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Living in the Intelligent Workplace

Structuring and Managing Building Operation Information

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ABSTRACT

Buildings are complex systems that provide the setting and conditions for many day-to-day critical commercial and industrial activities. Buildings aggregate and integrate HVAC and lighting system components from multiple manufacturers. These systems are subject to change over time, their controllers must respond to varying outdoor environments while maintaining specific indoor conditions. Technological advances over time also influence the composition and configuration of building systems. Buildings create technical challenges of providing individual comfort, organizational flexibility, technological adaptability, environmental sustainability, while at the same time minimizing energy consumption. With emerging trends of using large scale systems with broadly-distributed components in the built environment, a single interface interaction to change the temperature in a space can spawn many backend transactions among multiple nodes that offer specific services. For a flexible and redistributable solution, some form of building information management is needed. This paper discusses the development of a tool to structure building operation information in the Robert L Preger Intelligent Workplace at Carnegie Mellon University.

1. THE ROBERT L. PREGER INTELLIGENT WORKPLACE

Completed in 1997, the Robert L. Preger Intelligent Workplace (IW) is a 7000 square foot rooftop extension of Margaret Morrison Carnegie Hall on the Carnegie Mellon University campus. The IW is a testbed for innovation in information technology, product performance, integration in materials, components and systems, and sensing and actuation instrumentation to record and evaluate operational performance of building components and user comfort *(figure 1).*

So far the IW has experimented with integration of smart building technologies with advanced design and engineering strategies, enabling the utilization of natural forms of energy, such as day-lighting, natural ventilation, passive heating and cooling, in combination with active strategies such as photovoltaic technologies. Other potential experiments may include the integration of innovative and advanced energy generation systems, such as fuel cells, gas turbines, heat recovery steam generators, as well as advanced heating and cooling generators such as dual-fired double effect absorption chillers, and desiccant dehumidification equipment.

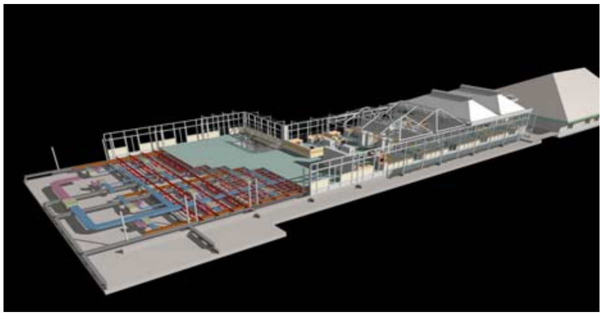

Figure 1: Peel -away view of the Intelligent Workplace™ illustrating the floor-based integration

Consequently, the IW, a living – continuously updated and improved, and lived-in – occupied by the faculty, staff and graduate students of the Center for Building Performance and Diagnostics (CBPD), laboratory provides the ideal setting to integrate, test, research and further develop cutting-edge prototypical sensors and sensor networks, creating opportunities to advance the whole field of green building technologies.

Dynamic change in a facility recorded systematically and in real-time, is of interest to designers, facility managers, occupants, and owners. In the IW detailed data about the behavior of various systems is used as a basis for diagnostics, preventative maintenance, and decision-making regarding system operations. Real–time information on building state (information about as built and as operated conditions) is valuable for security systems and emergency services. Occupants benefit from timely facility management services and potentially greater control of the environmental quality of their workplaces.

In order to evaluate the operational performance and user comfort of the IW, three major sensor systems have been implemented: (a) the JCI Metasys™ sensor system collects data (160 data points) associated with the Heating, Ventilation, and Air-Conditioning (HVAC) system; (b) the Carma Energy Sentry™ system collects electrical usage data (72 data points); (c) the Weather Station collects outdoor environmental information (8 data points). A sub system to collect lighting control data has been added to the sensor suite.

2. THE IW ENERGY SENTINEL (IWES)

This pilot project focused on the creation of a user friendly tool to evaluate the performance of the IW using the sensor data collected. The project implemented a framework for data management over the lifecycle of the building.

2.1. Current State of Practice

The lack of integrated information from the discrete building systems about the qualitative performance of a building is a problem faced by building operators. The concept of coupling frequent, accurate, and detailed data with advanced data mining tools is revolutionary in the field of buildings operations. Currently to understand the implications of the measured data, data-mining experts are required. A commonly accepted method of analyzing these various building data streams / types is not available.

2.2. Objectives

To address the above situation the IW Energy Sentinel (IWES) tool is developed. The objectives are:
(a) Actively capture continuous streams of data from different sources, process and aggregate them into a common format, and provide useful information.
(b) Create a central repository for storing building system information and sensor information such as specification and maintenance history, throughout the life cycle of the building.
(c) Provide visual data displays, reports and alarms that work with multiple building systems.
(d) Assist the user to correlate different types of data and find meaningful information in vast amounts of data quickly.

2.3. Development Environment

IWES *(figure 2)* links with existing data logging software in the IW. It is non intrusive and requires no modification to these software. IWES reads the data archive files created by the building data systems. IWES enables seamless extraction of data from diverse building operation systems and generates a common data model. This produces a uniform and normalized database for researchers or other applications to use. In addition to building operational data recorded by the fixed sensors in the building, the database contains facility information such as data sheets for building system components. These data sheets contain specifications and maintenance history for the components. The data extraction approach adopted in IWES is easily adaptable and expandable to include new component types with different protocols, thus allowing the owner increased system expansion flexibility while selecting equipment.

2.4. Functions Implemented In IWES

This section describes features that have been completed so far in this ongoing project.

2.4.1. Network Capabilities

IWES has been developed as two components on a network – a server and a client. The server component retrieves, processes and collates data, the client component is used to remotely view and analyze the collated data. The sources of data can be distributed within the network with appropriate security settings. The components have been developed to allow communication of sensor data using the standard IT network in a building. Using mobile devices the building operator can view *(figure 3)* real time sensor data without the need to use a static workstation.

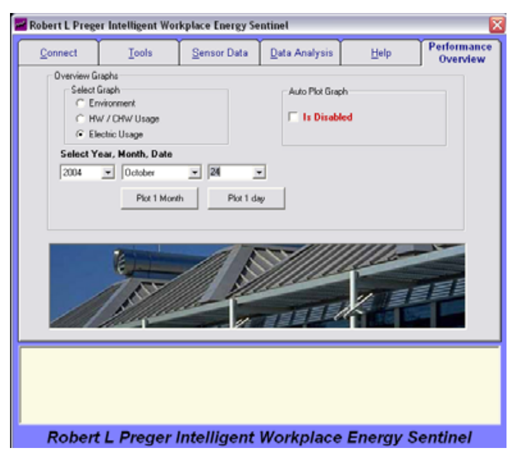

Figure 2: The IWES interface

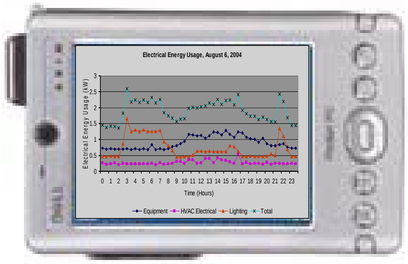

Figure 3: A performance overview graph for electrical energy consumption for August 6, 2004 created by the IWES tool deployed on a mobile pocket pc.

2.4.2. Auto Update And Cleaning

IWES has data management capabilities. The tool can automatically update the database on a specified time interval in addition to a manual update as commanded by the operator. The specification of the time interval is based on the recording interval of the building data acquisition system.

During the update process the data is cleaned and invalid values are removed. Currently, this is performed using rule based algorithms that check for thresholds in the stream of data being examined as well as thresholds in certain other related streams. The long term goal is to make this feature adaptive with self learning capabilities for enhanced data management.

Another feature implemented is a system of neural networks is applied to estimate and fill in missing data. A commercially available neural network tool was used that allowed interfacing with IWES.

2.4.3. Information Display

Statistical information, graphical trending and query capability for every data stream are available through this tool. This includes daily profiles, overlays of other streams, upper and lower values, standard deviation and percentage of records present. Graphical trending can be defined by the user, multiple parameters originating from different building systems can be plotted together and compared, the same parameter from different time periods can be plotted against itself. A framework has been implemented in IWES to allow the user to store datasheets *(figure 4)*. Sensor specifications, schematic diagrams, and maintenance history are stored and are displayed when required. This enables easy detection of performance abnormalities and equipment degradation. Data may be exported for further specific analysis.

In the IW data sheets are created for all objects required for environmental control. These are actively maintained and stored in a searchable database. The sheets include information about the device make and model, installation date and maintenance history and the location of more detailed information about the device. Also included is information about the schematic and physical location of the device and an "as installed" picture. This information is invaluable in the effective and efficient operation of a building.

2.4.4. Report Generation

Reports and overviews of current and historical data are created by the tool. To analyze metering information, IWES generates user specified energy consumption reports for heating, cooling, lighting, office and kitchen equipment, and HVAC electrical. Automated overviews allow the user to easily create graphs *(figure 5, 6)* of energy performance of different building systems. This allows easy review of current and past performance of the IW.

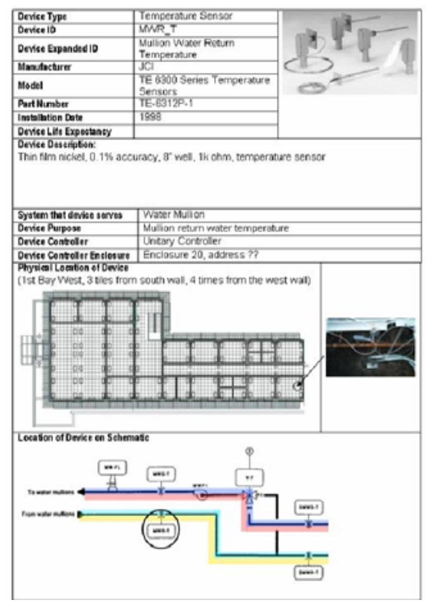

Figure 4: A data sheet created for a water temperature sensor.

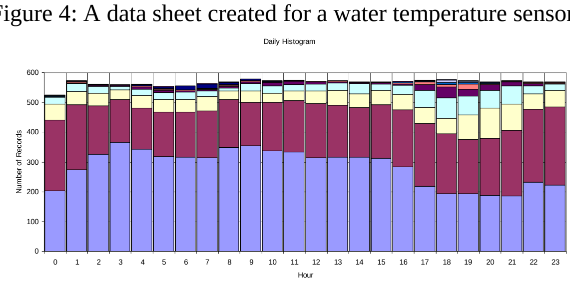

Figure 5: The histogram for lighting shows averaged hourly for one year. Such histograms are easily created using the IWES tool and provide detailed knowledge about energy use characteristics. Average daily profiles are also created, these are useful in energy demand management.

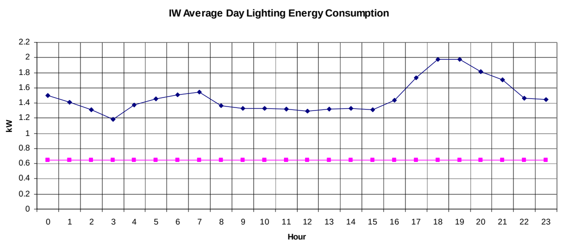

Figure 6: A study of a daily profile for lighting energy use showed a constant energy use even when the lights were known to be off. The flat line represents the lowest value of energy consumption, this was discovered to be the phantom load that is always present due to the use of voltage transformers.

2.5. Analysis And Results Obtained

The use of this tool has provided valuable insights into the actual performance characteristics of the IW. These include detailed information about loads and energy use patterns over the year for different occupancy and weather conditions. It also provides a thermal behavior "signature" of the building, e.g. the time lag effect of the thermal environment within an operational cycle of the HVAC system. The maintenance of data sheets and the ability to view them in conjunction with recorded data has greatly enhanced the building diagnostic process in the IW.

The IWES tool enabled a simulation calibration exercise to be performed. Hourly data was used to validate simulation results with actual building performance. This calibrated model can then be used to examine building performance under different conditions (figure 7) of set points, and envelop properties for different design and system operation alternatives, e.g. temperature setpoints, material properties, etc.

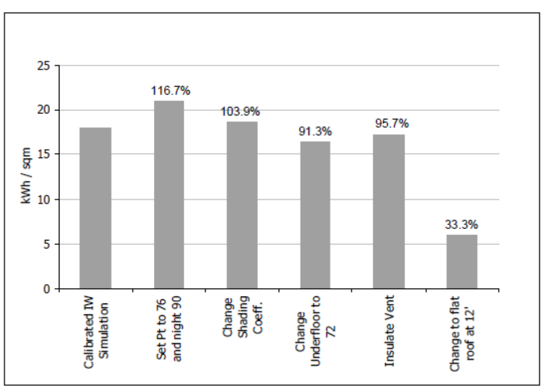

Figure 7: Cooling loads of the IW with changed setpoint and envelop conditions obtained by using the calibrated model.

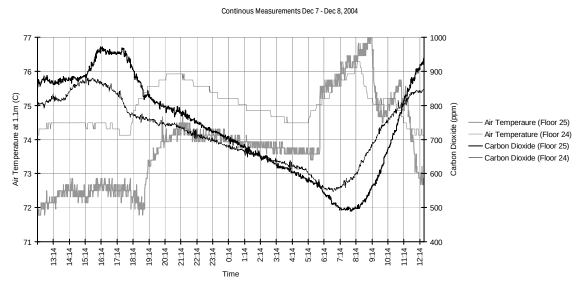

Figure 8: Graph showing values of Air Temperature and Carbon Dioxide for floors 24 and 25 of a building in Atlanta, Georgia.

The IWES tool has been applied to other buildings besides the IW. Indoor air temperature and carbon dioxide data for buildings obtained from the WorkPlace 2020 project at CBPD, Carnegie Mellon University were analyzed using this tool. The following example is based on data from floors 24 and 25 of an office building in downtown Atlanta, Georgia, measured from 12:14pm Dec 7 to 12:14pm Dec 8 at 1 minute intervals.

In figure 8, the temperature curve increases (from 72.5°F to 74.5°F for floor 25) around 18:30 that shows the cooling is turned off, the carbon dioxide curve begins to fall (from 950 ppm to 850 ppm) at 17:30, and is representative of occupants leaving. This demonstrates a reasonable control strategy is applied since the temperature is allowed to rise only after the occupants have left. However, if the behavior of the temperature profile of the space is "learnt" through continuous monitoring, the operation cycle can be further optimized.

3. GENESIS OF A DYNAMIC BUILDING INFORMATION MODEL

Implementation of the IWES project has revealed the need for a comprehensive adaptable and extensible network-based solution to monitoring and control in buildings. Building control systems which rely on remote sensor–driven, high–resolution building models have the potential to significantly affect and enhance service quality and effectiveness in all relevant phases of a building life-cycle: from design to construction, commissioning, operation, and disposal or recycling. Furthermore, detailed real–time information about a facility's state serves as an invaluable resource for security and emergency services, and might enable novel kinds of services to become feasible, such as detailed life–cycle analysis of products on a large scale. Manufacturers can analyze data tracking of the performance of their products in various facility settings in order to develop better products, coordinate marketing efforts, and/or offer customized services related to their products. Databases containing detailed historical records of buildings could serve as a rich asset for collective learning by providing building practitioners, researchers, organizations, and manufacturers with feedback and a better understanding of the value and implications of their services and products.

Current work in this project focuses on extending the methodology adopted in IWES to create sensor–driven, high resolution building management systems that use a Building Information Model (BIM). This model will be capable of a comprehensive and detailed representation of the state and operation of a facility. In addition, the model will be capable of supporting decision making.

In the building operation phase this BIM will most accurately represent the current state of the building. In addition to information about the space characteristics (geometry, material, space use etc.), the BIM includes data from sensors placed in the building, information about system maintenance, and occupant feedback. Issues of interoperability are addressed using an IFC based data structure.

Advances in sensor hardware – e.g., sensor integration, electronic miniaturization (e.g., commercial research in Micro-Electro-Mechanical Systems), and low power wireless communication have revolutionized the ability to collect building data. Stick on sensors discretely attached to walls, or embedded in floors and ceilings, active badges for users, sensors embedded in objects in a facility provide vast amounts of data. The flexible BIM framework provides an effective data management strategy to scale and integrate diverse types of sensors and actuators.

For building operation information from the BIM can be used for (1) real-time fault detection at low-levels (individual sensors and clusters of sensors), and mid-level (building heating, cooling, and power generation system components such as control valves, pumps, fans, heat exchangers); (2) performance monitoring at the individual room, zone, and building system level; (3) intelligent decision making for building operations and maintenance.

Within a BIM, streams of data obtained from sensors in a building are environmental signatures of that building under various criteria. Signatures will be correlated with user behavior to determine successes and failures. A self updating database of environmental signatures will be created to better detect problems. This will allow the operator to more easily see how a failure occurred rather than only providing information that a failure has occurred. This will increase the forensic capabilities available to building operators. This will enhance the maintenance process and reduce operating costs. When additional devices are added or devices fail, device controllers will re-organize themselves to provide optimum performance.

4. FUTURE WORK

The continuous and automated evaluation of facility state data for maintaining design specifications, monitoring of component performance over time, and operational process improvement will lead to increased operation effectiveness. The features currently available in the IWES tool have the potential to be extended to provide a robust and systematic approach to facility state information through the life cycle of the facility. Some of these features are:

4.1. Automated Validation of Data Reliability and Sensor Calibration

Sensors operate in and must respond to very dynamic environments. The diverse and sometimes conflicting information obtained from multiple sensors give rise to the problem of how the information can be combined in a consistent and coherent manner. Information about sensor degradation, sensor calibration and data time stamping is critical in maintaining an accurate model. Self calibrating networks will be able to adapt themselves to user response and also to sensor fault modes such as excessive noise, dead sensor, drift, and offset. The first two may be detected using statistics at the sensor, whereas the latter two by comparing with information from other sensors. Building some redundancy into the system along with continuous monitoring of data and comparison with historical data for trends, noise and periodicity will detect faults. These measures will increase the reliability at no extra cost as the technologies to do so have already matured and is applied in other domains.

4.2. Automated Diagnostics and Identification of Failures

Currently rule based threshold algorithms such as minimum and maximum limits are used to trigger alarms. These are not sufficient to detect problems with building systems. The gradual lead up to building failures is often subtle. They are not as straightforward and obvious as major equipment failures but are of a transient nature affecting sections of users. Each individual piece of equipment may be functioning properly but the building system as a whole may not be delivering the expected performance.

Diagnostic algorithms typically examine single streams of data at any one time, such as the error between actual indoor air temperature and set point temperature, or the duty cycle of an actuator to determine the stability of control. Once a failure occurs in a building system data from multiple alternate streams is required to diagnose the failure. Building operators often use their experience in working with a particular building to diagnose building problems. However, in large facilities it is not possible to depend solely on human experience alone. For such systems to be effective they must provide a high dependability in unattended operational conditions. Increasing number of nodes in a system also results in a high susceptibility to failures. Sensor and sensor network failure detection algorithms are therefore required to better manage anomalous data.

4.3. Active Learning And Adaptive Control

Studies show that there is a higher level of satisfaction if provided with individual user control. To enhance and encourage these user control systems, supplementary information about the interaction of the user with the control interface will be collected. This will assist in creating user centered systems that will learn from and adapt to user behavior. Thus control strategies will be actively updated based on collected data.

In a model based approach, advanced control algorithms are used in which mechanical non-linear systems are represented as a combination of linear systems where classical control design techniques such as PID control can be applicable. In buildings, transformation is apparent over the life cycle, requiring re-tuning of control processes. A protocol is required to re-tune control processes in real time based on data collected from the building. Examples of such scenarios are - when air temperature and window operation (figure 9) is collected continuously over a period of time and combined with information about the outside weather, it will be possible to predict the effect of the window operation on the indoor environment and to use this knowledge for window control.

When air temperature both indoor and outdoor, and solar radiation data (figure 10) are collected continuously and analysed, the information gained about the thermal characteristics of the space could be used to tune algorithms used for control. When automated, this process will greatly increase the efficiency of control algorithms. With the use of personal environment conditioning devices such processes could be used to gain knowledge about the interaction of different thermal environments within a space.

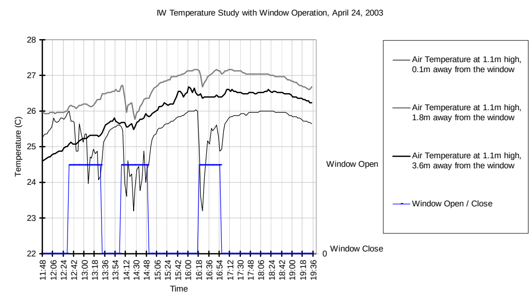

Figure 9: This graph shows the values of air temperature and window operation for a bay in the IW, measured from 11:48am Apr 24,03 to 19:36pm Apr 24,03 at 1 minute intervals.

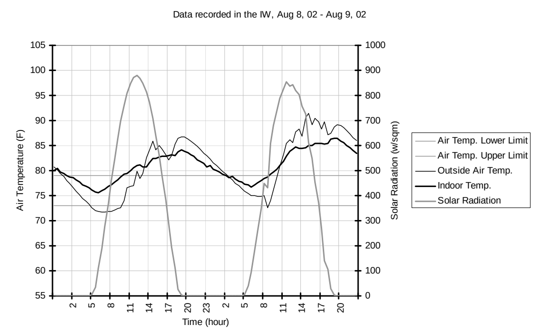

Figure 10: This graph shows the values of indoor and outdoor air temperature and solar radiation measured in the IW, on Aug 08,02 and Aug 09,02 at 1 minute intervals.

4. CONCLUSION

The IWES tool provides functions for data management, data viewing and data analysis. The lessons learnt have been used to develop a prototype BIM model that is envisaged to enhance building management.

The strategies developed to support individual control over the personal work space environment will enhance the quality of the work environment, promoting user health, safety and comfort. Automated diagnostic capabilities will allow early detection of building failure thus reducing operational disruptions and consequential costs.

The future research aims to have the potential to be transferable to other applications, such as the transportation domain. It is envisaged that the methodology developed will be implemented and demonstrated in a real-scale in the Robert L Preger Intelligent Workplace at Carnegie Mellon University, with the goal of integration into the Building as Power Plant project at Carnegie Mellon University.

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