Evaluation of various visualization forms for facility operation and maintenance

Xue Yang [1]*, and Semiha Ergan [1]

[1] Department of Civil and Environmental Engineering, Carnegie Mellon University, Pittsburgh, USA
** Corresponding author (xueyang@andrew.cmu.edu)*

Purpose Ongoing case studies in different facility settings revealed that current industry solutions (such as BAS and CMMS) still lack the capability to enable users to understand and interpret raw data for operation efficiency as well as plan for maintenance tasks in complex facilities efficiently. There is still a need for facility operators to put data into spatial or knowledge context and make decisions for actions during operation and maintenance (OM). Visualization is a promising aid to provide intuitive support for facility personnel while dealing with complex spatial data and large amount of raw/processed data and to enable them to respond promptly to issues that arise. This research focuses on identifying visualization requirements for facility personnel, evaluating various visualization forms for supporting OM-decisions and developing a formal approach to supporting visualization requirements. **Method** Two case studies and shadowing work are still ongoing in two different types of facilities (one is in a complex campus building, the other one is in a highly-sensed conservatory). The purpose of these studies is to identify the inefficiencies or difficulties associated with the lack of visualization support in current OM-practice. We have identified an initial set of visualization requirements from these studies and analyzed different scientific visualization forms (e.g. 2D, 3D, desktop virtual environment, and immersive virtual environment) as well as information visualization forms (e.g. color/pattern coding, text/number overlay, graph, etc.) used in human computer interaction and architectural engineering construction and FM (facility management) domain through extensive literature review. We developed a matrix of initial set of visualization requirements for different OM-tasks and visualization platforms to understand characteristics of visualization support requirements. **Results & Discussion** This paper provides an initial set of visualization requirements for typical tasks identified from the two case studies and a synthesis of extensive literature review on scientific and information visualization platforms that exist in the current body of knowledge. The mapping of the initial set of requirements to visualization platforms reveals that OM-work efficiency can be improved by multiple visualization forms, and the characteristics observed from this mapping can be used as a basis for a formal approach to identify applicable visualization platforms for a given task from the OM-domain.

***Keywords**: information technology, facility operation and maintenance, visualization*

INTRODUCTION

Modern buildings, especially large scale public buildings, are usually equipped with Building Automation Systems (BASs) to help facility managers to deal with large amounts of sensor data generated during operation and take automated action for control. Usually, there is a typical control strategy selected based on a given season/setting and BAS runs under this strategy. However, BAS cannot respond to changes in the physical environment that are not measured by sensors and programmed in the control logic. We call these physical settings as information requirements related to external parameters and define them as factors that will influence building operation monitoring and control strategy but are not captured by BAS.

Exploratory studies that we have done with operators revealed that external parameters are indispensable for effective building operations, and facility operators need to understand the external parameters and their changes in relation to internal parameters being monitored. On one hand, facility operators need to interpret the sensor readings provided from BAS under the effect of external parameters and see if the control strategy in the BAS is still valid or not. For example, under a given spatial setting, facility operators would ignore the temperature reading fluctuations of a certain sensor since s/he knows that the sensor is installed near roof vents and the fluctuation is due to the status of the roof vents (being open or close). Without knowing the physical proximity of the sensors to the control equipment (i.e., the roof vent in this example) and the status of the control equipment, the fluctuations would be misunderstood and would result in unnecessary actions such as sensor recalibration or equipment's over-running. Similarly, facility operators' intervention for equipment control (equipment referred to as HVAC equipment in this paper) is necessary when changes in the environment are beyond the sensing capabilities of sensors or not reflected in the control strategy. For example, when a laboratory is under renovation, facility operators should shut off the air supply valve to stop the supply to that room. Facility operators need to be aware of the changes in this external parameter (i.e., space being renovated) and adjust the temperature requirement in the laboratory accordingly. In large scale or complex facilities, it's difficult for human to keep up with all kinds of internal/external parameters and their changes to figure out if the sensor readings are meaningful or any equipment needs to be adjusted. Current industry solutions for BASs still lack the capability to provide intuitive interface about such internal/external parameters and enable users to understand sensor data as well as manipulating control equipment efficiently. Hence, there is a need for interpreting the internal parameters captured and monitored by BAS under the influence of the external parameters and making wise decisions accordingly.

Visualization is able to provide intuitive support for facility operators while dealing with complex spatial data and large amounts of parameters being monitored; however visualization techniques have not been fully leveraged in the domain. Visualization is divided into two high-level categories as scientific visualization and information visualization[1,2]. The former typically refers to visual representation of physically based objects, such as buildings, human body, components in a building, for full cognition, while the latter focuses on data or information which is non-physically based, such as semantic information about building components and sensor readings, and targets on providing visual representation of such concepts to improve human knowledge and capability to identify trends or patterns.

This paper provides an overview and initial results of two ongoing case studies for identifying what internal/external parameters operators consider when they interact with BAS and their visualization requirements, and proposes an initial discussion of visualization techniques that can be leveraged to display such requirements in an effective way. The case studies are ongoing for the last 5 months and involve shadowing and interviews with facility operators working in two different facility settings. The scenarios, workflows, difficulties or inefficiencies of facility operators' interactions with BAS in their daily routine were captured, documented and synthesized. The next section provides the need for combining internal parameters with external parameters visually and discusses the problems in the current practice in visualizing this information.

THE NEED FOR VISUALIZING MONITORED DATA IN PHYSICAL SETTINGS AND THE PROBLEMS IN THE CURRENT PRACTICE

Exploratory studies have been done in a highly-sensed conservatory and a large scale campus with the objective of identifying facility operator's information and visualization requirements. The conservatory has 35 rooms or zones where many types of plants, having different temperature and humidity requirements, are grown. The plants are delicate and indoor environment needs to be monitored and controlled strictly. The campus represents the large scale case with more than 100 buildings with complex HVAC systems. Initially, we investigated the user interfaces of the BASs that the facility operators are using, referred to as BAS1 and BAS2. The investigation of BAS1 interface of the conservatory showed that it lists sensor readings for temperature and humidity in zones and thresholds in a tabular format as shown in Figure 1. There are 16 sensors tabulated in this interface without any color coding. It's difficult for facility operators to identify which readings in which zones are beyond thresholds promptly so that they can figure out if BAS is working properly or if manual intervention is necessary. The BAS2 interface in the campus is able to show sensor reading status by visualization of color coding in floor plans, as shown is Figure 2 for a specific building in the campus.

Room	T (°F)	H (%RH)	Temperature thresholds		Humidity thresholds	
A1	65.6	65.8	66	72	99	65
A2	56.7	82.3	50	55	99	65
B1	65.4	73.5	65	70	99	65
B2	64.9	72.3	65	70	99	65
C	60.4	81.5	62	68	99	60
D	72.1	63.7	71	75	80	60
E1	64.3	82.2	65	68	99	65
E2	65.6	71.4	65	70	90	65
F1	63.4	77.4	62	65	99	65
F2	61.6	77.4	62	65	99	65
G1	72.5	72.6	75	80	99	65
G2	68.7	76.5	74	77	99	60
G3	56.9	73.7	55	60	99	65
H1	76.3	73.3	72	75	99	60
H2	69.8	53.0	70	75	99	65
H3	49.6	83.5	40	45	99	20

RVM-1,2	Manual close
RVM-3,4,5,6	Manual close
RVM-7 to 12	Automatic 0%
RVM-13,15	Automatic 0%
RVM-14,16	Automatic 0%
SHM-1	Manual open100%
SHW-2	Automatic 0%
SHW-3	Automatic 50%
LSVM-24	Manual close
LSVM-25	Manual open
HSVM-26	Automatic 0%
HSVM-27	Automatic 0%
NVM-28	Manual Off
NVM-29	Auto On
...	...

Fig. 1. BAS interface showing sensor reading/threshold and equipment status in the conservatory

HW VALVE CONTROL	60.0 F
HW VALVE ANALOG	100% CLOSED
CHW VALVE CONTROL	60.0 F
CHW VALVE ANALOG	100% OPEN
SUPPLY AIR TEMP	70.1 F
MIXED AIR TEMP	68.4 F
MIXED AIR CONTROL	55.0 F
MIXED AIR ANALOG	85% OPEN
...	

Fig. 2. BAS interface showing sensor reading status and equipment status in a specific campus building

Generally speaking BAS2 is better than BAS1 in terms of providing more intuitive interface by leveraging a scientific visualization technique, a floor plan, and information visualization techniques such as color coding and text overlay. However, both of them lack functions of providing external parameters that are required by facility operators. For example, precise sensor location along with the control equipment location to figure out sensor proximities to equipment (such as sensors being close to vents) is not possible to be captured from the two BAS interfaces and thus it relies on the familiarity of the operator with the physical space.

Equipment control has similar problems. The user interfaces through which facility operators input control command for both buildings contain tables, which list the IDs of the equipment and their statuses and working parameters. Whenever, a facility operator wants to manipulate a certain equipment (e.g., close a vent to protect the plants that are nearby the vents), s/he has to look at the annotated floor plan s/he prepared with control equipment IDs marked on it and find the ID of the specific vent s/he wanted to close and then matched it to the IDs in the user interface. It was also observed that after the facility operator manually changes equipment control parameters, a following visit to the site is needed to make sure the right equipment was manipulated; if it is the wrong one, s/he has to go back to the main office to re-input command and revisit the site. In addition to that, facility operators typically want to leave the control of equipment to BAS. In cases when control equipment is manually overridden, for example, manually shutting off the equipment which is under maintenance, facility operators would like to keep track of which equipment is on manual mode and their current status (e.g., a valve being open or close, or the percentage of opening) in an effective way. The current way of tracking such large amounts of information in the tabular format is not intuitive for people to get insights in a short time when the number of control equipment is large. This at times results in facility operator not identifying which equipment needed to be turned to automated mode or not remembering which the equipment was in manual mode. This is especially problematic when there is day and night shifts for monitoring and different people are responsible for different shifts. Equipment that is under manual mode should be identified at a quick look when shifts occur.

We also grouped the information items captured by BAS, defined as internal parameters, and additional information that are required by facility operators to do their tasks but not captured by BAS, defined as external parameters. Table 1 shows the list of internal parameters, and the current way of displaying this information to facility operators. BAS cannot respond to these internal parameters correctly with respect to sensor and equipment's external parameters such as their spatial context. Table 1 also shows an initial set of external parameters that we identified from exploratory studies and needed by facility operators to interpret the internal parameters. Also, majority of internal and external parameters to be interpreted together require this information embedded in the physical setting (integration of scientific and in-

Table 1. Information displayed to operators through BAS interface and the current way of visualization

Information displayed (internal parameters)	**Displayed on BAS interface?**	**Current display form**	**Problems of current display forms**	**Visualization category**
Temperature, sunlight intensity and direction	Both BAS1 and BAS2	Text	N/A	Information Visualization
Sensor readings measuring room temperature and humidity	BAS1	Tabular format	Hard to interpret when there is a long list of sensors and control equipment	Integration of Scientific and Information Visualization
Sensor thresholds of room temperature and humidity				
Equipment's working/control status and working parameters, such as water/air supply/return temperature, air flow rates, etc.				
Sensor reading status measuring rooms' temperature (current readings compared with thresholds)	BAS2	Color coded floor plan	N/A	Integration of Scientific and Information Visualization
Equipment's working/control status and working parameters such as water/air supply/return temperature, air flow rates, etc.		Text overlay on equipment pictures	N/A	
An example set of external parameters required to be visualized with internal parameters				
Content location and requirements	No	N/A	N/A	Integration of Scientific and Information Visualization
Equipment location with respect to spatial layout and content requirements	No	N/A	N/A	
Sensor location with respect to spatial layout and equipment locations	No	N/A	N/A	
Equipment's maintenance status with respect to content requirements	No	N/A	N/A	
Sensor's maintenance status with respect to content requirements	No	N/A	N/A	

formation visualization). In the current practice, it is left to facility operators to bring this information together in mind and visualize under the physical context of the facility.

In summary, these exploratory studies showed that current industry solutions are not able to provide sufficient visualization support for facility operators when they need to do interaction with BAS. Thus, in order to improve the efficiency of facility monitoring and control, integration of scientific visualization and information visualization is needed.

REVIEW OF SCIENTIFIC AND INFORMATION VISUALIZATION TECHNIQUES IN AEC/FM AND HCI DOMAIN

In order to understand what visualization techniques that exist in current body of knowledge can be leveraged for facility operators during monitoring and control tasks, we examined the previous research studies on visualization in Architecture Engineering Construction and Facility Management (AEC/FM) and Human Computer Interaction (HCI) domains. In the AEC/FM domain, physically and non-physically based information is closely related. For example, a Gantt chart, showing non-physically based information about the construction processes are actually related to building elements (physical objects). Thus, we see that many visualization related research works in the AEC/FM domain contain integration of scientific and information visualization techniques, with applications ranging from construction simulation/monitoring[3-5], facility maintenance[6,7] and facility operation[8,9]. There are studies in the HCI domain that look at embedding non-physically based information in 3D virtual world, with the purpose of helping user build the link between perceptual environment and the related abstract information[10-12]. Previous studies on the integration of scientific and information visualization from both AEC/FM and HCI domains provide various visualization techniques of displaying non-physical based information in physical based environment, such as color coding [4-9]; text overlay[4,9], icon[10], or graph[7,9], etc. In addition, multi-views in coordination with the primary visualization can provide more detailed information by separated window[13]. Various techniques of integrating scientific and information visualization are different in terms of their capabilities of visualizing various data type, information priority and supporting different analysis purposes. For example, color coding is very intuitive and easy to grasp user's attention, thus it is appropriate to visually represent information with high priority, but the limitation is that color coding cannot show high-dimensional data. The various visualization techniques need to be analyzed and evaluated in order to match their capabilities with visualization requirements for facility operators.

AN INITIAL SET OF VISUALIZATION REQUIREMENTS OF FACILITY OPERATORS IDENTIFIED FROM CASE STUDIES

The purpose of the case studies is to identify (a) the patterns of facility operators' interactions with BAS during sensor data interpretation and equipment control manipulation, at different scales, (b) what internal and external parameters they consider during these tasks and (c) inefficiencies or difficulties associated with insufficient visualization support in their interaction process. The major differences in the two case settings are that the operators in the campus are responsible for multiple buildings which have different load conditions, while the conservatory requires delicate content to be monitored and it has unique requirements to be met in multiple zones.

Various instances of sensor data interpretation and manual overriding of control equipment were observed throughout the research period, where internal and external parameters would need to be considered together for decision making. These instances are synthesized together to categorize what parameters are needed for facility operators and summarized in Table 2. Internal and external parameters or their changes can be categorized under four categories: (a) *outdoor environment related*, which are defined as outside weather and time related factors, such as outside air temperature, light intensity and direction. (b) *indoor environment related*, which are defined as indoor special layout, space characteristics (e.g., room type, glass wall location, room temperature requirement, etc.) and content related factors; (c) *equipment status related*, which are defined as equipment's status properties, such as equipment working status (e.g., open/close), maintenance status (e.g. working properly or waiting for repair) and control status (e.g. auto/manual) ; (d) *sensor status related*, which are defined as sensor's status properties, such as sensor maintenance status. What worth mentioning is that some internal parameters' changes still require facility operator's manual intervention even though they are captured by BAS, because no programmed logic was created to respond to the specific case.

The examples identified from case studies, which involve facility operator's manual actions or decision-makings triggered by different internal/external parameters or their changes, are listed in Table 2. Table 2 also provides what external and internal parameters operators consider in each example and what needs to be visualized for the operators. We categorized these identified examples based on their visualization requirements. The examples show different patterns in terms of what combination of parameters should be considered for visualization, shown as below:

Visualization that requires equipment + indoor and outdoor environment related parameters

This visualization requirement necessitates equipment related parameters to be visualized in relation to indoor and outdoor environment. Visualization requirement incorporates control equipment's locations ,status properties, and indoor and outdoor environment related parameters such as content requirements and space requirement changes so that facility operator can react to these parameter changes promptly by manipulate the correct equipment in a spatial context.

Example 1: In the conservatory case for instance, when the outdoor environment changes – temperature is lower than 50 °F, facility operator will manually overwrite control command of the side-wall vents (equipment related) near tropical plants (indoor environment related) to "Manual close 100%", to prevent those plants from constant cold air.

Example 2: In the conservatory case, the facility operator has to overwrite the control command of a shade curtain (equipment related) to "Manual close 100%" to protect a certain type of tree nearby (content, indoor environment related) which is sensitive to strong sunlight.

Example 3: In the campus case, when a laboratory is under renovation (indoor environment related), facility operators will shut off the air supply valve (equipment related) to stop cooling supply feeding that room.

Visualization that requires indoor environment + sensor related parameters

This visualization requirement necessitates internal parameters of sensor's reading and threshold, external sensor related parameters – sensor location and sensor working/maintenance status, to be integrated with indoor environment related parameters, such as space characteristics or content requirement, so that operators can interpret sensor reading under spatial context correctly.

Example 4: In the conservatory case, sensors (sensor related) located near glass walls (indoor environment related) have the chances being exposed in hot spot under direct sunlight, and it leads to higher temperature reading, which will be interpreted as normal when strong sunlight is against glass wall and BAS's cooling behavior will be stopped manually.

Example 5: In the campus case, facility operators will pay attention to sensor readings which have frequent or sharp fluctuation (sensor related). If the sensor is installed in a classroom with varied occupancy status (indoor environment related), fluctuations will be interpreted as normal thus no need for recalibration.

Example 6: In the conservatory case whenever gardener waters plants, sensor (sensor related) near the plants (indoor environment related) will have extremely high humidity reading resulting sharp fluctuations, which will also be interpreted as normal and eliminate redundant working of dehumidifier.

Table 2 External and internal parameters to be visualized and examples from case studies

Internal parameters/ Change in internal parameters		**Examples of facility operator's decisions/actions triggered by the parameters or parameter changes**	**What needs to be visualized?**
Outdoor environment related	Outside air temperature change	Example 1: Keep the vents near tropical plants close manually when outside air temperature < 50 °F	Equipment + Indoor and Outdoor environment parameters
	Sunlight intensity and direction	Example 4: Interpret high temperature reading as normal when sensor near glass wall is in hotspot	Indoor environment + Sensor parameters
Equipment status related	Working status	Example 7: Interpret low temperature reading as normal when vents near sensor is open for dehumidifying	Sensor + Equipment + Indoor parameters
	Control status	Example 10: Switch control model to automatic when specific occasion lapses	Equipment parameters
External parameters/ Change in external parameters			
Indoor environment related	Space requirement change	Example 3: Shut off air supply valve to the room which is under renovation	Equipment + Indoor environment parameters
	Space usage type	Example 5: Interpret temperature fluctuation in classroom as normal	Indoor environment + Sensor parameters
	Content requirement change	Example 2: Manual open curtain to protect a certain tree nearby which is sensitive to sunlight	Equipment + Indoor environment parameters
		Example 6: Interpret high humidity reading as normal when sensor locates near plants being watered	Indoor environment + Sensor parameters
Equipment status related	Maintenance status	Example 8: Keep roof vent close manually when it is waiting for maintenance; Example 9: Stop the chiller whose motor is malfunctioning	Equipment parameters
Sensor status related	Maintenance status	Sensor readings are unreliable when network or sensor is malfunctioning	Sensor parameters

Visualization that requires sensor + equipment + indoor related parameters

This visualization requirement necessitates bringing sensors' and equipment's location with respect to special layout (indoor environment related), and their status properties together, so that facility operator can better understand sensor readings, equipment's behavior and their relationship in spatial layout, in order to prevent misunderstanding of sensor reading and unnecessary equipment operation.

Example 7: In the conservatory case, sensors (sensor related) located near roof vents (equipment related) in the tropical forest (indoor environment related) will have lower than normal temperature readings when vents are open for dehumidifying, which will be interpreted as all right considering the opening of vents.

Visualization that requires equipment related parameters

This visualization requirement necessitates highlighting equipment related parameters, control equipment's unusual status, such as under maintenance or manual control mode. With this information, facility operators will have less chance to mistakenly open broken equipment or forget to switch manual control equipment back to automatic promptly.

Example 8: In the conservatory case, facility operator overwrites the control command of a row of roof vents to "Manual close" because s/he knows the motor of that specific row of vents was broken and is waiting for repair.

Example 9: In the campus case, the facility operator manually stops one chiller because the chiller motor is malfunctioning and is waiting for maintenance.

Example 10: In the conservatory case, the facility operator overwrites control command of a row of vents to "Manual open" for maintenance purposes but forgets to switch the control mode back to automatic before he is off work on Friday, which resulted in cancelation of an important event scheduled for that weekend because rain fell inside through the open roof vents.

CONCLUSION

Two ongoing case studies on operation monitoring and control in different facility settings reveal the fact that physical setting is indispensable when facility operators interpret sensor readings and manipulate control equipment. The initial set of parameters that influence facility operator's decision-making identified from the case studies can be grouped into four categories: outdoor environment related; indoor environment related; equipment status related and sensor status related. Examples of facility operator's manual interaction triggered by different internal/external parameters or their changes are analyzed, and the external and internal parameters operators consider in each example and what needs to be visualized for the operators is identified. Detailed analysis of current information display forms of the identified visualization requirements showed that current practice still lacks the functions of bringing external and internal parameters needed by facility operators in an intuitive way. Visualization, with the capabilities of helping human to deal with complex spatial information and large volumes of abstract data effectively, is a promising aid to improve the efficiency and effectiveness of facility operators' sensor data interpretation and equipment manipulation. The information and visualization requirements show that facility operation requires both spatial information and semantic information, thus needs the integration of scientific visualization and information visualization. Further works need to be done to evaluate capabilities of various visualization techniques for supporting facility operator's decisions and then the capability evaluation can be used as the basis for a formal approach to identify applicable visualization techniques for a given task from facility operation domain.

References

1. Gershon, N., Eick, S.G., and Card, S., "Information visualization", *Interactions*, Vol. 5(2), pp.9-15, 1998.
2. Card, S.K., Mackinlay, J.D., Shneiderman, B., "Readings in Information Visualization: Using Vision to Think". Morgan Kaufmann, 1999.
3. Savioja, L., Mantere, M., Olli, I., et al., "Utilizing Virtual Environment in Construction Project". *ITcon*, Vol. 8, pp.85-99, 2003.
4. Liston, K., Fischer, M. et al., "Designing and evaluating visualization techniques for construction planning." *Computing in Civil and Building Engineering*, pp.1293-1300, 2000.
5. Song, K., Pollalis, S. N. et al., "Project dashboard: Concurrent visual representation method of project metrics on 3D building models". Proceedings of the 2005 ASCE International Conference on Computing in Civil Engineering, 2005.
6. Sampaio, A.Z., Ferreira, M.M. et al., "3D virtual environment used to support lighting system management in a building". Proceedings of the 6th international conference on Cooperative design, visualization, and engineering. Luxembourg, Luxembourg, pp.177-184, 2009.
7. Akcamete, A., Liu, X., Akinci, B. and Garrett, J., "Integration and visualization maintenance and repair work orders in BIM: lessons learned from a prototype". Proceedings of the Conference on Construction Applications of Virtual Reality (CONVR 2011), pp.639-649, 2011.
8. Schulze, J.P., "Advanced monitoring techniques for data centers using virtual reality". *SMPTE Motion Imaging Journal,* Vol. 119(5), pp.43-46, 2010.
9. Kim, S.A., Shin, D. et al., "Integrated energy monitoring and visualization system for Smart Green City

development: Designing a spatial information integrated energy monitoring model in the context of massive data management on a web based platform." *Automation in Construction*, Vol. 22(0), pp.51-59, 2012.

10. Einsfeld, K., Ebert, A. et al., "Modified Virtual Reality for Intuitive Semantic Information Visualization". 12th International Conference on Information Visualisation, 2008.
11. Kirner, T.G., and Martins, V.F., "Development of an information visualization tool using virtual reality". Proceedings of the 2000 ACM symposium on Applied computing - Volume 2. Como, Italy, pp.604-606, 2000.
12. Bowman, D.A., North, C. et al., "Information-rich virtual environments: theory, tools, and research agenda". Proceedings of the ACM symposium on Virtual reality software and technology. Osaka, Japan, pp.81-90, 2003.
13. Polys, N.F., North, C. et al., "Snap2Diverse: Coordinating Information Visualizations and Virtual Environments". Technical Report TR-03-23, Computer Science, Virginia Tech, 2003.