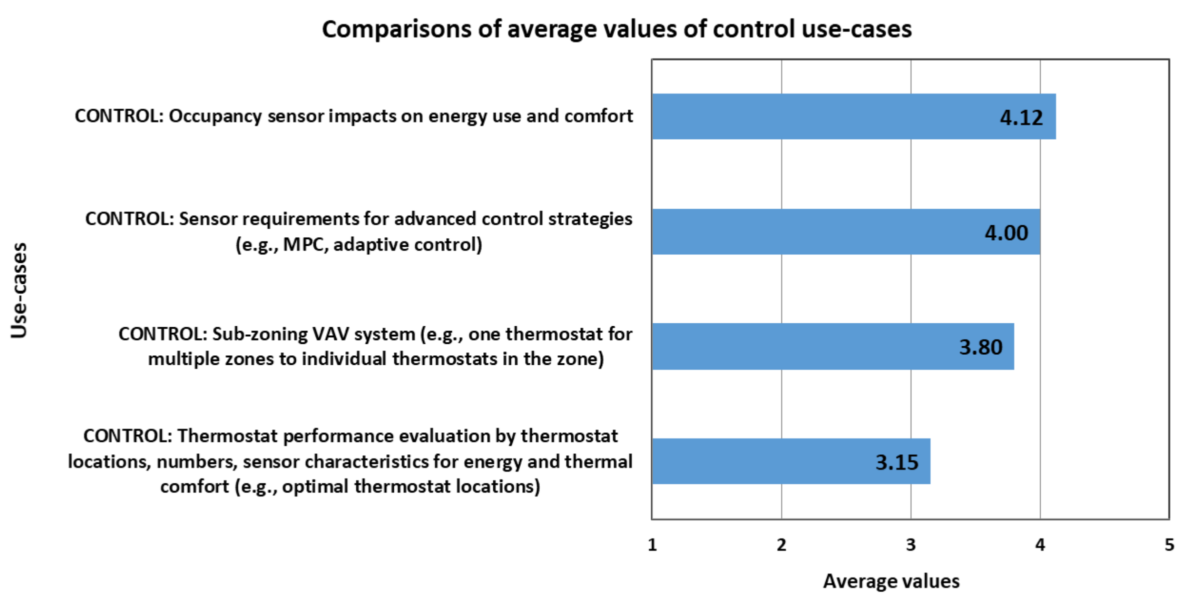


Figure 7. Comparisons of average values of control use-cases.

Figure 8 shows the rankings of research potential of a control use-case—thermostat performance evaluation by thermostat location, number, and sensor characteristics for energy and thermal comfort. The selection percentages were calculated by dividing the sum of the selections for each research potential by the total number of interviewees making selections (26 for this use-case). It is obvious that most interviewees selected comfort and energy saving potential and fewer selected economic/cost and grid-interactivity potential.

The rankings of research limitations for the same control use-case are shown in Figure 9. It is interesting that the interviewees selected only three limitations—no cost benefit, already investigated, and practically not feasible— and the other two were not selected at all.

Application suggestion: Since thermostats are the most commonly used type of sensor and directly control HVAC systems, proper design and improvement of thermostats can have a high impact on building thermal comfort. However, one researcher stated that the impact of the uses-case greatly depends on the situation or scenario and varies by case (e.g., size and shape of the zone). Best-practices recommendations could be made available; but in reality, using computer simulation tools to determine thermostat location before installation/design stage could be challenging.

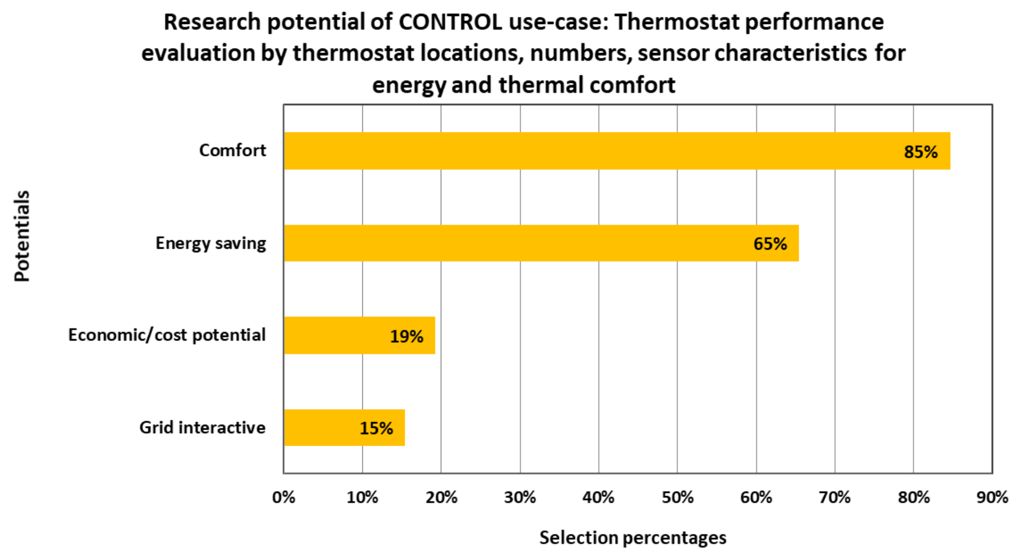


Figure 8. Summary of research potential of the control use-case for thermostat performance evaluation by thermostat location, number, and sensor characteristics for energy and thermal comfort.

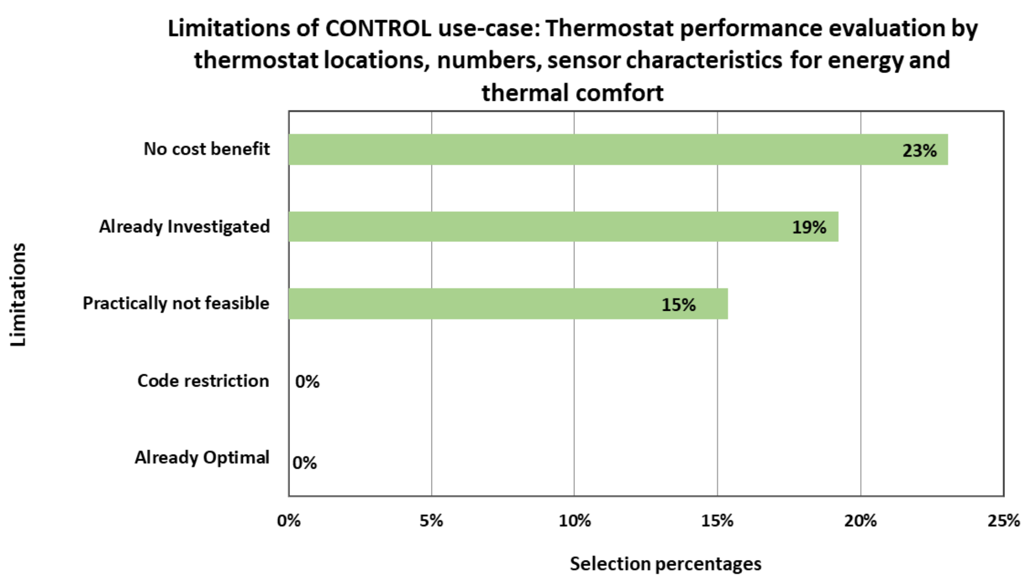


Figure 9. Summary of limitations of the control use-case for thermostat performance evaluation by thermostat location, number, and sensor characteristics for energy and thermal comfort.

Figure 10 shows the rankings for research potential of the control use-case for sub-zoning VAV systems (e.g., one thermostat in a zone controls multiple zones associated with the thermostat). Most interviewees (88%) selected research potential for comfort and 56% selected energy savings potential. The rankings for the limitations of the same control use-case are shown in Figure 11. The major limitation of this use-case is that this subject has been already investigated. One researcher stated that this subject has been investigated by research, but the findings and solutions have not been deployed widely in practice.

Application suggestion: One researcher stated that a sub-zoning VAV system has significant potential for retrofitting. However, another researcher stated that a sub-zoning VAV system can increase operating costs, and the effect is uncertain. Therefore, thorough investigation of this use-case is needed to evaluate trade-offs between investment and building performance (i.e., energy efficiency and thermal comfort).

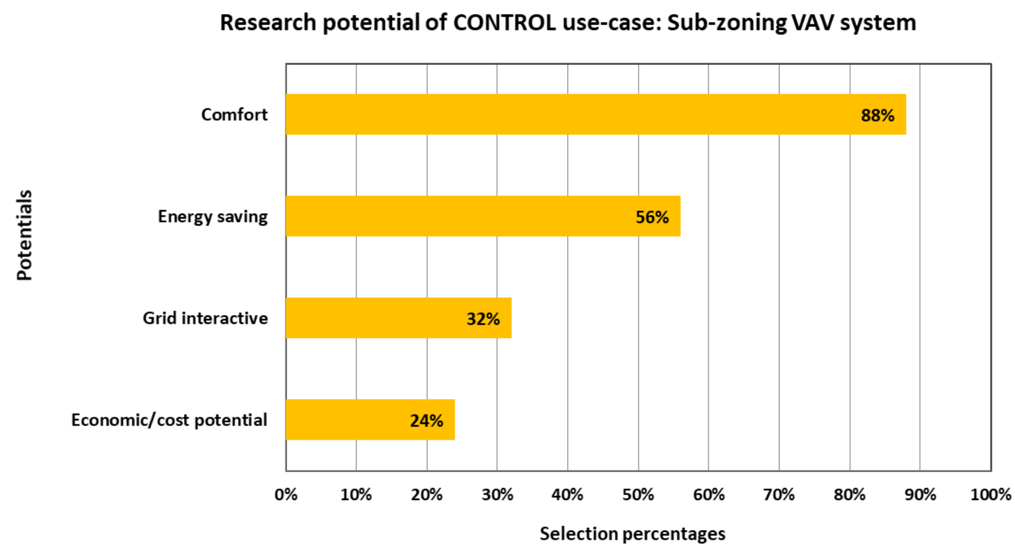


Figure 10. Summary of research potential of the control use-case for sub-zoning VAV system for energy and thermal comfort.

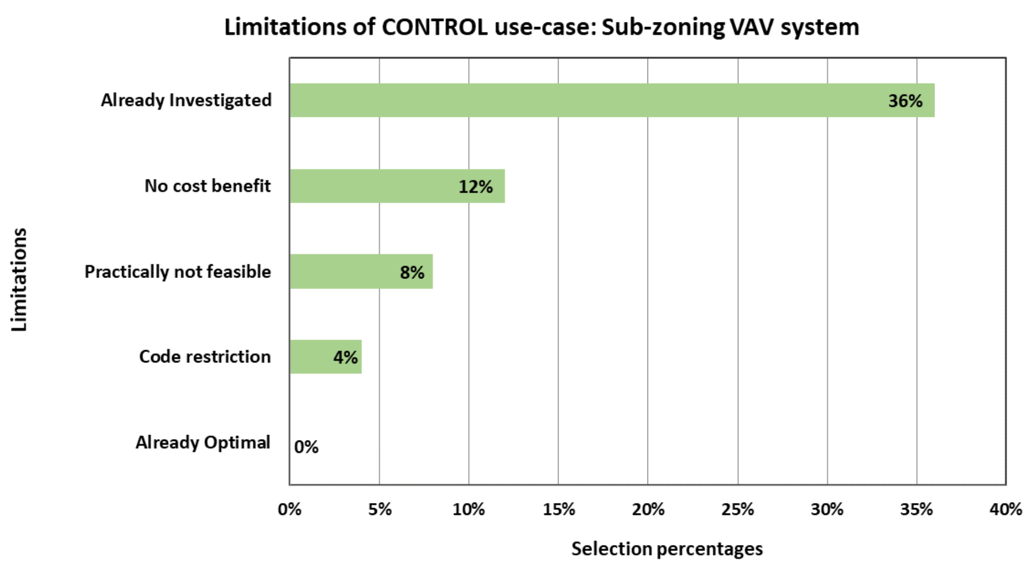


Figure 11. Summary of limitations of control use-case for sub-zoning VAV system for energy and thermal comfort

Figure 12 shows the rankings for the research potential of the control use-case for occupancy sensor impacts on energy use and comfort. Most interviewees (92%) selected research potential for energy savings, and 60% selected research potential for comfort. The rankings for the limitations of the same control use-case are shown in Figure 13. The major limitation mentioned for this use-case is that it has already been widely investigated.

Application suggestion: It is necessary to consider the cost-benefit trade-off of deploying occupancy sensors. The resulting benefits, in terms of energy savings and thermal comfort improvement, depend on the occupancy patterns in a building. One researcher suggested optimization based on measured dynamic occupancy may be more realistic than the optimization based on "static" existing building and engineering/HVAC design codes or local standards and permits. Often, a significant portion of HVAC energy use is wasted in an office building to condition the whole building while many zones are not occupied for this reason.

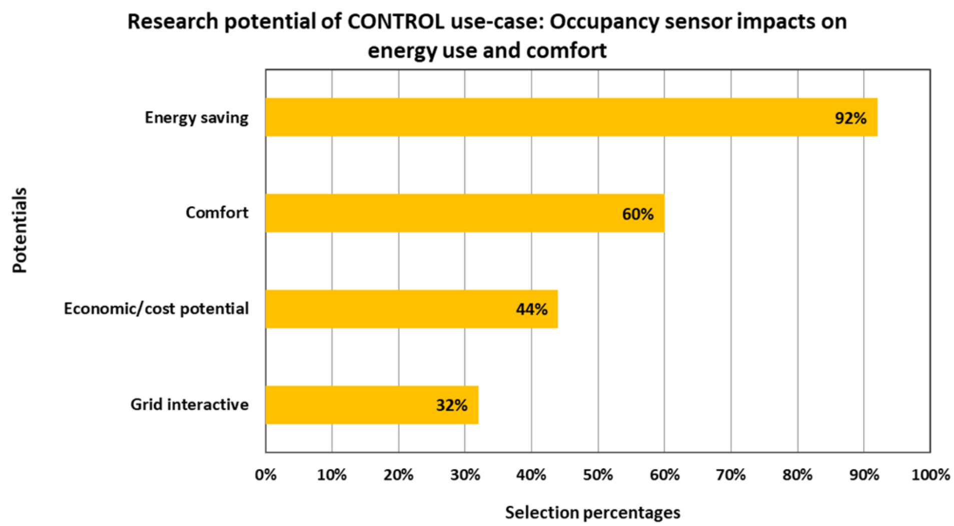


Figure 12. Summary of potential of the control use-case for occupancy sensor impact on energy use and comfort.

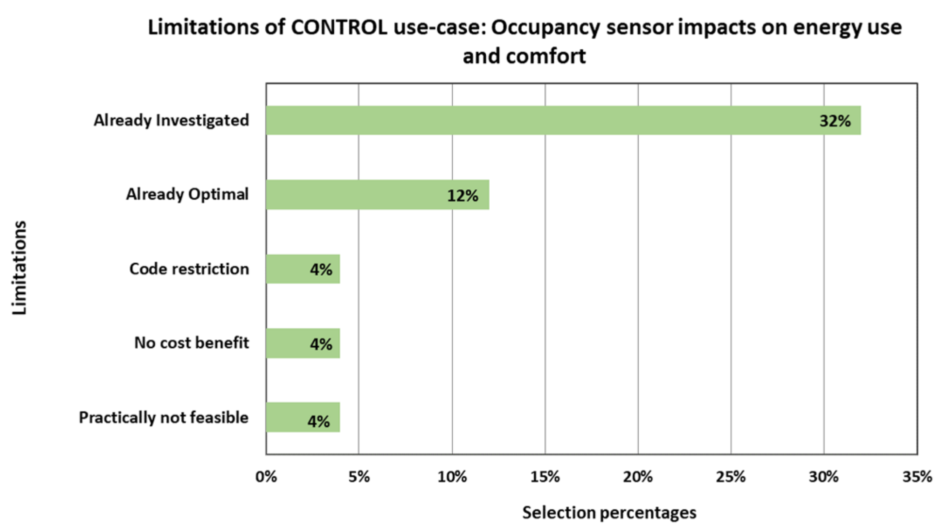


Figure 13. Summary of limitations of the control use-case for occupancy sensor impacts on energy use and comfort.

Figure 14 shows the rankings of the research potential of the control use-case for sensor requirements for advanced control strategies (e.g., MPC, adaptive control, machine-learning (ML)-based control). Many interviewees (79%) selected research potential in energy savings and 50% selected research potential in grid interactivity. The rankings of the limitations of the same control use-case are shown in Figure 15. The major limitation of this use-case is that no cost benefit is expected. The reason for this limitation is probably that MPC cannot perform ideally in real-world situations (especially complicated systems) because of inaccurate prediction of inputs and unstable model performance. In addition, MPC requires more sensors, which increases its application cost.

Application suggestion: One significant challenge in the application of advanced control strategies, e.g. MPC, is accurate prediction of the inputs that have dominant impacts on the control results. In addition, the development of an accurate model (e.g., resistance-capacitance (RC) model, data-driven model) is critical for advanced control. MPC algorithms have been applied only to rather simple buildings or simulations. Therefore, it is necessary to investigate the impact of MPC on full-scale buildings with more realistic sensor systems.

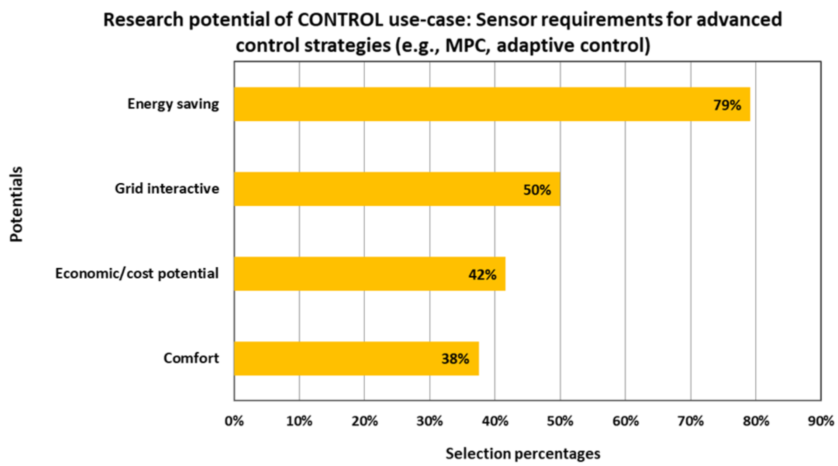


Figure 14. Summary of potential of the control use-case for sensor requirements for advanced control strategies.

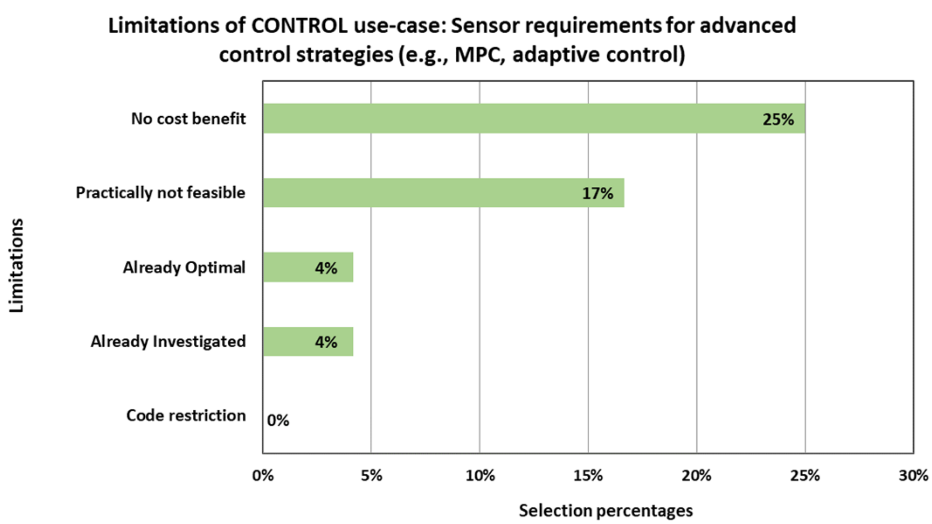


Figure 15. Summary of limitations of the control use-case for sensor requirements for advanced control strategies.

In addition to the control use-cases discussed above, some control use-cases were also proposed by the interviewees: system-level use-cases—hot/chilled water systems that use water/refrigerant-side sensors; building-to-grid use-cases—submetering at the equipment level; evaluation and monitoring of energy system performance (e.g., a systematic approach to evaluating performance with data points, time intervals, minimum accuracy, and so on); auto-commissioning using selected sensor systems; grid services, such as demand response; and metering required for load leveling and measurement and verification.

5.2 SENSOR IMPACTS ON FDD

The weighted average values of FDD use-cases are shown in Figure 16. The weighted average value of each use-case was calculated by dividing the sum of the scales by the total number of interviewees who made selections. It can be seen clearly that the weighted average value for the economizer damper/sensor issue and inappropriate set points/schedule or biased thermostat/sensor malfunction was somewhat higher than those for the four other use-cases.

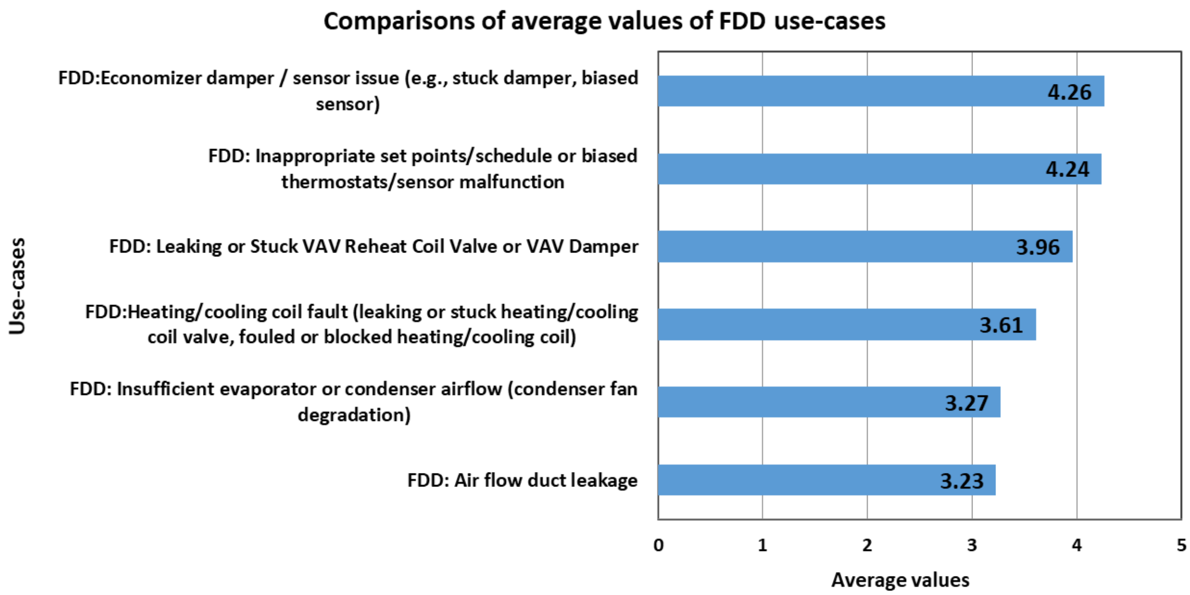


Figure 16. Comparisons of average values of FDD use-cases.

Figure 17 shows the rankings for the research potential of the FDD use-case for inappropriate set points/schedule or biased thermostat/sensor malfunction, and Figure 18 shows the research limitations. In general, the interviewees answered that this use-case has research potential for energy savings (90%), and some interviewees expected research potential for comfort. The major limitation of this use-case is many researchers have already investigated this issue.

Application suggestion: One researcher stated that there is a big opportunity to investigate "virtual sensors" on which inappropriate set points or biased thermostats have a large impact. Another researcher stated that the impact of this use-case depends on the building type and building size. If the target building is small (e.g. residential, small office building), the energy savings potential would not be significant.

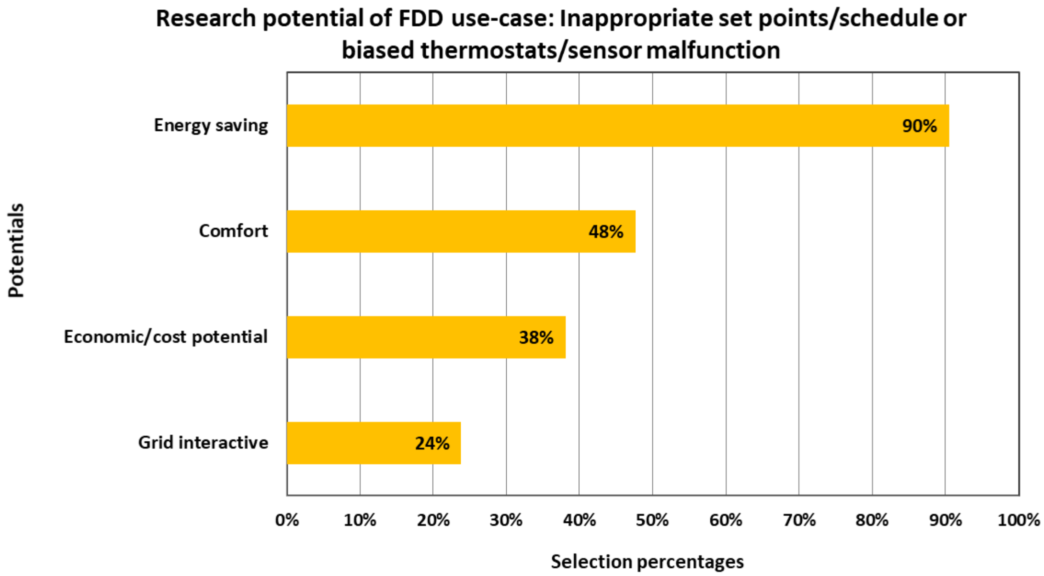


Figure 17. Summary of potential of the FDD use-case for inappropriate set point/schedule or biased thermostats/sensor malfunction.

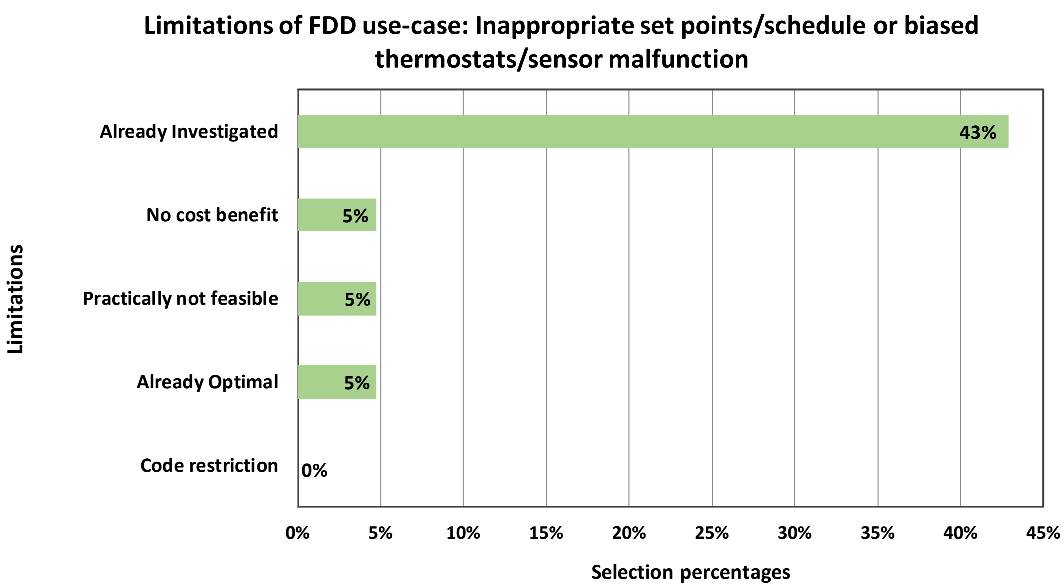


Figure 18. Summary of limitations of the FDD use-case for inappropriate set point/schedule or biased thermostats/sensor malfunction.

Figure 17 shows the rankings for the research potential of the FDD use-case for air flow and duct leakage, and Figure 20 shows the research limitations. In general, the interviewees answered that this use-case has high research potential in terms of offering energy savings (73%). The limitation of this use-case is that much research has already investigated it, and some researchers noted that no cost benefit is expected for it.

Application suggestion: Two researchers pointed out that this use-case is important and has energy savings potential for occupied zones and large buildings, whereas it has no obvious impact on unoccupied zones such as basements or attics.

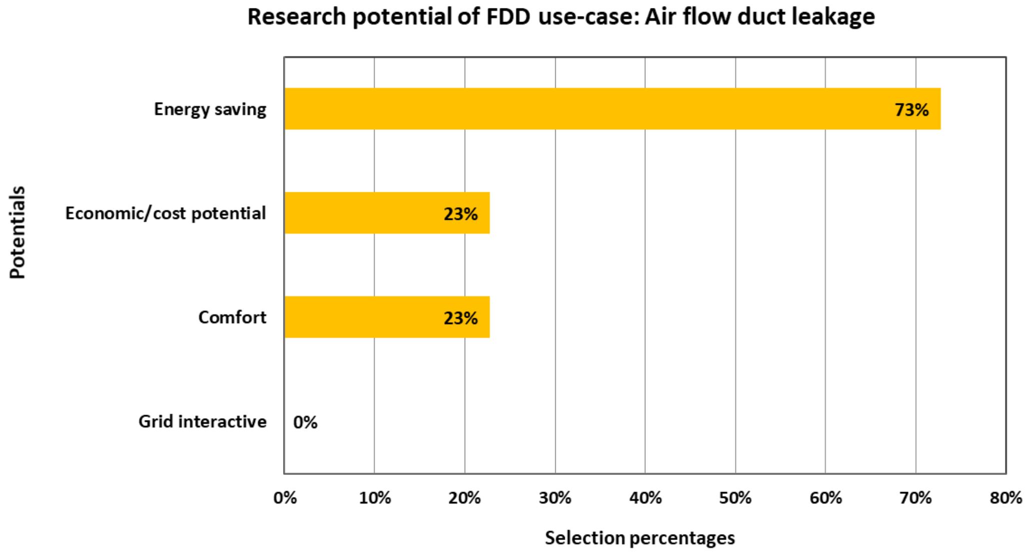


Figure 19. Summary of potential of the FDD use-case for air flow duct leakage.

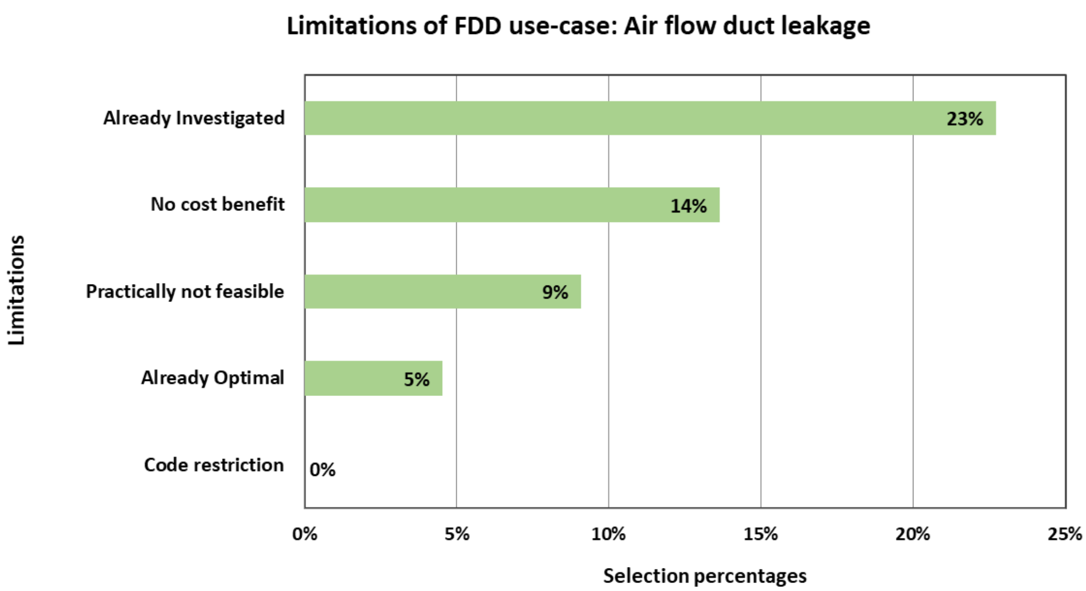


Figure 20. Summary of limitations of the FDD use-case for air flow duct leakage.

Figure 17 shows the rankings for the research potential of the FDD use-case for insufficient evaporator or condenser air flow (condenser fan degradation), and Figure 22 shows the research limitations. In general, the interviewees answered this that use-case has research potential in terms of energy savings (77%). The limitation of this use-case is that much research has already investigated it, and some researchers noted that no cost benefit is expected in this use-case.

Application suggestion: This fault could have a big impact on the suction pressure of an evaporator and accordingly its efficiency, and the accuracy of the sensors could generate a large effect on the FDD performance for this fault.

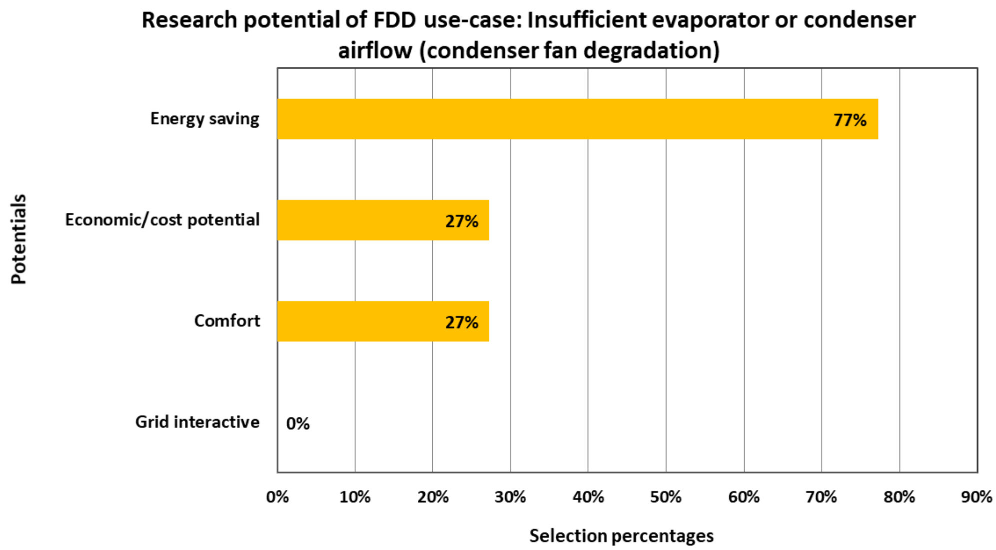


Figure 21. Summary of potential of the FDD use-case for insufficient evaporator or condenser airflow.

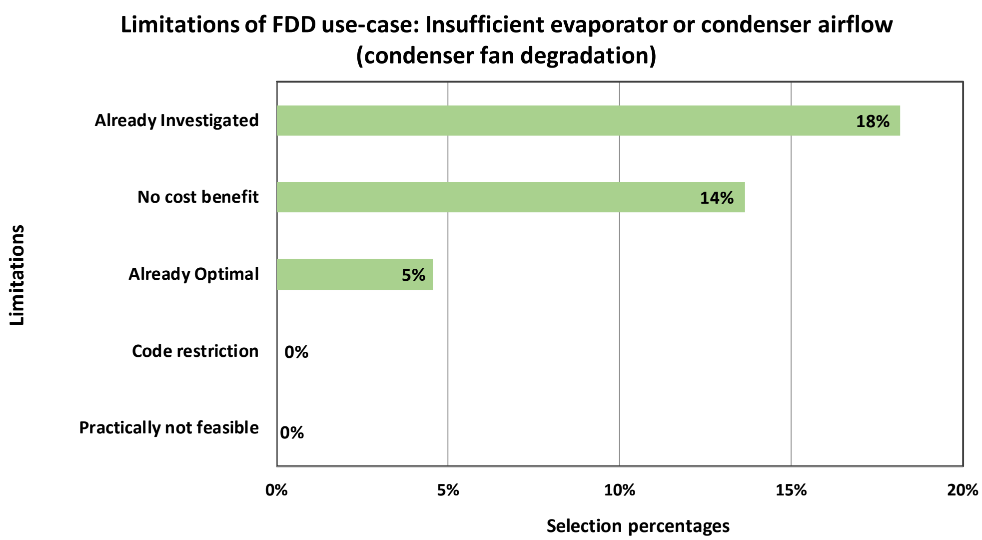


Figure 22. Summary of limitations of the FDD use-case for insufficient evaporator or condenser airflow.

Figure 23 shows the rankings for the research potential of the FDD use-case for economizer damper/sensor issues (e.g., stuck damper, biased sensor), and Figure 24 shows the research limitations. In general, the interviewees answered that this use-case has research potential in the area of energy savings (87%), and 52% of interviewees expected economic and cost benefits from research related to it. The major limitation of this use-case mentioned was that much research has already investigated it.

Application suggestion: One researcher stated that studies of more advanced and effective control algorithms for economizers are required. The potential benefit of such research varies for different regions because their demands for economizers are different; e.g., California has more demand for economizers. Another researcher noted that an economizer is a significant component in achieving energy savings, yet economizer control is relatively straightforward. It is noteworthy, however, that the resulting amount of wasted energy is larger than the amount saved if an economizer is not properly controlled.

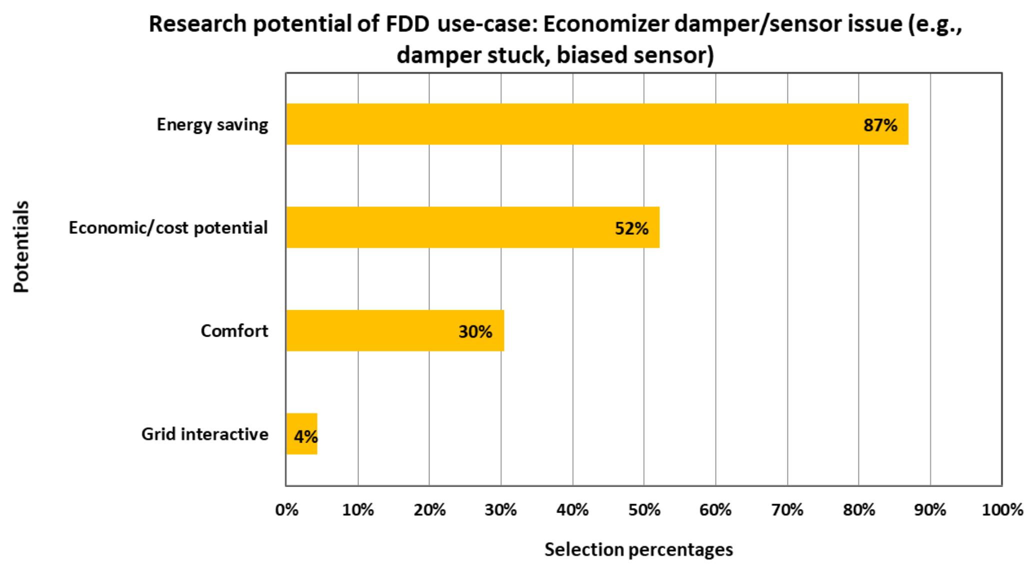


Figure 23. Summary of potential of the FDD use-case for economizer damper/sensor issues.

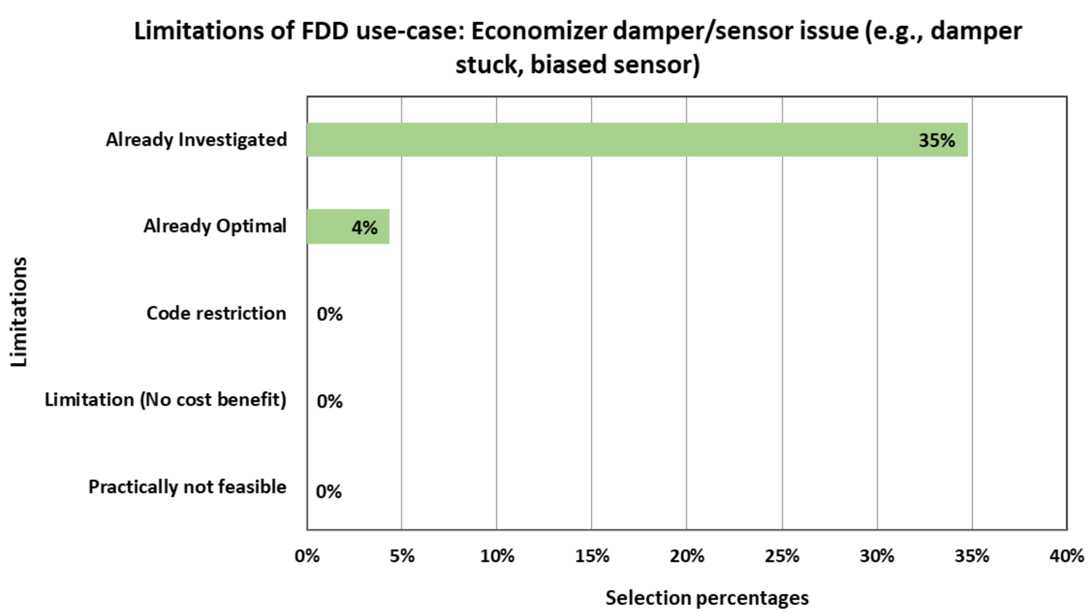


Figure 24. Summary of limitations of the FDD use-case for economizer damper/sensor issues.

Figure 25 shows the rankings of the research potential of the FDD use-case for heating/cooling coil fault (leaking or stuck heating/cooling coil valve, fouled or blocked heating/cooling coil), and Figure 26 shows the research limitations. In general, the interviewees answered that this use-case has research potential in the area of energy savings (93%), 48% of interviewees saw research potential for comfort issues, and 43% of interviewees saw potential for research related to economics/cost. The limitation of this use-case is that much research has already investigated it.

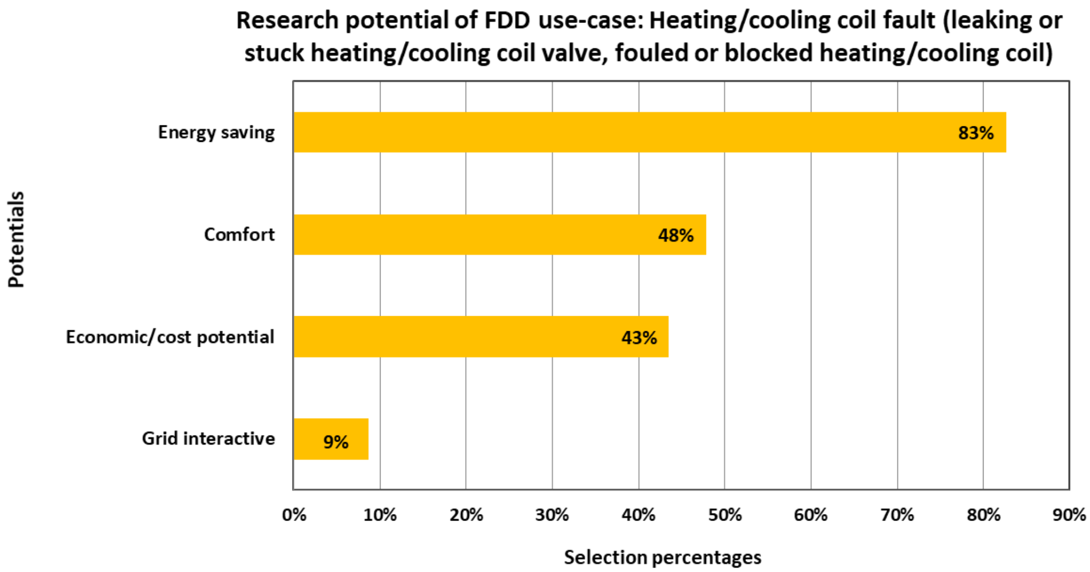


Figure 25. Summary of potential of the FDD use-case for heating/cooling coil faults.

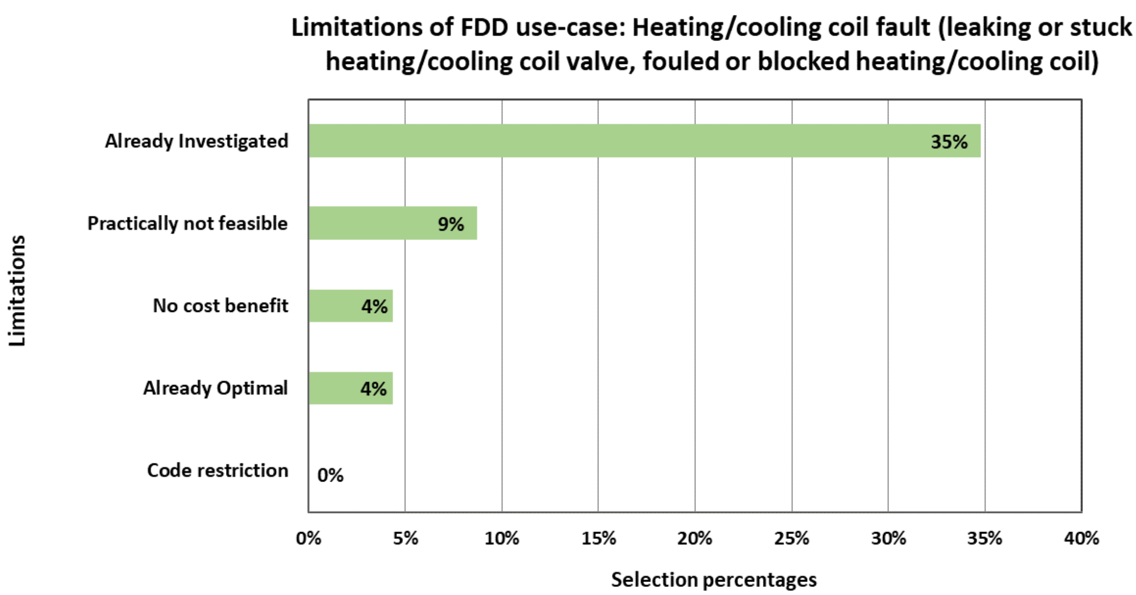


Figure 26. Summary of limitations of the FDD use-case for heating/cooling coil faults.

Figure 25 shows the rankings for the research potential of the FDD use-case for leaking or stuck VAV reheat coil valve or VAV damper, and Figure 28 shows the research limitation rakings. In general, the interviewees answered that this use-case has research potential in the area of energy savings (83%), and 65% of interviewees saw research potential in comfort issues. The limitation of this use-case is that it has already been well investigated.

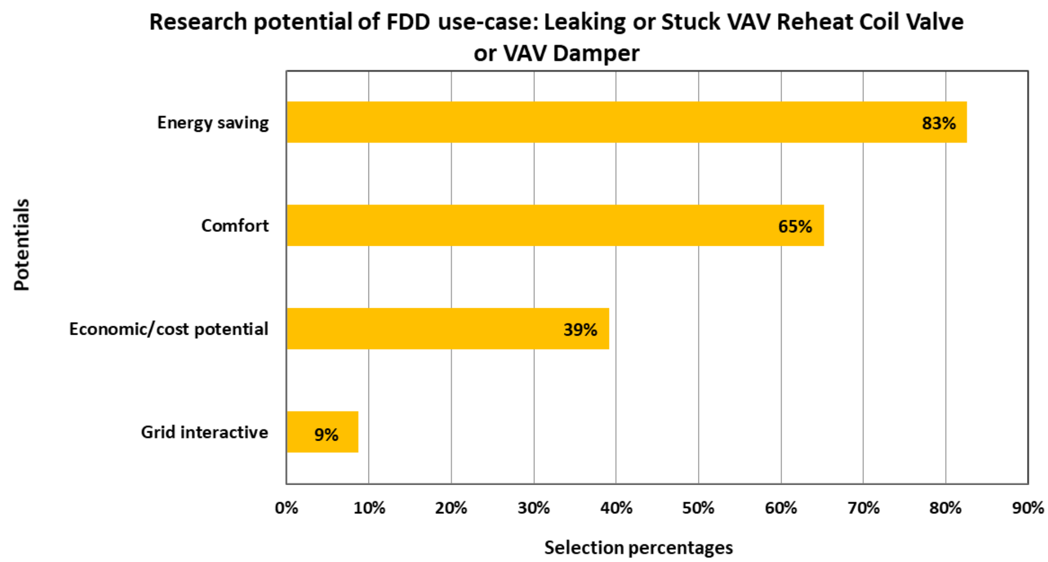


Figure 27. Summary of potentials of the FDD use-case for leaking/stuck VAV reheat coil valve or VAV damper.

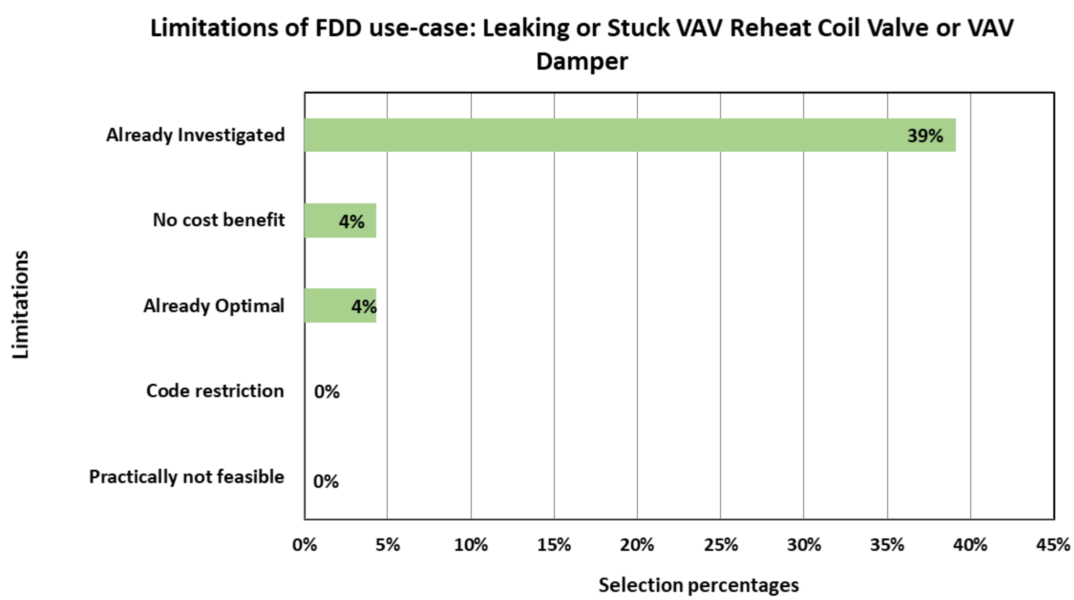


Figure 28. Summary of limitations of the FDD use-case for leaking/stuck VAV reheat coil valve or VAV damper.

In addition to the FDD use-cases listed above, some FDD use-cases were also proposed by the interviewees: inappropriate static pressure settings, hot water systems and biased sensors, building pressurization issues, and cooling tower performance issues.

6. SUMMARY

To accomplish the project's goals, a series of expert interviews were performed to augment the findings of the literature review. The interview results contributed to (1) investigating the current status and limitations of sensor configuration, (2) identifying the research gaps and expectations for potential improvement of sensor configuration/deployment, and (3) integrating expert (e.g., researcher, building operation practitioner) knowledge and experience to develop use-case scenarios. The interview results can be summarized as follows, and Tables 2–5 provide a detailed summary of the interview results.

- The purpose of using sensor systems was not distinct by interviewee; most interviewees used sensor systems to address energy/power consumption, system efficiency, thermal comfort, and fault detection

- Interviewees considered initial cost, reliability, and accuracy to be significant factors for selecting sensor sets. Similarly, current issues the mentioned for sensor deployment were initial cost, reliability, accuracy, and maintenance cost.

- Interviewees identified thermal comfort, control, indoor air quality, and occupancy sensors as important sensor systems in terms of building energy/thermal comfort performance and FDD. It is worth noting that control sensors were in the HVAC category and other sensors belonged to the room category.

- To improve sensor performance for new or existing buildings, the common selections among the proposed methods were (1) improve the current practices of sensor configuration/design, (2) install additional sensor sets, and (3) install advanced sensor systems(s).

- The average value for control use-cases ranged from 3.15 to 4.12, and interviewees verified that control use-cases have research potential in the areas of energy savings and thermal comfort improvement. The major concern/limitation mentioned for control use-cases was that the use-cases were already investigated in active academic research.

- The average value for FDD use-cases ranged from 3.23 to 4.26, and interviewees verified that FDD use-cases have research potential in the areas of energy savings, thermal comfort improvement, and economic/cost potential. The major concern/limitation for FDD use-cases was that they have already been investigated and are the subject of active academic research as well.

Table 2. Summary of interview results: current sensor configuration practice.

Interview selection	Selection percentage
Purpose of using sensor system	
Energy / power consumption, system efficiency	84%
Thermal comfort	74%
Fault detection: e.g., FDD performance	65%
Significant factors for selecting sensor set	
Initial cost	74%
Reliability (e.g., data missing)	68%
Accuracy (e.g., resolution, noise)	65%
Connectivity (wide-area network (WAN)/local-area network LAN)/BAS)	23%
Maintenance cost	23%
Design guideline	16%
Lifespan/battery	16%
Physical constraint/restriction	10%
Building code	10%

Table 2. Summary of interview results: current sensor configuration practice (continued).

Interview selection	Selection percentage
Compatibility issue (retrofit, update, new installation, etc.)	6%
Security	6%
Building type/size/HVAC system type	6%
Current issues for sensor deployment	
Reliability (e.g., data missing)	52%
Initial cost (including labor cost)	45%
Accuracy (e.g., resolution, noise)	39%
Maintenance cost	32%
Compatibility issue (e.g., retrofit, update, new installation)	19%
Connectivity (WAN/LAN/BAS)	16%
Physical constraint/restriction	13%
Security	13%
Lifespan/battery	10%
Design guideline	3%
Building type/size	3%
Building code	0%

Table 3. Summary of interview results: influential sensor system and building performance improvement.

Interview selection	Selection percentage
Most important sensor system	
Thermal comfort (e.g., temperature, humidity sensors)	94%
Control sensors	74%
Indoor air quality (e.g. CO_2, volatile organic compound sensors)	65%
Occupancy	52%
Lighting/ daylighting	32%
Efficiency sensors	29%
Fault detection sensors	26%
How to improve current sensor system	
Improve current practice of sensor configuration/design	52%
Install advanced sensor system(s)	48%
Install additional sensor sets	48%
Improve/revise BMS	29%
Improve/revise control method	23%

Table 4. Summary of control use-case evaluations.

Research potential/limitations		Selection percentage
Control use-case 1:	Thermostat performance evaluation by thermostat location, number, sensor characteristics for energy and thermal comfort (e.g., optimal thermostat locations)	Weighted average values: 3.15
Potentials	Comfort	85%
	Energy saving	65%
	Economic/cost potential	19%
	Grid interactive	15%
Limitations	No cost benefit	23%
	Already investigated	19%
	Practically not feasible	15%
	Code restriction	0%
	Already optimal	0%
Control use-case 2:	Sub-zoning VAV system (e.g., one thermostat for multiple zones to individual thermostats in the zone)	Weighted average values: 3.80
Potentials	Comfort	88%
	Energy saving	56%
	Grid interactive	32%
	Economic/cost potential	24%
Limitations	Already investigated	36%
	No cost benefit	12%
	Practically not feasible	8%
	Code restriction	4%
	Already optimal	0%
Control use-case 3:	Occupancy sensor impacts on energy usage and comfort	Weighted average values: 4.12
Potentials	Energy saving	92%
	Comfort	60%
	Economic/cost potential	44%
	Grid interactive	32%
Limitations	Already investigated	32%
	Already optimal	12%
	Code restriction	4%
	No cost benefit	4%
	Practically not feasible	4%
Control use-case 4:	Sensor requirements for advanced control strategies (e.g., MPC, adaptive control)	Weighted average values: 4.00
Potentials	Energy saving	92%
	Grid interactive	60%
	Economic/cost potential	44%
	Comfort	32%
Limitations	No cost benefit	25%
	Practically not feasible	17%
	Already optimal	4%
	Already investigated	4%
	Code restriction	0%

Table 5. Summary of FDD use-case evaluations.

Research potential/limitations		Selection percentage
FDD use-case 1:	Inappropriate set points/schedule or biased thermostats/sensor malfunction	Weighted average values: 4.24
Potentials	Energy saving	90%
	Comfort	48%
	Economic/cost potential	38%
	Grid interactive	24%
Limitations	Already investigated	43%
	No cost benefit	5%
	Practically not feasible	5%
	Already optimal	5%
	Code restriction	0%
FDD use-case 2:	Air flow duct leakage	Weighted average values: 3.23
Potentials	Energy saving	73%
	Economic/cost potential	23%
	Comfort	23%
	Grid interactive	0%
Limitations	Already Investigated	23%
	No cost benefit	14%
	Practically not feasible	9%
	Already optimal	5%
	Code restriction	0%
FDD use-case 3:	Insufficient evaporator or condenser airflow (condenser fan degradation)	Weighted average values: 3.27
Potentials	Energy saving	77%
	Economic/cost potential	27%
	Comfort	27%
	Grid interactive	0%
Limitations	Already investigated	18%
	No cost benefit	14%
	Practically not feasible	5%
	Already optimal	0%
	Code restriction	0%
FDD use-case 4:	Economizer damper/sensor issue (e.g., stuck damper, biased sensor)	Weighted average values: 4.26
Potentials	Energy saving	87%
	Economic/cost potential	52%
	Comfort	30%
	Grid interactive	4%

Table 5. Summary of FDD use-case evaluations (continued).

Research potential/limitations		Selection percentage
Limitations	Already investigated	35%
	Already optimal	4%
	Code restriction	0%
	No cost benefit	0%
	Practically not feasible	0%
FDD use-case 5:	Heating/cooling coil fault (leaking or stuck heating/cooling coil valve, fouled or blocked heating/cooling coil)	Weighted average values: 3.61
Potentials	Energy saving	83%
	Comfort	48%
	Economic/cost potential	43%
	Grid interactive	9%
Limitations	Already investigated	35%
	Practically not feasible	9%
	No cost benefit	4%
	Already optimal	4%
	Code restriction	0%
FDD use-case 6:	Leaking or stuck VAV reheat coil valve or VAV damper	Weighted average values: 3.96
Potentials	Energy saving	83%
	Comfort	65%
	Economic/cost potential	39%
	Grid interactive	9%
Limitations	Already investigated	35%
	No cost benefit	4%
	Already optimal	4%
	Code restriction	0%
	Practically not feasible	0%

APPENDIX A. A COMPLETE QUESTIONNAIRE OF THE INTERVIEW

Expert Interview

Sensor impacts on building performance

I. Background of the study

The operation and maintenance of building systems are based on data from various sensors in the buildings. Hence, the sensor configuration and deployment have critical impacts on building performances. However, traditional practices are not necessarily optimal in terms of energy efficiency and thermal comfort.
In order to achieve the following purposes, Oak Ridge National Laboratory (ORNL), Pacific Northwest National Laboratory (PNNL) and National Renewable Energy Laboratory (NREL request experts' opinions via this survey.

This interview is conducted as part of a research project: Sensor Impact Evaluation and Verification, funded by the U.S. Department of Energy under FOA No. DE-LC-000L070.

II. Purpose of the interview

A. Investigate current status and limitations of sensor configuration impacts on building performance.

B. Identify the research gaps and expectation for potential improvement of sensor configuration/deployment.

C. Integrate expert (e.g. researcher, building operation practitioner) knowledge and experiences to develop use-case scenarios.

III. What is your area of expertise? You can choose multiple categories.

A. HVAC: equipment [ ]

B. HVAC: design/sizing [ ]

C. HVAC: control/operation [ ]

D. HVAC: heat transfer [ ]

E. HVAC: renewable energy [ ]

F. HVAC: maintenance [ ]

G. HVAC: building automation [ ]

H. Building operation: building-to-grid [ ]

I. Building operation: transactive/predictive control [ ]

J. Building operation: sensor network [ ]

K. Building operation: sensor design/deployment [ ]

L. Building operation: building data acquisition (DAQ) [ ]

M. Building operation: fault detection & diagnosis (FDD) [ ]

N. Building operation: lighting controls [ ]

O. Building operation: energy metering [ ]

P. Indoor environment: computational fluid dynamics (CFD) [ ]

Q. Indoor environment: thermal comfort [ ]

R. Indoor environment: indoor air quality (IAQ) [ ]

S. Indoor environment: occupant-related [ ]

T. Building: building envelope [ ]

U. Building: architectural design [ ]

V. Building: retrofit [ ]

W. Building: building system integration [ ]

X. Building: lighting [ ]

Y. Building: construction [ ]

Z. Policy: building energy policy makers [ ]

AA. Policy: building code [ ]

BB. Policy: decision making [ ]

CC. Others: ____

IV. Current sensor configuration practice

Please select factor(s) or issue(s) for Section A through C for your application or based on your engineering judgment.

A. What is your purpose of using sensor system for building performance/maintenance?

1. Thermal comfort [ ]
2. Energy / power consumption, system efficiency) [ ]
3. Fault detection: e.g., FDD performance
4. Others: ________________

B. What are the most **significant factors** for selecting the sensor set? (Select up to 3 factors)

1. Budget
    a) initial cost (e.g., device cost, labor cost) [ ]
    b) Maintenance cost [ ]
2. Sensor characteristics / maintenance
    a) Accuracy (e.g., resolution, noise) [ ]
    b) Reliability (e.g., data missing) [ ]
    c) Lifespan / battery [ ]
3. Design criteria
    a) Building code [ ]
    b) Design guideline [ ]
    c) Physical constraint/restriction [ ]
4. Building type/size/HVAC system type [ ]

5. Security [ ]
6. Compatibility issue (retrofit, update, new installation, etc.) [ ]
7. Connectivity (WAN/LAN/BAS)
8. Others: ___________________________

C. What is are the **current issue** of sensor performance? (Select up to 3 issues)

1. Budget
    a) initial cost (e.g., device cost, labor cost) [ ]
    b) Maintenance cost [ ]
2. Sensor characteristics / maintenance
    a) Accuracy (e.g., resolution, noise) [ ]
    b) Reliability (e.g., data missing) [ ]
    c) Lifespan / battery [ ]
3. Design criteria
    a) Building code [ ]
    b) Design guideline [ ]
    c) Physical constraint/restriction [ ]
4. Building type/size [ ]
5. Security [ ]
6. Compatibility issue (retrofit, update, new installation, etc.) [ ]
7. Connectivity (WAN/LAN/BAS)
8. Others: ___________________________

V. How to improve building performance with sensor systems

Please select the most influential sensor systems and corresponding design method(s) in terms of building energy, thermal comfort performance or FDD <u>based on your application</u>.

A. What are the most important sensor systems in terms of building energy/thermal comfort performance and FDD? (Please select at least 1 in each category and list sensors)

1. Room
    a) Thermal comfort (e.g. temperature, humidity sensors) [ ]
        Specify: __________________________
    b) Indoor air quality (e.g. CO_2, VOC sensors) [ ]
        Specify: __________________________
    c) Occupancy [ ]
        Specify: __________________________

d) Lighting / daylighting [ ]

Specify: ________________________

e) Others: _______________________

2. HVAC

(e.g. temperature, air flow meter, energy meter, gas meter, static pressure)

a) Control sensors [ ]

Specify: ________________________

b) Efficiency sensors [ ]

Specify: ________________________

c) Fault detection sensors [ ]

Specify: ________________________

d) Others: _________________

3. Others: ____

B. How would you improve current issue of sensor performance for new building or existing building design?

1. Install advanced sensor system(s) (i.e. state-of-the-art sensors sets) [ ]

a) Specify: __________________________________

2. Install additional sensor sets [ ]

a) Specify: __________________________________

3. Improve current practice of sensor configuration/design [ ]

a) Specify: __________________________________

4. Improve/revise control method [ ]

a) Specify: __________________________________

5. Improve/revise BMS [ ]

a) Specify: __________________________________

6. Others: ____

VI. Use-cases evaluation

Please evaluate each use-case in the following tables by choosing the scales (1 means least impact and 5 means highest impact) and select corresponding reason(s) for scale.

A. Building control related use-cases

Building control related use-cases refer to the applications which investigate the impact of sensor configuration and displacement on building control performance (e.g., energy consumption, cost or thermal comfort).

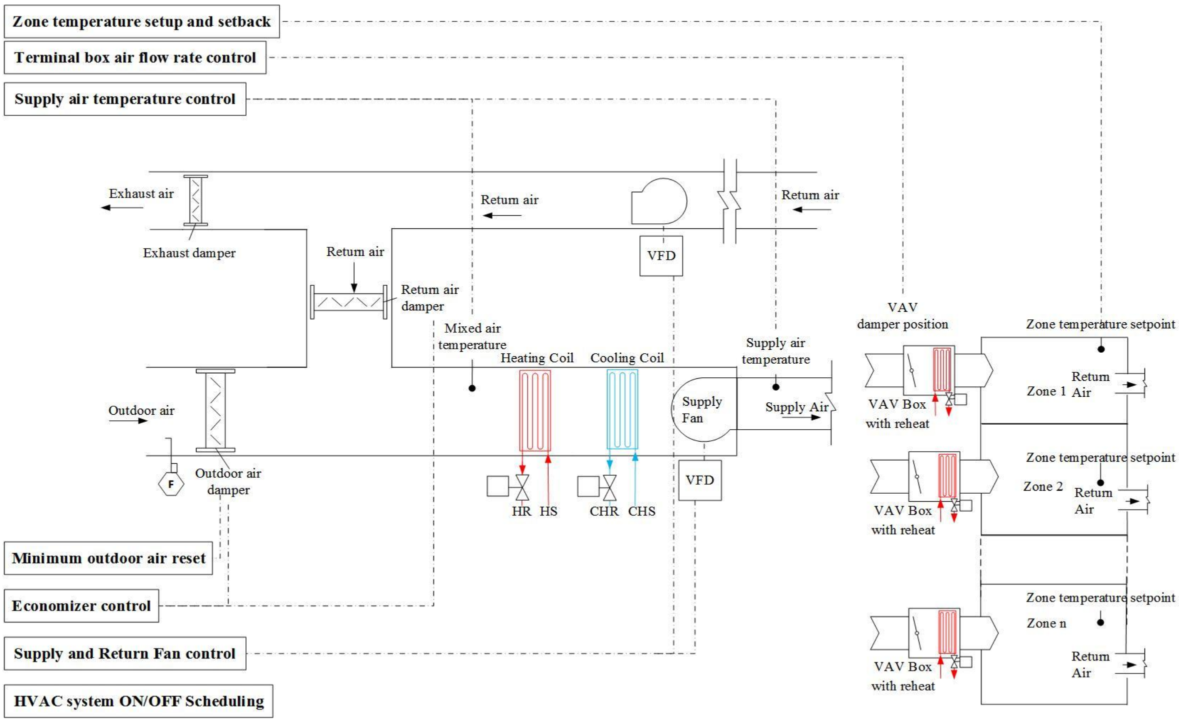
Use-cases	Scale (5: highest impact)					Rationale for scale								
						Research potential				Research limitation				
	1	2	3	4	5	Energy Saving	Comfort	Grid interactive	Economic /cost potential	Already investiga ted	Already Optimal	Practicall y not feasible	No cost benefit	Code restrictio n
Thermostat performance evaluation by thermostat locations, numbers, different sensor characteristics for energy and thermal comfort (e.g., optimal thermostat locations)														
Sub-zoning VAV system (e.g., one thermostat for multi-zones into individual thermostats in the zone)														
Occupancy sensor impacts on energy usage and comfort														
Sensor requirements for advanced control strategies (e.g., model predictive control (MPC), adaptive control)														
Other use cases:														

B. FDD related use-cases

FDD related use-cases refer to the applications which investigate the impact of sensor configuration and displacement on building fault detection & diagnostics performance. Please refer section D (page 9). for assumed AHU/VAV system.

Use-cases	Scale (5: highest impact)					Rationale for scale									Difficulty to detect/diagnose (scale 5: most difficult)				
						Research potential				Research limitation									
	1	2	3	4	5	Energy Saving	Comfort	Grid interactive	Economic /cost potential	Already investiga ted	Already Optimal	Practicall y not feasible	No cost benefit	Code restrictio n	1	2	3	4	5
Inappropriate set points/schedule or biased thermostats/sensor malfunction																			
Air flow-duct leakage																			
Insufficient evaporator or condenser airflow (condenser fan degradation)																			
Economizer damper / sensor issue (e.g., stuck damper, biased sensor)																			
Heating/cooling coil fault (leaking / stuck heating/cooling coil valve, fouled / blocked heating/cooling coil)																			
Leaking / Stuck VAV Reheat Coil Valve or VAV Damper																			
Other use cases:																			

C. Diagram of assumed AHU/VAV system:



VII. Use-case suggestions

Are there any potential use-cases missing in the survey? Please provide feedback on potential development strategies for these use-cases based on your expertise:
