Measured Data Reliability for Building Performance and Maintenance

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Occupants' health and wellbeing are becoming the focus in the building and construction industry. Indoor factors like thermal, visual, acoustic, and chemical exposure all impact occupants' wellbeing. One of the main approaches to improve wellbeing is to have continuous monitoring of the building. Similarly, building design issues or technical flaws in the building software can have negative impact on occupants' health [1].

Modern *building systems* include sensors, actuators, and control devices, including a tight coupling of hardware and software features. Advanced building systems collect data to improve building performance, operation, and maintenance. Building systems today use a variety of state-of-the-art equipment, such as embedded hardware, wide-area connectivity, and software for decision making [2].

Despite good intentions, the diverse types of equipment and the enormous data they can collect have increased buildings systems' complexity, making them more fragile and prone to faults and failure [3]. For example, faults in sensors can occur because of aging, battery exhaustion, physical damage, or noise [4]. These faults and failures also affect data collection and performance, which can be studied by analyzing work orders (WOs), which include occupants' complaints and service requirements for building systems and can be used to track the evolution of faults. These logs can be used for benchmarking as they show trends and patterns that can be used to evaluate improve building operation and maintenance. These logs are usually textual, including enormous detail and complexity (for instance the WO descriptions); consequently, while they are recorded and collected, they are not fully deployed because of data quality [5]. The textual data are mostly unstructured, which is a barrier to extracting insightful information. To this end, we use text mining to translate data into information, which allows inferring and benchmarking the maintenance performance of buildings. There is also a conflict in using data collected in real-time through sensors, actuators, and textual work logs, as they are from different systems with different timings within the buildings.

Our research explores various techniques to facilitate the ease of storage, processing and access to data, using new building design aspect that has not been fully explored for building systems reliability. We use cloud computing to increase collaboration among various building stakeholders and to display real-time data from building systems for performance and maintenance analysis. Using cloud services, designers can store large Building Information Models (BIM), historical data or simulated data. BIM allows managing the digital representation of building components, their digital geometry, metadata, relationships, and the parametric rules to manipulate them [6]. Building industry stakeholders can use these services to collaborate and visualize information in real-time on BIM [7].

We research how to enhance measured data reliability by modeling building systems' faults and failures, a text- mining framework to process WOs, using cloud computing services for data storage, analysis, and data visualization in BIM. We define a system architecture and a workflow called SUSTAIN (Sensor-based Unified Simulation Techniques for Advanced In-building Networks) which allows us to:

- Combine different data collection schemes to aggregate data from dissimilar sources
- Provide a cloud storage service for the collected real-time sensor and control data and building information like 2D, 3D, and building systems.
- Facilitate the adoption of fault tolerance models to improve building system reliability, including an integration with text-mining methods to process WOs logs.
- Enable various building industry stakeholders to visualize all of these results in real-time through building information modelling (BIM) deployed using cloud services.

We discuss how to increase the reliability of building data through fault tolerance models, a text-mining framework to process WOs to benchmark the building operation, and maintenance data and a prototype implementation defining an API that integrates these models in a cloud-based platform for contextual visualization.

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We show a prototype application using a digital twin of Carleton University campus, the *Carleton Digital Campus (CDC)*, which has been built for virtual experience and building performance analysis. CDC allows access to BIM at various levels (site, building, or room) and is available in standalone fashion for research projects; here we use CDC models to improve data reliability in the buildings at various building levels.

Carleton Campus Digital Models

Carleton University comprises more than fifty buildings linked by five kilometers of underground tunnels and a rich network of roads and pathways. These attributes make the campus an ideal proxy for a distinct urban entity, the equivalent of a 1:1 laboratory. A few buildings have advanced building systems to monitor the energy usage, maintenance, and operation. CDC includes a BIM of Carleton University that permits visualization of complex datasets. CDC is used in three key areas: university facilities management and operations (FMO), university outreach activities for incoming students, and digital twin development to understand and manage the dynamics of the physical campus using its digital version. For FMO, CDC allows intuitive 3D visualization of campus dynamics. The integration of sensor data into the model provides a basis for optimizing building operations, performance, management, and rehabilitation on campus. The model is augmented with sensor data related to existing conditions (such as energy consumption, daylight simulations, parking availability, and occupancy) and scenarios including campus planning (future developments, circulation, landscaping, etc.).

SUSTAIN

SUSTAIN integrates fault tolerance models, a text-mining framework and BIM to improve building system reliability. The overall software architecture is shown in Fig. 1. The smart buildings generate data which can be stored or used in real-time. The process includes building simulations, a physical model (maquette) for experimental purposes, and a database to store data collected from the various sources, as well as BIM to visualize the output of the models contextually. Data can be collected and used based on the building type, conditions, and available systems.

The several types of data that can be used to evaluate the operation and performance of the buildings include *simulated*, *experimental*, *historical* and *real-time* data. Simulated data are used to study various scenarios and simulation experimental conditions, while experimental data are directly obtained from measurements performed on the physical model of the building in which real world scenarios are replicated. Historical data are available from user/operator reports, metered, sensed, fault logs, work logs and raw databases exported from computerized maintenance management systems (CMMS).

The data collected from the various sources are aggregated and stored in a database and used to train fault tolerance models. Regardless of the source, it is important that the data collected are representative of the operation of the building system. Carefully planned efforts should be put into experiments, measurements, and validation of the data. While requirements for data collection may not be fulfilled by the building system's historical data, we can complete them combining historical data with data from simulation and experimentation on the physical model. The data collected should cover the operating range of the building system, be time-stamped, have proper metadata, and provide data points for fault information.

SUSTAIN also includes a text-mining framework. While the fault tolerance models aim to ensure reliability of the building systems, they cannot prevent all faults and failures. The text-mining framework applied on maintenance WOs can identify other faults that can be used to improve the fault tolerance models.

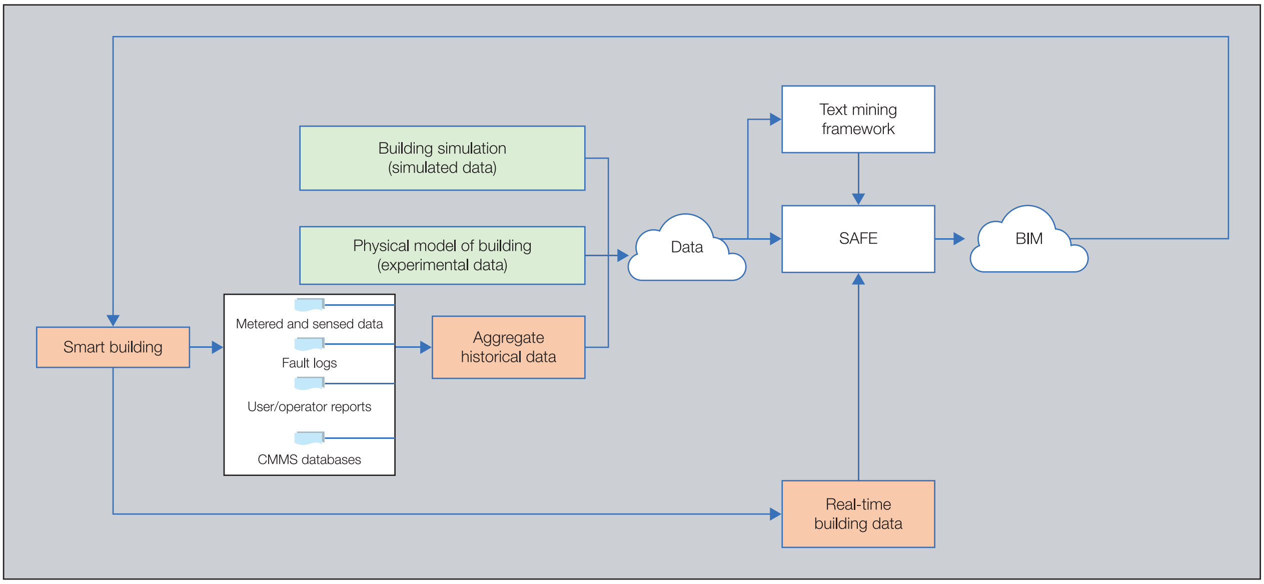


Fig. 1. SUSTAIN architecture and workflow.

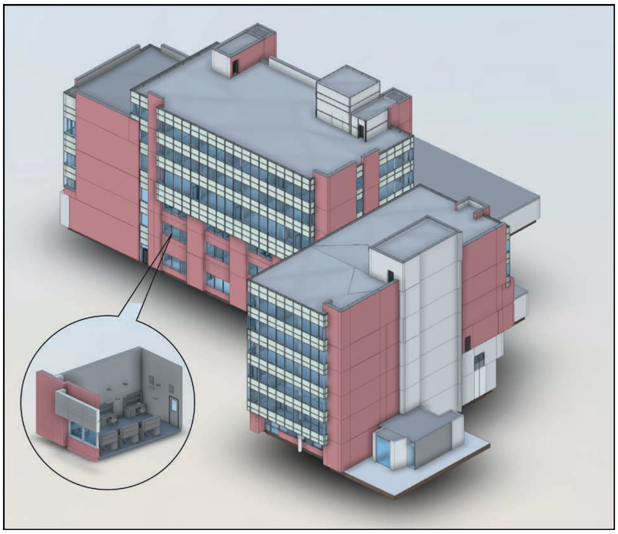


Fig. 2. A rendered model of the VSIM building at Carleton University.

Text Mining Framework for Benchmarking

The text mining framework is applied to the raw databases exported from CMMS, processing the WO logs to extract insightful information (the spatial distribution of WOs, or a categorization based on the building system or component causing a complaint or corrective order). Sometimes the original WO logs do not provide the accurate location of a WO issued. For instance, knowing that there are a certain number of WOs in a building alone cannot assist with measuring performance in detail. The text-mining algorithm, instead, allows it to identify the room number or their equivalent name automatically, making apparent the resulting spatial distribution of WOs. Moreover, other metrics such as the WO intensity per floor area or intensity change rate of WOs are valuable for campus-level facility decision-making. By comparing the values of those metrics for each building with other buildings, the operational performance of buildings can be benchmarked. By adopting this approach, facility managers can focus on the buildings with a larger number of WOs.

Fault Tolerance Models

The models trained for fault tolerance are deployed to the smart buildings to detect faults (here we focus on sensor faults). Detecting faults does not guarantee that faults may not occur; therefore, the SAFE (Simple, Applicable, Flexible, and Extensible) fault tolerance module [8] facilitates adding redundancy to the sensor system using sensor replication and sensor fusion. SAFE ensures that we still have a valid sensor reading when some sensors fail or have faulty readings.

Building Information Model

The data collected from SAFE is integrated into BIM through Autodesk Forge [9], a cloud-based platform. Autodesk Forge allows the system to store and access various BIM and includes an integrated visualization component to visualize the real-time data through various web services. The BIM displays the sensor locations and ties the timeline data to its location. The aggregated data are represented as a shader to the room volume, depending on the data parameters like temperature, humidity, or CO_2 concentration.

Applying SUSTAIN to CDC

We show the use of SUSTAIN by applying it to a physical prototype of a research lab including:

- The digital representation of the University campus defined in Carleton Digital Campus (CDC).
- BIM extraction of a research lab from CDC, digital fabrication, and hardware integration for a physical model (maquette) of the lab.
- Application of the text-mining framework and sensor fusion model.
- BIM integration process of the collected data using cloud services.

The CDC model is an accurate digital representation of the physical campus, created over an 8-year period using heterogeneous datasets: archive plans (both historic hand-drawn plans and CAD), LIDAR scans and point clouds, databases, and photos. These digital assets were translated and incorporated into a single federated model in BIM software (Autodesk Revit). Translation of the data was partially automated using the visual programming tool Dynamo [10] and custom Python scripts. CDC allows us to access the campus site at the levels of site, building, floor, or room.

Fig. 2 shows the BIM of a building we use in our study (VSIM), and a research lab, both extracted from CDC. The

Fig. 3. Physical prototype for experimentation. (a) BIM modelling; (b) Digital fabrication; (c) Hardware integration.

VSIM BIM is a replica of the actual building with all of the building elements (windows, doors, desks, etc.) and building systems (sensors, HVAC, etc.). We show a case study using temperature sensors with an operating range 0 °C – 50 °C (with an accuracy of ±2 °C). We conduct simulation studies with different temperature readings within the measuring range. To evaluate the SAFE framework, faults were deliberately injected in both simulation and experimentation using different scenarios.

The BIM of the lab (Fig. 3a) was used to fabricate a maquette at a scale of 1:20 (Fig. 3b) using laser cutting on acrylic sheets and adding control hardware (Fig. 3c). The hardware integrates an STM32 based Nucleo-144 microcontroller (NUCLEO-H743ZI). Multiple sensors were used: DHT11 (Temperature and Humidity, through digital input pins), MG811 (CO_2 through analog input pins), VEML7700 (Light Intensity through I2C protocol), and PIR Motion Detection (Digital Input pin). The sensors are mounted to the physical model at specific locations (on the top) to mimic the actual context. Besides their use for control, the sensor readings were stored in the cloud environment every five minutes.

This physical model mimics the real-world setting of the research lab, which consists of six workstations, a fixed window, an operable window blind, automated HVAC, and lighting controls. Fig. 3c shows the integration of the various sensors. Although the physical model does not behave as the real-world setting (e.g., the temperature in the maquette becomes steady faster than in the real building; however, when they are both in steady-state, their behavior is similar), the objective here is different. SUSTAIN is focused on the development of the building control software, the integration with 3D visualization, and simulation and support in a cloud environment. The physical model permits conducting a variety of experiments useful during the software development cycle, and this

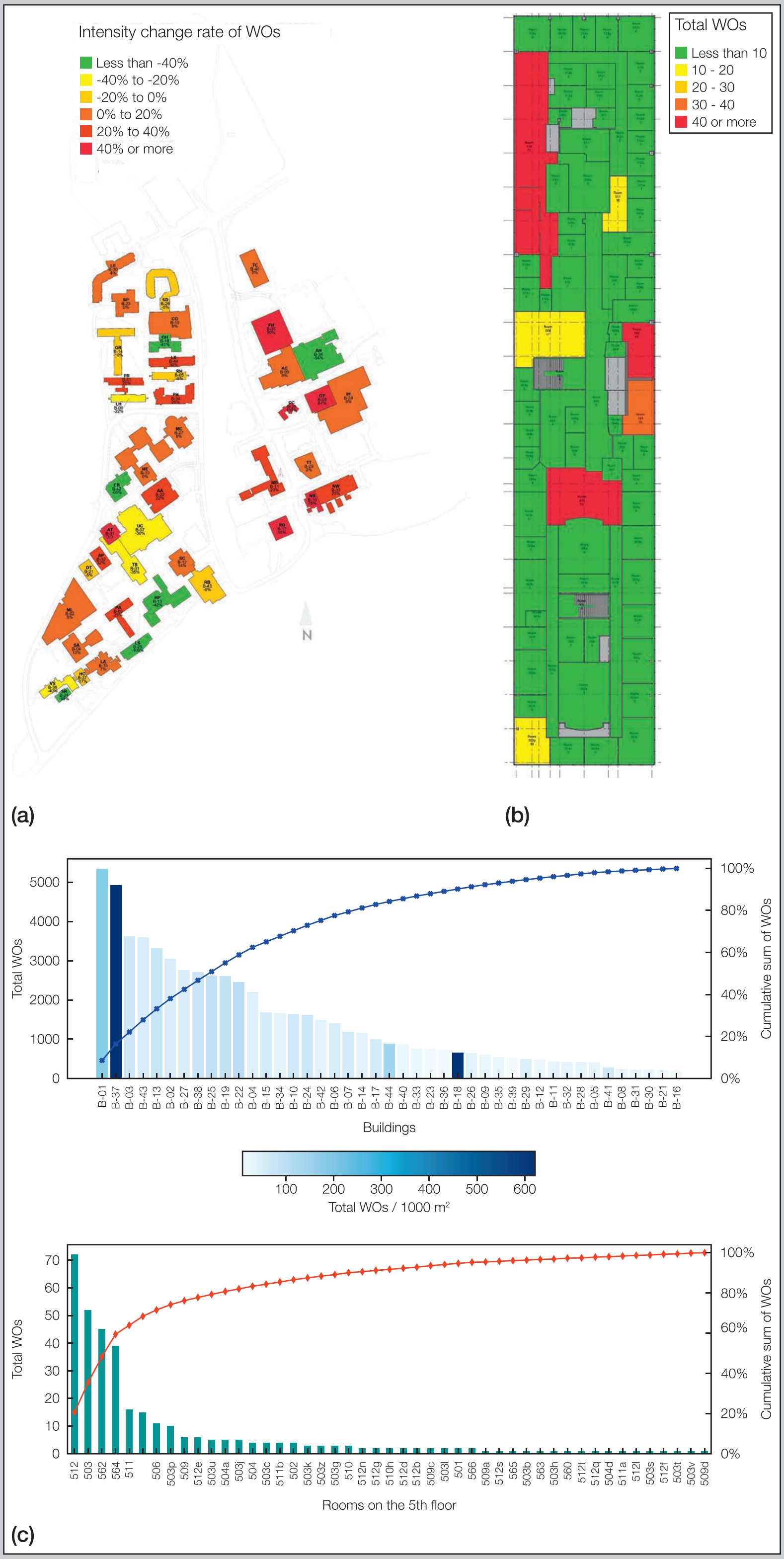


Fig. 4. (a) Campus-level fault map: Intensity change rate of WOs; (b) Building-level fault map: Total WOs; (c) Spatial WO distributions.

can be done safely and without affecting the actual building operations.

The sensor data are collected from simulation and experimentation on the physical model of the building, while WOs are collected in the CMMS database (from occupants' calls or operator's inspections) and are shown in Fig. 4.

Since there are numerous processed datasets available, the BIM has a vital role in the storage and visualization of information for use by decision-makers. In practice, when operators want to extract temperature WO, they must run the CMMS application and toggle between several programs to process the raw data, spending a great deal of time to get through this process which may lead to inaccurate decisions. We automate this process by transforming the datasets into a set of maps using Dynamo [10], as shown in Fig. 4. Maintenance teams can analyze the spatial distribution of WOs at diverse scales (room, building, or campus) using different metrics (total WO, WO intensity or intensity change rate of WOs). Such maps can expedite and facilitate the measurement of the operational performance of buildings. Changes in the data are displayed, based on their parameters, and they are reflected in plans, schedules, and 3D views. For instance, Fig. 4c (top chart) shows that 80% of all WOs were issued for 19 buildings out of 42 located on the campus. Similarly, the building-level results (bottom chart) allow building operators to focus on the spaces with more corrective orders or complaints in each building. This way, the performance and fault patterns of the research lab are identified, based on a distinct data source other than sensor readings. Also, the quantified maintenance performance of the studied lab along with the other spaces in the building are graphically displayed in the model by color-coding objects and using existing color schemes to represent ranges of numerical data. The illustrative outcomes allow the maintenance teams to analyze the spatial distribution of WOs. The raw data can be processed and transformed into quantifiable information [11] and stored in the cloud to assess the performance of the sensor fusion model.

Sensor Fusion Model (SAFE)

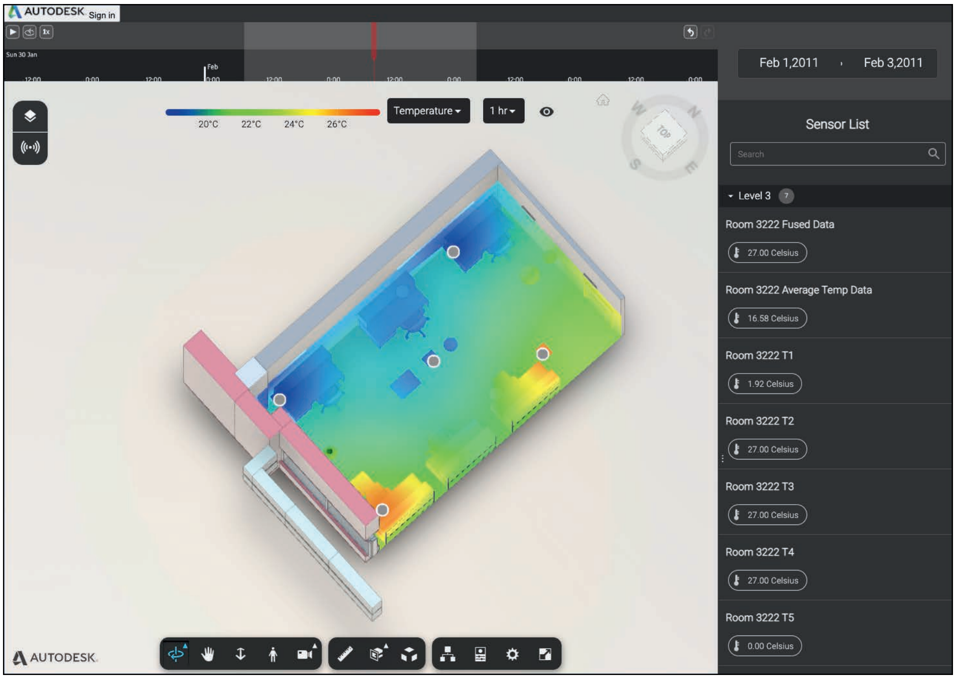
The sensor layer contains a group of sensors measuring temperature. SAFE adopted a competitive sensor fusion configuration in which each sensor measures temperature the same way and sends its output to the sensor fusion algorithm, which examines the values and decides what readings to keep or discard. The algorithm takes raw measurements from the sensors as inputs, performs a principal component analysis calculation, and returns a single output. The output values from the sensor fusion model are considered correct even if some input sensors have incorrect readings [8]. This algorithm requires no prior knowledge, avoids subjectivity in the calculation of correlation matrices, and its implementation is simple and easy to understand.

We look for spikes and outliers in the sensor readings to confirm sensor failures. Also, we check for erratic values which occur when most of the input sensors to the fusion layer have different readings.

BIM Integration

The data collected from SAFE is displayed into a BIM using cloud services [9]. Fig. 5 shows the integration of the data collected from various sensors, fused temperature, and the average temperature of the room using SUSTAIN. The application allows an interface to be built, including a timeline scrubber (to query data at a certain time), sensor lists (with temperature values) and a BIM integrated with temperature readings visually and contextually (using different colors for temperature values). Fig. 5 shows the sensor values, for instance the value of Room 3222 T1 is 1.92 °C and Room 3222 T5 is 0 °C, indicating two faults in the system. Each sensor is also linked to a line chart to show the temperature readings over time, as seen in Fig. 6, which shows the fused temperature and the average temperature of the sensor readings.

The average temperature has many variations due to faulty readings we introduced during experimentation, but fused temperature provides a steadier temperature value by



Room 3222 Fused Data
27.00 Celsius

Room 3222 Average Temp Data
16.58 Celsius

Room 3222 T1
1.92 Celsius

Room 3222 T2
27.00 Celsius

Room 3222 T3
27.00 Celsius

Room 3222 T4
27.00 Celsius

Room 3222 T5
0.00 Celsius

Fig. 5. Integration of data with BIM using Autodesk Forge [9].

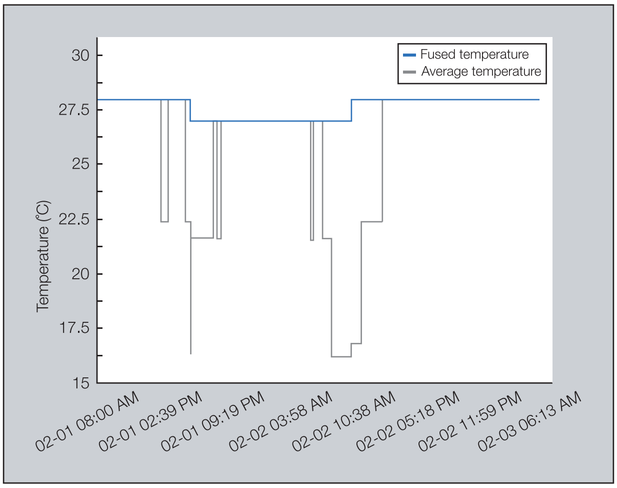


Fig. 6. Comparison of Fused temperature with average room temperature.

providing weights to all of the sensors implemented. The WOs output follows a similar process.

Conclusion

Monitoring data helps improve occupants' health and wellbeing by automating building systems and providing information for building managers to make informed design decisions. Accurate data from building systems will improve forecasting and identify the cause of issues in building energy performance. The issues could be a faulty system or occupants' interactive behavior in the buildings.

SUSTAIN uses different methods to assess and improve the measured data and considers contextual visualization for data analysis by integrating the results into BIM. Fault Tolerance Model and Text-Mining frameworks improve the reliability of the collected data. Also, the physical model helps with various experimental setups. For example, in the case study presented, we disconnected some sensors to experiment with faulty situations and recorded data. The text-mining framework provides a method to classify and quantify work order descriptions.

The results from SAFE ensures that correct temperature measurements are used by the HVAC control systems to regulate the room temperature. If the temperature is still not comfortable for the occupants, it could mean some components within the SAFE framework might be faulty—the WOs help in assessing these data. If the occupants complain that the room is still uncomfortable, the information could be cross-checked with the SAFE. Currently, the text-mining framework allows us to quantify and classify the work order description, but it is not integrated with SAFE results for comparison.

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