SENSOR-BASED INFORMATION MODELING FOR LIFE CYCLE COMMISSIONING OF RESIDENTIAL BUILDINGS

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ABSTRACT

According to the National Institute of Building Science (2006), one of the main goals of building commissioning is to "maintain facility performance across its life cycle". In recent years, the maturing of sensing technology has helped to advance this vision through sensor-assisted building commissioning. For residential projects, however, the overhead associated with long-term sensor performance and quality assurance and sensor data analysis creates a barrier that diminishes the benefit of such technological advancement.

This paper describes how the principles of complex system theory can be applied to address these issues in the context of residential building. Two cases are presented. First case demonstrates the application of "scale" and "format" that underline the idea of "bounded rationality" in dealing with imperfect sensor data. Second case refers to the idea of "decomposable hierarchical system" as the framework for building system information modeling to reduce the level of difficulty for resident's participation in life cycle commissioning.

KEYWORDS

Information Model; Life Cycle Commissioning; Residential Building; Sensor-Assisted; Complex System Theory

INTRODUCTION

In recent years, the maturing of sensing technology has helped to advance the role of building commissioning in "maintain facility performance across its life cycle" through sensor-assisted continuous commissioning. Several studies of sensor-assisted building commissioning have been conducted under non-residential context. Piette (2000) evaluated a prototype Web-based Information Monitoring and Diagnostic System (IMDS) that covers main components of the HVAC system in an office building through 57 high-quality sensors. The IMDS is used for control problem and equipment fault detection. Piette estimated the yearly saving in building operation is worth $20,000 - enough to pay off the IMDS in about 5 years. Wang (2002) developed a strategy based on generic algorithm to automatically diagnose and evaluate the sensors of building refrigeration systems during initial and continuous commissioning to assure the accuracy and reliability that are essential to the effectiveness of the building management system (BMS). Singhvi (2005) deployed a pervasive temperature sensor network to determine the effects of room usage on building conditions. The results show that the building state is dynamic and the indoor environmental parameters vary significantly based on occupancy and layout of the room. The results also suggest that for collecting building performance data, it requires a pervasive, rather than sparse, sensor network.

These case studies suggest that cost of system monitoring and diagnostics, reliability of sensor data and the metrics of sensors to capture sufficient information are three key factors to the success of sensor-assisted building commissioning.

A series of studies (Matson 2002, Wray 2002, Wray 2000) have identified the metrics and benefits of residential building commissioning. However, the issue of commissioning cost was not specifically addressed. Earlier, Westergren (1999) conducted research with continuous sampling of whole house energy consumption data and applied statistical method to construct a single-family energy consumption model. Yet the reliability of the monitoring data has not been discussed at all. Literature review indicates that there is a lack of research focus on issues related to sensor-assisted commissioning in the context of residential building.

Figure 1. InfoMonitors web-interface database (www.infomonitors.com/IBACOS)

Two sets of detailed annual sensor data are acquired from IBACOS InfoMonitors database (Fig. 1) for this study. The first data set is from an occupied residential house in Aspen, Colorado equipped with PV (Photovoltaic) system. The second data set is from an occupied residential house in Buffalo, New York, equipped with CHP/FC (Combined Heat and Power /Fuel Cell) system. Sensor data include parameters such as room temperature, humidity, solar radiation, total and circuit by circuit electricity consumption, water flow and temperature, and natural gas consumption (Fig. 2, Fig. 3).

Figure 2. Front page of Aspen house in InfoMonitors

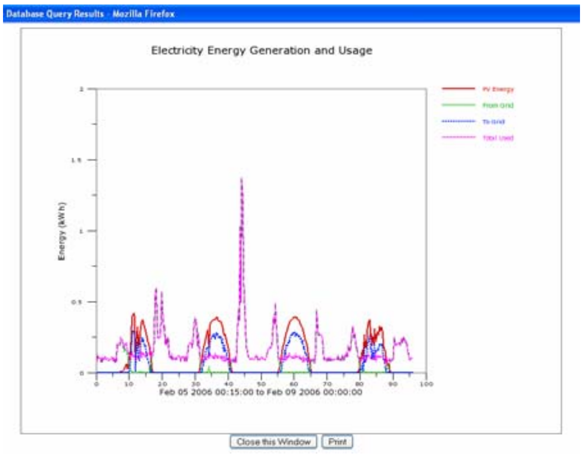

Figure 3. Sensor data graphs generated by InfoMonitors

Sensor data quality remains the primary challenge and concern. System setting records and on-site investigation indicate that quality issues embedded in the sensor data include system performance, occupant life style, sensor accuracy and precision, data capturing schedule settings, and data organization. Due to the heterogeneous nature of these causes, noise in data stream is difficult to filter out through conventional top-down reductionism methodology.

"Bounded rationality" from complex system theory (Simon 1996) is adapted in this study to deal with the problem of data analysis. This concept provides an alternative view to look at the noise in sensor data and guides the definition of the boundaries of multi-level views for the design of the sensor data embedded hierarchical information model. "Bounded rationality" can be interpreted as "human rationality is bounded by the accessibility of relevant information". The value of information depends largely upon its accessibility to the decision maker. The accessibility of information has much to do with the format of presentation. The assertion of this study is, even when the quality of data is less than perfect or the sensor data is ambiguous in meaning, if it is presented in a form appropriate for the designated decision context, information derived from sensor data can still lead to high-quality decision making.

Different issues occur during building commissioning which can be result from different problem domains as well as problem resolutions. By adopting principles of "complex system theory", characterized by decomposable hierarchical structure (multi-scale model structure) and bounded rationality (expertise-oriented product unit), sensor data are processed and transferred into "accessible" information format. Through this approach, this study shows that the seemingly interwoven yet heterogeneous issues can be disentangled and categorized into knowledge domains in respective hierarchies, thus greatly reducing cost and knowledge overhead that prevents the implementation of continuous commissioning in residential scale.

In the Aspen house, the objective of data analysis is to identify opportunities in reducing on-site electricity consumption. Data analysis shows that, regardless of the uncertainty of the accuracy and precision of sensor data, the resulting graphs, when formatted correctly, still provide highly useful information on how to achieve this objective.

Sensor data from Buffalo house is used to construct the information model to monitor the house's operational energy efficiency. The information model demonstrates the use of "multi-level information modeling" approach (transforming sensor data to hierarchical information structure of system, sub-system and components) for building operation fault detection, system diagnostics and knowledge discovery. It has greatly simplified the knowledge requirement for system diagnostics thus enabling the occupants to assume the daily role of the facility manager for residential building.

SENSOR DATA PROCESSING

Aspen house electricity consumption analysis

IBACOS InfoMonitors database collects Aspen house sensor data from December 2004 through April 2006. The Aspen house project contains 19 room and equipment temperature (F) channels, 3 relative humidity (%) channels, 35 circuit-by-circuit (Amps) channels, 2 equipment runtime channels, 4 water flow (Gal) channels, 3 whole system electricity (PV gain, to Grid, from Grid) (kWh) channels, 4 heat output (BTU) channels, all recorded in 15 minute time step. The electricity consumption sensor data is extracted from the circuit-by-circuit channels and the whole system electricity channels.

Data are processed in two ways. First, Amp readings of all 35 circuits are converted to kWh unit and summed up to compare against the readings of the sum of whole system electricity 3 channels to verify the consistency of the sensor data. Second, 35 circuits are ranked by their electricity consumption. To understand the patterns of electricity consumption of the key circuits, data of top 10 circuits are presented in graphs for further analysis. Two pieces of external information namely occupancy and event changes during the period of data collection are used to assist the circuit-by-circuit sensor data processing. A working couple and their young baby live in the Aspen house. In expectation of the significant difference of occupancy patterns between workday and non-workday, each "top 10" circuit has a graph with pair of curves derived from weekday/ weekend data. Second, sensor data provider (IBACOS) has verified several sensor metrics anomalies and changes of occupancy pattern during the one year experiment period. Additional graphs are generated for the observation of the effects of these documented events.

Buffalo house energy conversion efficiency information model

The Buffalo house energy conversion efficiency information model is implemented in two steps: information schema design and the proof-of-concept web-based information model deployment. Its goal is to enable occupants to monitor the performance and to pinpoint the problem of the system with minimum training.

On the information schema design, all sensor points on the heat and electricity system diagram are associated with corresponding sensor channels in the data set. From the system diagram, a new IDEF0 hierarchical system diagram is constructed based on process unit and its resolutions. With the guidance of the new IDEF0 diagram, the sensor data are organized to provide "views" of the state of the respective process unit and energy flow.

On web-base information model deployment, a mirror database of all sensor data is created using a local MySQL database management system. General Java programming tools linked to the MySQL database enable data organization and processing. Finally, the IDEF0 information schema is placed on a tomcat web server with Java Servlet connected to MySQL with Java 2D graph library to implement the Web-based information model.

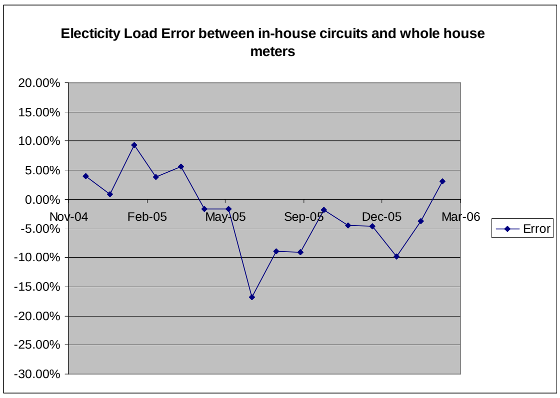

Figure 4. Difference between the sums of in-house circuits and of whole house meters (in %)

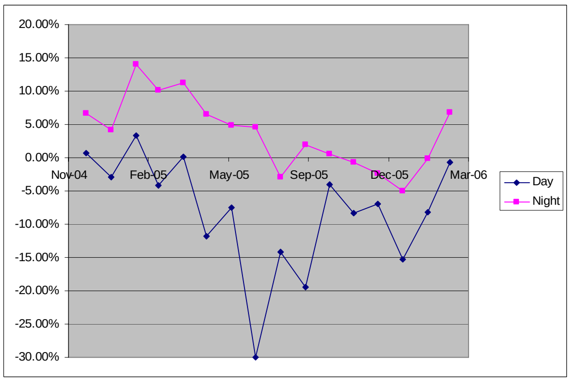

Figure 5 Difference between the sums of in-house circuits and of whole house meters (day vs. night)

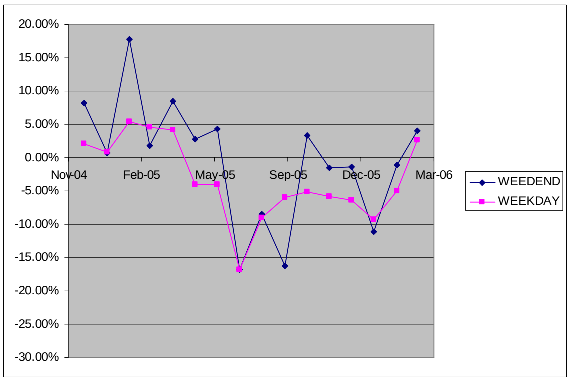

Figure 6. Difference between the sums of in-house circuits and of whole house meters (weekday /end)

RESULT AND DISCUSSION

Aspen house electricity consumption analysis

The consistency check between individual circuit and the whole house electricity meter indicates that the sensor readings are not of good quality. Not only is there significant difference between the sums of two types of (circuit vs. whole house) sensor readings, the difference (Fig. 4) varies with time and does not show any recognizable pattern. When data is separated into day-night pair (Fig. 5) and weekday-weekend pair (Fig. 6) in monthly electricity load graphs, it is noted that besides PV system reading and life style of occupants, there are other unidentified factors contributing to this discrepancy

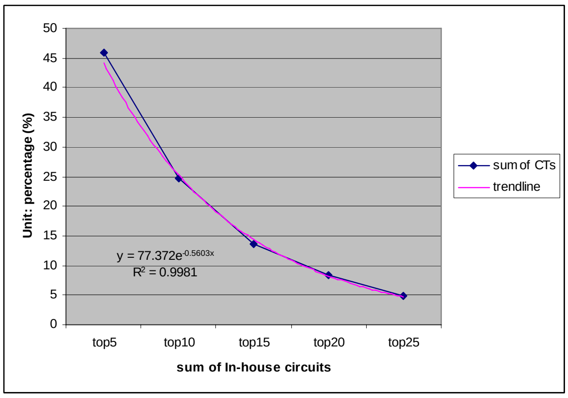

Figure 7. Log scale (percentage of total electricity load of top ranked circuits)

On the circuit-by-circuit comparison, top 5, top 10, top 15, top 20 and top 25 circuits account for 46.0%, 70.7%, 84.4%, 92.7% and 97.5% of total electricity consumption respectively. There is a strong showing of "power law" (Fig. 7) relationship of electricity consumption among the top 25 circuits. The top 10 circuits are Living Room (16.9 %), Clothes Dryer (7.9 %), Air Handler (7.4 %), Kitchen Lights (7.0 %), Kitchen Refrigerator (6.8%), Maser Bedroom Power Plug and Lights (5.9 %), Garage Power Plug (5.2 %), Hot Water Boiler (5.2 %), Condenser (4.8%), and North Bedroom Power Plug and Lights (3.7 %).

Comparative graphs of two circuits are presented to demonstrate that the data quality problem does not affect the outcome of proposed solution as far as identifying opportunities to reduce electricity consumption is concerned.

There were problems with readings of the living room (Fig. 8) plug-in load sensor and the sensor was "reset" by May 2005. The "before and after" graphs show that, as a result of this reset, the reading drop on average 0.1 Amp or 25% of the non-pick hours value. 25% error in reading is significant, but from the perspective of finding energy saving opportunity, it has little effect. Stand-by load, represented by the area under the non-pick hour line, still accounts for more than 50% of the total living room electricity consumption. With or without accounting for the 25% reading error, the proposed solution is still to eliminate the stand-by load.

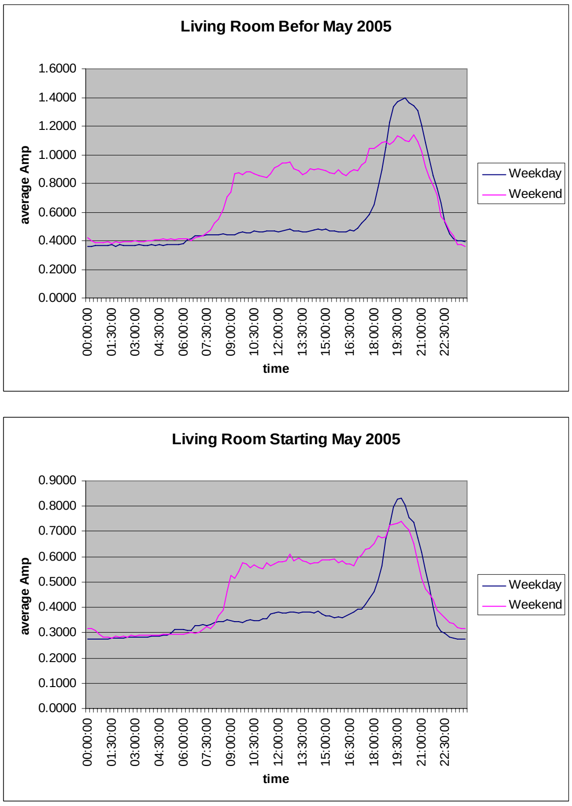

Figure 8. Living room hourly electricity load before and after May 2005

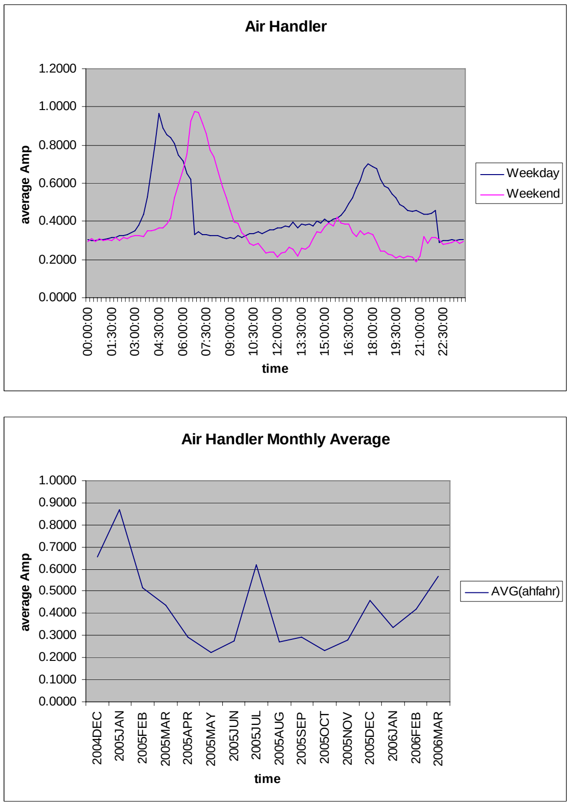

Figure 9. Air handler hourly and monthly electricity loads

The Air Handler graph (Fig. 9) reflects the life style of a typical American working family. To accommodate occupancy activities, AHU load pecks at early morning and late afternoon hours during weekdays, but pecks at morning and has lower peck in the afternoon during weekend. The monthly graph shows that the AHU electricity load pecks at summer and winter, which is understandable but it can not offer an explanation why 2005 winter in the Wshaped curve consumed electricity twice as much as 2006 winter did. Although there is indication of problems in the quality of the sensor reading, the hourly graph still provides useful information to help identify that we can reduce AHU electricity consumption by turning it off in weekday afternoon, when there is little occupancy activities.

Figure 10. Master Bedroom hourly electricity load

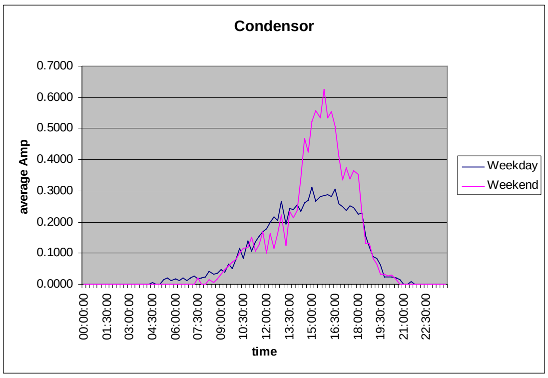

Figure 11. Condenser hourly electricity load

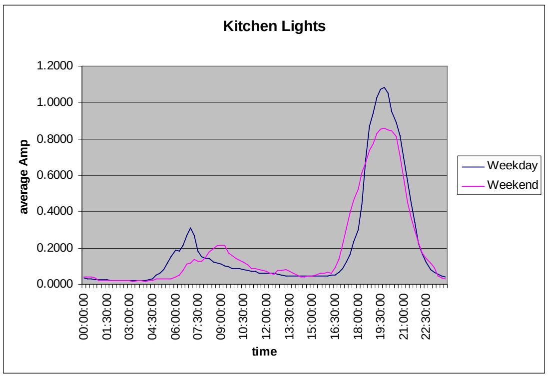

Figure 12. Kitchen Lights hourly electricity load

In complex system theory, functional units of different scales do not necessarily share the same properties. A system which does not work globally does not mean its components do not work locally. Although sensor data is problematic in monthly scale, hourly data in the living room and AHU graphs vividly illustrate the usefulness of sensor data. Other graphs from top 10 circuits, such as master bedroom (Fig. 10), condenser (Fig. 11) and kitchen light (Fig. 12), also faithfully depict the life style of a typical American working family.

Buffalo house energy conversion efficiency information model

The case of Aspen house's electricity consumption demonstrates what difference "scale" and "format" can make in the usability of sensor data. The concept of "local vs. global" view of sensor data is further extended to develop a complex system representation for the system performance of Buffalo house in terms of energy conversion efficiency.

Two documents were acquired in the beginning: the system diagram of CHF/FC/Boiler marked with sensor points and the year-long sensor readings of these sensors. Because of the advantage of diagram over text on sharing of structured information (Larkin 1987), the system diagram (Fig. 13) is converted to a 3-tiered hierarchical structure, also presented in a diagrammatic form (Fig. 14). Top tier view (A0) shows the energy conversion efficiency from aggregate effects of all components in the system. Second tier views show the conversion efficiency of two sub-systems – the CHP/FC system (A1) and conventional boiler system (A2). Third tier views show the energy conversion performance of four fundamental product units belong to those two sub-systems- FC chemical energy reaction unit (A11) , FC exhaust heat recovery unit (A12) (components of CHP/FC system) and domestic hot water (DHW) heat exchange unit (A21), space heating heat exchange unit (A22) (components of boiler heat exchange system). A main characteristic of this hierarchical information model is that it maps the multi-resolution views to actual product units. The knowledge of problem solving is thus embedded in this system because the information model not only detects problems but also pinpoint the problematic component thus the corresponding specialist can be called in to deal with it. An example of the home-owner self-help continuous commissioning is illustrated as following.

The focus of this example is the diagnostics of the A22 space heating boiler. We pick 3 days (152, 302, 362) in year 2004 as inputs. After submitting the times, the information model (Fig. 14) generates with a table of energy conversion efficiency of various process units and the detailed efficiency graph of A22 process unit (the boiler for space heating). On day 152 (Fig. 15), the resulting table indicates problem with the space heating boiler. The detailed graph shows that there is no energy inflow and outflow and water temperatures are constant. Thus the diagnostics is that the boiler is not in operation. It is reasonable considering that day 152 is not in the heating season. On day 302 (Fig. 16), again the resulting table indicates problem with the space heating boiler. The A22 graph shows that there is energy outflow but no energy inflow and water flow

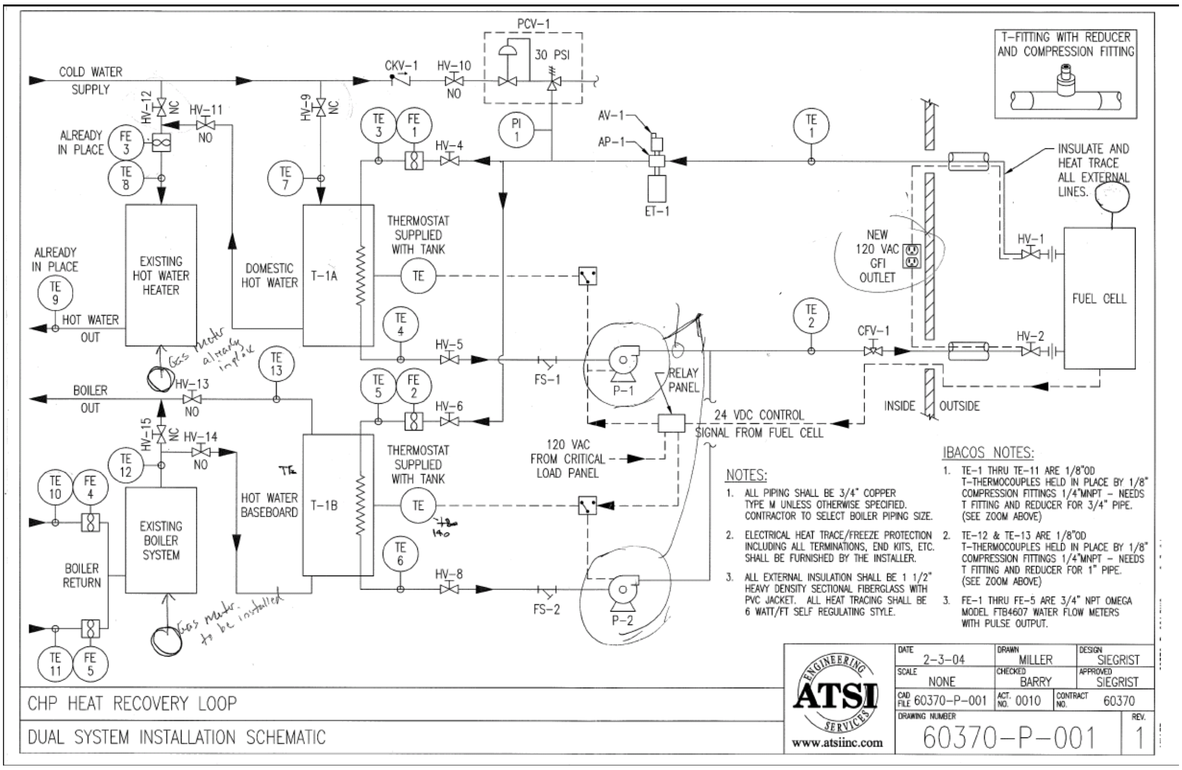

Figure 13. Buffalo house CHP/FC/Boiler System schematic diagram (circles denote sensor points)

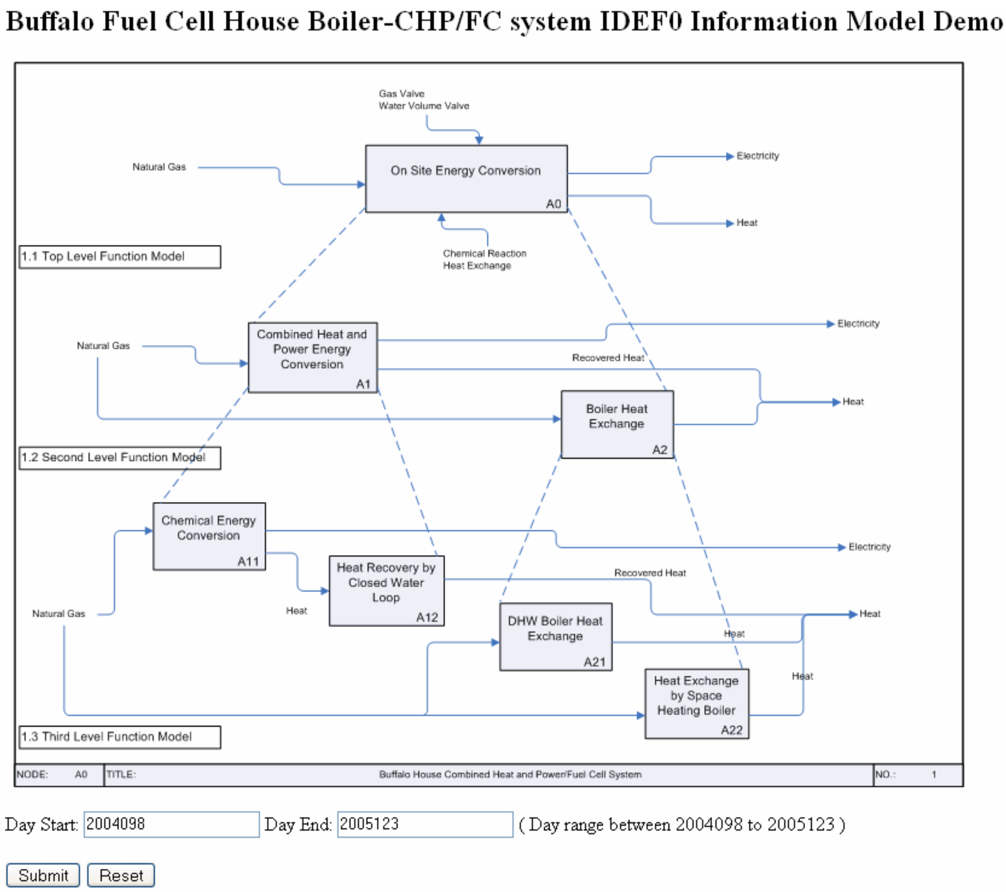

Figure 14. IDEF0 product unit based buffalo house energy efficiency hierarchical system diagram

and water temperature readings of various loops fluctuate dramatically. The A22 graph suggests the inflow energy meter (natural gas meter) is faulty. On day 362 (Fig. 17), space heating boiler energy efficiency reading (A22) is in normal range. Looking down the table to the CHP/FC system, it is noted that the heat output efficiency (A11h) of the fuel cell system is only 1/10 of the reference value.

Buffalo Fuel Cell House Performance Monitoring

Please contact the agent of the "Process Unit"
when "Measured Efficiency" is lower than "Reference Efficiency" or higher than 1 !

No.	Process Unit	Measured Efficiency**	Reference Efficiency
A22	Space Heating Boiler	3.25	0.5
A21	Domestic Hot Water Boiler	0.05501725409027778	N/A
A12	CHP heat recovery Jacket	0.4729623	0.5
A11e	FC Electricity Generation	0.32687999999999995	0.3
A11h	FC Heat Generation	0.040345110947227515	0.4
A2	Boiler Total Heat Exchange	0.05501725409027778	N/A
A1	CHP/FC System Energy	0.3456334992119444	N/A

** When the process unit is not operating or sensor data is missing, the efficiency value is 3.25!

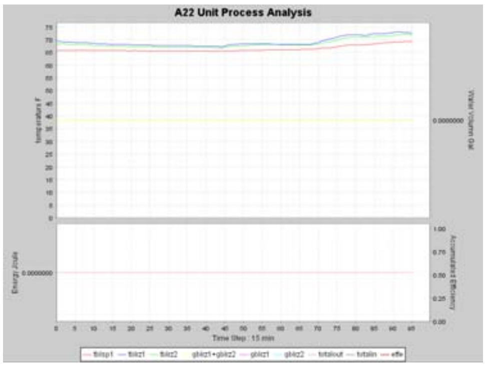

Figure 15. Composite view: efficiency table and A22 "space heating boiler" process unit energy conversion efficiency graph (date: 2004-152)

Besides the space heating boiler diagnostics, with little expertise of the inner working of CHP/FC system, the occupants should be alerted to call the specialist to check up on problem of low fuel cell heat output because the knowledge of the system is imbedded in the information model.

In real world application, this hierarchical information model approach suggests a huge reduction in "expertise knowledge" overhead. It should make sensor-assisted life cycle commissioning a more realistic option to the building industry in residential sector.

CONCLUSION

"Complexity system theory" sees the world as a bottom-up, nearly-decomposable hierarchic system. A system is an aggregate of its functional subsystems. A subsystem is an aggregate of its functional components. Each functional component is an autonomous entity that carries out its designated task. The performance of a system is the aggregated performance of subsystem (and individual functional components). However, functional component does not know, neither does it care how it fit in the "grand scheme" of the system from the top-down view.

Buffalo Fuel Cell House Performance Monitoring

Please contact the agent of the "Process Unit"
when "Measured Efficiency" is lower than "Reference Efficiency" or higher than 1 !

No.	Process Unit	Measured Efficiency**	Reference Efficiency
A22	Space Heating Boiler	3.25	0.5
A21	Domestic Hot Water Boiler	3.25	N/A
A12	CHP heat recovery Jacket	0.6368184	0.5
A11e	FC Electricity Generation	0.29018	0.3
A11h	FC Heat Generation	0.19510125156915872	0.4
A2	Boiler Total Heat Exchange	3.25	N/A
A1	CHP/FC System Energy	0.4097958453037963	N/A

** When the process unit is not operating or sensor data is missing, the efficiency value is 3.25!

Figure 16. Composite view: efficiency table and A22 "space heating boiler" process unit energy conversion efficiency graph (date: 2004-302)

Buffalo Fuel Cell House Performance Monitoring

Please contact the agent of the "Process Unit"
when "Measured Efficiency" is lower than "Reference Efficiency" or higher than 1 !

No.	Process Unit	Measured Efficiency**	Reference Efficiency
A22	Space Heating Boiler	0.48877528887811471	0.5
A21	Domestic Hot Water Boiler	0.07588305712303499	N/A
A12	CHP heat recovery Jacket	0.4332854	0.5
A11e	FC Electricity Generation	0.3065366666666666	0.3
A11h	FC Heat Generation	0.04249749351653607	0.4
A2	Boiler Total Heat Exchange	0.4711427356614152	N/A
A1	CHP/FC System Energy	0.32569420814916666	N/A

** When the process unit is not operating or sensor data is missing, the efficiency value is 3.25!

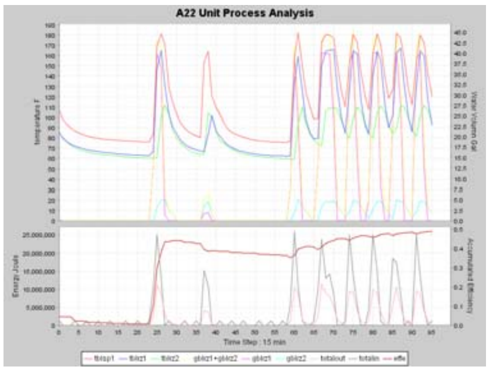

Figure 17. Composite view: efficiency table and A22 "space heating boiler" process unit energy conversion efficiency graph (date: 2004-362)

From the building operation perspective, complex system represents a "local-to-global" view of the building system. The whole system energy consumption is the aggregate of individual functional units. The improvement of the whole must come from the improvement of the parts. In addition, to construct a system based on complex theory, the parts (functional components) that make up the system and the relationship among them must be known. In other words, in sensor data analysis, the prior knowledge of appropriate methodology that can be applied on the whole system such as multiple regression or artificial neural network is replaced by the prior knowledge of how the building (system) was assembled from functional parts.

The study applied this local view concept to structure multi-channel sensor data. The result shows that sensor data whose quality is problematic at system level may not be problematic at component level. Toward the ultimate goal of improving the performance of entire system, we believe, from the solution discovery point of view, the focus needs to start from functional components.

On the individual component level, Aspen house case demonstrates that if data is organized in a scale and format appropriate for designated objective (i.e., identifying ways to reduce electricity consumption), even data of poor quality can provide information of good quality for decision making.

On the system level, Buffalo house case demonstrates how the prior knowledge of the system can be used to design a hierarchical information schema of the system. Based on the hierarchal information schema, the sensor data is processed, structured and presented in a way that occupants with minimum training are able to assume day-to day duty of the facility manager – detecting and pinpoint the problematic process unit of the system and referring the problem to right people to fix it.

On the final note, the component-based complex system data analysis and diagnostic methodology does not intend to and cannot replace the whole system-based data analysis and diagnostics. It should be considered as a pre-processing tool to decompose a "heterogeneous system" into "homogenous indecomposable subsystems" to improve the performance of whole system-based methodology applied on the subsystems. Complex system based data analysis is better suited for the facility manager than for the specialist of subsystems and components. For instance, the information model of Buffalo house can help to identify the faulty subsystem. But the information model cannot explain why a certain component of subsystem is faulty or how it can be fixed. The solution the information model provides is to alert the occupant-facility manager to refer this problem to proper specialist, who then will use system-based diagnostics methodology to figure out why and how to fix it.

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