PRODUCT AND PROCESS MODELING FOR FUNCTIONAL PERFORMANCE TESTING IN LOW-ENERGY BUILDING EMBEDDED COMMISSIONING CASES

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ABSTRACT

Our work deals with creating information assistance for commissioning (Cx) low-energy buildings throughout their life-cycle. We call this *Embedded Commissioning* in reference to the integration of persistent and reliable Cx information. We have developed digital models of the Cx process and products. Currently, we are testing system inspection and functional performance test (FPT) protocols developed by others to verify their applicability to individual facilities and compatibility with our product models, as well as standards, such as IFC and aecXML. To date we have tested a fin-tube radiant heat system FPT. Our findings include lessons learned in several areas: (1) adapting standard FPTs to specific facilities and their design intent, (2) common performance retarding system defects, and (3) implications for data representation in product/process models for FPT implementation.

CREATING INFORMATION ASSISTANCE FOR COMMISSIONING LOW-ENERGY BUILDINGS

Low-energy buildings, that by definition occupy the lower tail of energy consumptions distributions for new buildings, present a special problem for commissioning (Cx). They have higher standards of energy efficiency; sophisticated system technology including sensors and actuators; complex reasoning and control systems; and continuous need for monitoring. In order to realize this, Cx must rise to higher levels of precision and persistent application through digital and information technologies. In this paper, we describe just such an approach. We will provide a description of the information flow in the Cx process; an information model that supports the input and output of information within this flow; and the testing of functional performance tests (FPT) for the various low-energy buildings systems, such as heating and ventilation. The FPTs we used have been contributed by Portland Energy Conservation Inc (PECI) to the ANNEX 47 community of Energy Conservation in Buildings and Community Systems program of the International Energy Agency. As part of the process of developing this digital and information technology tool, it is necessary to determine which of these outputs needs to be exchanged with other parts of the information flow.

There are many such efforts that try to improve interoperability in the field such as Building Information Models (BIM) and the International Alliance for Interoperability (IAI). In this paper, we do not intend to provide a comprehensive review of all of these efforts. Suffice it to say that our work benefits from all of the prior work with which we are familiar (Akin, et.al, 2003) and tries to contribute to them directly or indirectly.

EMBEDDED COMMISSIONING: INTEGRATION FOR PERSISTENT, RELIABLE Cx INFORMATION

Cx of low-energy buildings is about continuous building evaluations, throughout the building delivery process, to provide the necessary feedback to the owner, designer, construction manager, O&M personnel, and occupant for high performance. In order to achieve this:

The Cx process must be systematic and standardized. Test procedures, evaluation methods and the Cx data should not differ between various Cx providers.

The Cx process must have computational support. Managing different phases of building evaluation from programming phase to facility occupation requires effective tools through which information can be kept digitally for ease of data exchange.

The Cx information should be embedded in the entire building life-cycle. Data produced during the Cx process should feed other evaluation procedures throughout the life of a building.

We call this the Embedded Commissioning Approach (ECxA). In this approach, Cx is defined as a building delivery embedded process, which persistently verifies and validates design intent throughout the building lifecycle. From this viewpoint, buildings are considered to have cradle-to-grave lifespan. They are modeled through a variety of different developmental phases, such as programming, design specification, facility construction, facility management, facility (de)commissioning, and facility (re-)occupancy. ECxA combines the processes of Cx and building life-cycle in order to provide a framework for managing the information exchange between them. The role of Cx here is to complement each of the lifecycle phases and their interactions through timely building system evaluation.

For instance, building construction normally would begin once design specification is complete. At this point, Cx would serve as the evaluation aspect of the construction process, periodically verifying the accuracy of what is being constructed against available specifications, whether these are of a design or requirement type. In response to this evaluation, the construction process would either continue as planned or be modified. This kind of feedback cycle is imaginable for all phases of the lifecycle process shown in Figure 1.

The primary mechanism in this approach is to execute each phase with the expectation that continuous evaluation will provide guidance for downstream decisions based on ongoing measurements and simulations. We expect that this will significantly improve performance during all of the stages of the building lifecycle.

Naturally this approach is feasible when it benefits from high-end digital technology in which data can be persistently used, its integrity and fidelity maintained through sophisticated data representation and maintenance techniques. In this paper, we merely allude to this technical aspect of our work (Turkaslan-Bulbul, et.al, 2005; Wang, et.al, 2004).

Our current ECxA is structured for supporting three features of the HVAC Cx process.

The first one is the *precise representation of the Cx data*. The main purpose of creating a data model is utilizing data exchange. Therefore, all Cx information that needs to be exchanged between Cx process and other building related documentation, such as equipment histories, Cx records, design intent, and other updates that accumulate during a building's lifecycle, should be included in the data model. Current practice of Cx does not use standard data. Data captured by Cx, during the multiple phases of building lifecycle is stored in reports prepared by Cx agents. These reports show variation according to the preferences of the preparing agents, the phase of building lifecycle in which they are used, the firm conducting the Cx process, and the goals of the client ordering the Cx task.

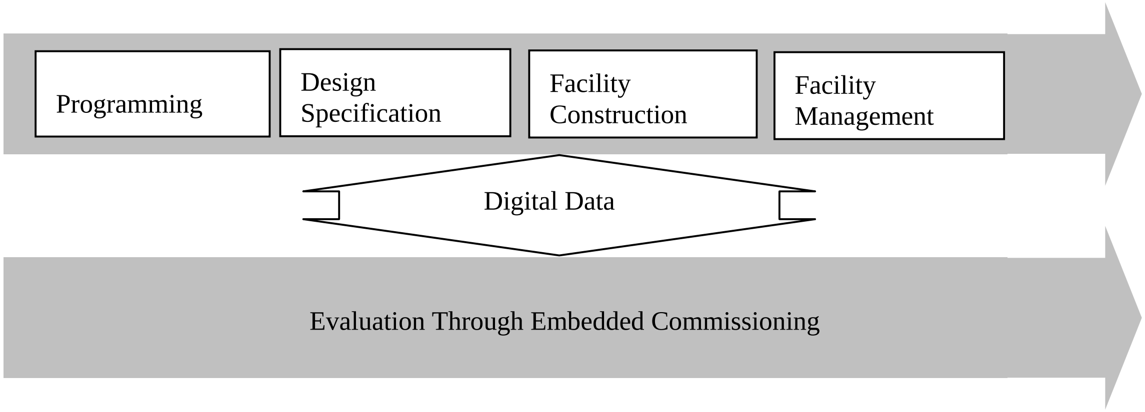

Figure 1: The Embedded Commissioning Approach

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There are also Cx guidelines produced by different organizations or government agencies, such as ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers), NIST (National Institute of Standards and Technology), and the DOE (Department of Energy). These guidelines describe a general outline for HVAC (Heating Ventilating and Cooling) Cx, while the Cx data needed by each of these have differences. Data models suitable for ECxA (Turkaslan-Bulbul, et.al, 2004) have been compiled from various sources, such as data sheets of practicing Cx agents, Cx guidelines from organizations, equipment specifications of mechanical system manufacturers and the work of other related research groups. We formatted the data obtained from these different sources through Comparative Analysis Tables (CAT), a method of data normalization based on specific cases (Akin, et.al, 2003).

The second feature of ECxA is to *differentiate distinct Cx phases*. Data and evaluation procedures for every phase of ECxA are not same. For example in order to commission an Air Handling Unit (AHU) during the programming and design phases, the Cx agent needs to know the system operating schedule but not the AHU make and model; in the design phase the Cx agent needs to evaluate design for the operability and maintainability of the AHU; and so on. While separate phases of ECxA require different types of information, low-energy building evaluation data has a cumulative character. As the ECxA process proceeds towards the post-construction phase, data becomes more detailed. In the programming phase, the AHU information is abstract and defined as a simple systems description. In the post-construction phase, the AHU Cx information is detailed to specify all attributes of every equipment type forming that specific AHU, such as supply fan capacity, heating coil entering/leaving water temperature or clean filter pressure drop.

The third feature of ECxA is the *relationships and associations between data entities*. Topology information is important for computationally supporting Cx activities. For instance, an AHU is a complex piece of equipment; it consists of other pieces of equipment, such as coils, air filters, control sensors, supply and exhaust fans. Different combinations of these pieces of equipment can potentially create unlimited AHU configurations. Performance of an AHU depends on the equipment types from which it is made. In order to evaluate the operability and maintainability of the AHU, a Cx provider needs to check every equipment type separately and inspect their connections and sequences of operation. The relationships between equipment types forming that specific AHU should be properly represented.

TESTING SYSTEM INSPECTION AND FUNCTIONAL PERFORMANCE TEST PROTOCOLS

Developing a testbed

In order to develop a testbed for the FPT we coordinated our efforts with those of the Intelligent Workplace (IW) at Carnegie Mellon University’s School of Architecture. Jointly, we develop procedures for and revision of the PECI protocols that would work with the IW systems. We organized several meetings with the following objectives:

- Initial agreement with lead mechanical engineer Dr. David Archer and PhD students
- Develop a working relationship with staff, students and faculty of IW
- Develop the final ECx protocols for the mullion and fan coil system

Through these meetings, we were able to establish a mutually beneficial plan of work in which the IW staff benefited from the results of our ECx work, and we from testing our product and process models. We drafted a seven step plan for carrying out our research:

- Develop a plan for the two systems selected for ECxA
- Invite input from IW and PECI on our plan
- Undertake limited implementation of plan to test its viability
- Review and adjust the ECxA

- Implement the final ECxA for retro-CX with the radiant mullion system
- Implement the final ECxA for the new fan coil system
- Publish the results and recommendations of ECxA implementation

Currently we are in the process of undertaking the first two steps of this plan. We have all but completed the implementation of our plan for the ECxA of the radiant mullion system, and are in the initial shadowing stages of the installation of the new fan coil system.

During recent meetings with IW staff including their controls specialist, Research Technician James Jarrett, we reviewed the relevant data for the two systems which we are commissioning: the radiant-heat mullion and fan coil systems. Through Mr. Jarrett's help we were able to verify the:

- applicability of the PECI FPT to the two systems available to us at the IW, and
- compatibility of these protocols with product models and standards, such as IFC, aecXML.

Preparation for radiant mullion system functional testing

The first obstacle we encountered was the adaptation of the Fin Tube Radiator FPT protocol to the existing radiant mullion system, at the IW. In order to do this, we began by collecting information on the existing system. We found that there was no comprehensive physical representation, such as, blueprints, 3D schematic drawings, or CAD files. However, we found a riser diagram which shows the system as it was designed and implemented (Figure 2). We have verified the fidelity of this document during our Cx application.

We learned that there is a four-level control strategy for the mullion system (Figure 3) designed and installed by Johnson Controls Inc.: the individual mullion, cluster of four mullions, the main controller, and the meta-control system. The design intent for the system is not detailed. It simply states that its purpose is to keep the ambient temperature warm enough for comfort and that it is the primary heating system for IW. While there is a lot of strategic information that has been developed since it was installed in 1996, the system was n-ever commissioned.

The goals of our ECxA have been to see if:

- the mullion system is installed the way it is supposed to be,
- its control signals work properly, and
- it provides the intended system performance.

Description of the existing radiant mullion system.

Mullions and overhead panels are the only heating and cooling devices used in the IW. Currently, the mullions are used only for heating and overhead panels are used only for cooling. The current HW/CHW system is shown in Figure 4 (Gong and Claridge, 2006). The mullions are constructed from ¾" hot water pipe attached to the curtain wall via an aluminum flange. One mullion is located on each side of every window unit on the east, west and north sides of the building. Four mullions are bundled into a cluster in order consolidate supply and return valves, each of which is located at the top or bottom of a cluster. Twenty-six clusters surround the entire IW space.

The campus loop supplies steam to a steam-water heat exchanger in the basement of the Margaret Morrison Building which in turn provides the hot water to the mullion system. Hot water is circulated in the winter between the mullions and the heat exchanger through hot water pumps located in the basement. The 33-gpm mullion pump located on the roof of fourth floor and underneath the IW currently runs 24 gpm during the daytime schedule. This mullion pump supports the additional pressure in order to overcome the head loss in the mullion system (Gong and Claridge, 2006). Temperature sensors located on the mullions are used by Johnson Control controllers to set the water flow in the valves to maintain the mullion set point.

Mullions system control logic.

The IW control system regulates the water temperature set point to each mullion cluster. Each cluster also has a multiplier in the control system that allows the operator

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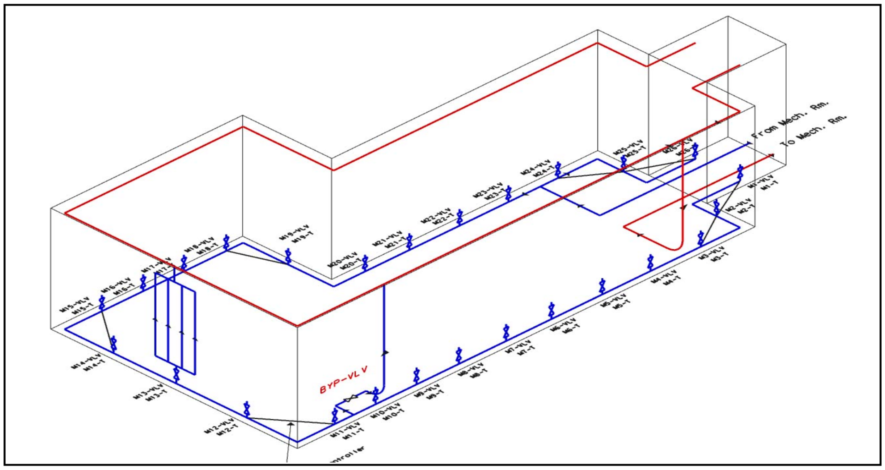

Figure 2. The riser diagram of the mullion system in

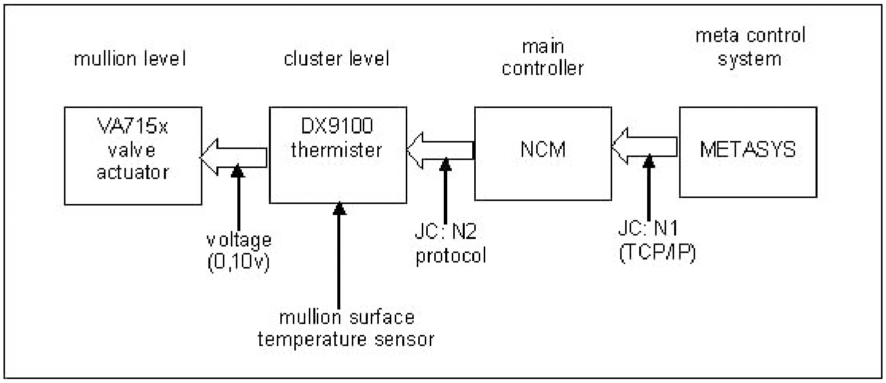

Figure 3. The control mechanism of the mullion system

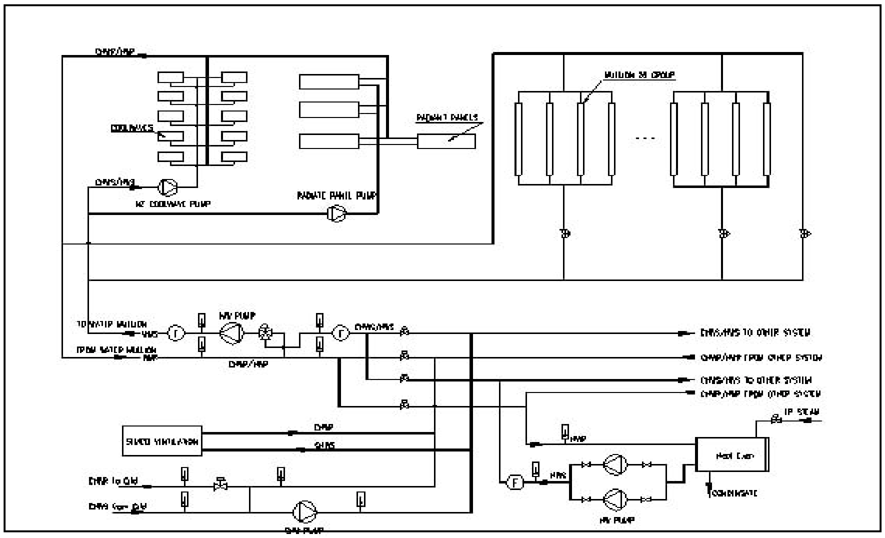

Figure 4. The current HW/CHW supply system

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to raise or lower the temperature of their mullions to match the comfort level. The basement pump (HWP1 or HWP2) or the fourth floor mullion water pump is turned on if the average south zone and north zone indoor temperature $((T_{south} + T_{north}) / 2))$ is below the pump set point (60^{o}F) or if the schedule calls for it (Gong and Claridge, 2006).

The indoor and outdoor temperature values and a comfort weighting factor are used to decide the hot water supply temperature set point (T_{HW_S}) based on the equation:

$$T_{HW\_S} = (38 - T_o) * f_{oA} + (72 - \frac{T_{south} + T_{north}}{2}) * f_{IA} + 120$$

where f_{OA} and f_{IA} are outside and inside air temperature weighting factors. The default values of these factors are 1,0. METASYS calculates mullion surface temperature set points (Mn-SPT) continuously as the median between indoor air and hot water supply based on the formulae, which is set at 91°F:

$$T_{mullion-s} = \frac{\frac{T_{south} + T_{north}}{2} + T_{hws}}{2}$$

Problems Found in the Radiant Mullion System

There were four kinds of system performance problems discovered as a result of our ECxA work: design errors, wiring installation errors, local anomalies, and obscure control parameters.

The design intent for the radiant mullion system, as indicated earlier, was a nebulous statement about the overall comfort level of the facility. Details of the installation and the impact on the final performance were not sufficiently considered in the early design. For instance, the differential in the ambient temperature of the sub-floor plenum area and the room above this space turned out to be a major factor in the calibration of the resident sensors attached to the mullions. Furthermore, the location of the sensor, whether it should be on the pipe or the aluminum flange connecting the pipe to the window mullion, turned out to be another point of consideration in the ECxA.

We discovered that some of the wiring connecting the sensors to the control system was inverted. When we tested the control system, it became obvious that the left and right sensors were reversed during the installation of one of the mullion clusters.

The readings we made in calibrating the sensors also indicated to us that over time a few of the valves were frozen, flow became discontinuous and as a result there were large jumps in our readings or alternatively very small change over long periods of time, i.e., 30-40 minute intervals.

Finally, the control system was ineffective in bringing about the desired effect within the time durations chosen as the control parameters. It was not clear whether the control protocol or the system hardware was the real culprit at the time of the writing of this report. We expect to expand these results and finalize them in the next half year of our research project.

Preparation for Fan Coil Unit Pre-functional and FPT.

The fan coil system has been purchased and its configuration is being designed by a Pittsburgh architectural firm. It consists of the components listed in Table 1. We are working with the design teams in IW and the architects to document this ECx activity from design intent to occupancy.

For controlling the fan coil system, IW staff has been working with Siemens' branch office in Pittsburgh to figure out the kinds of sensor and control system that would be feasible. Currently, they are planning to use a control module for terminal equipment (TE), a control module for compound equipment assemblies (CEA), and a control module for the entire building (CMIW) for the purpose of conducting conditioning experiments. We also learned that there will be a two-level control strategy for the fan coil system designed and installed by local Pittsburgh Siemens branch office; the individual fan coil per control system, wireless control from TE and CEA to CMIW (Figure 5). We expect that the final control system recommended by Siemens may well be different from what is shown in Figure 5.

Table 1 Fan Coil Unit Components of IW

Model Name	VKB-4/630	VKD-800	FVD-A 1245-300-R
Unit Number	15	6	1
Type & Location	Floor level FCU 3 in each east room	Floor level FCU 1 in each west room 1 in the southeast room	Façade FCU 1 in the southwest room
Air Intakes	Two air intakes Ventilated air from SEMCO & ambient air	Two air intakes Ventilated air from SEMCO & ducted return air	Two air intakes Outside air and ambient air
Number of Pipe	4-pipe w/ continuous heating and cooling valve control	4-pipe w/ continuous heating and cooling valve control	4-pipe w/ continuous valves control
Control	3-speed fan control	2 fans w/ 3-speed fan control	1 fan 3-speed fan control

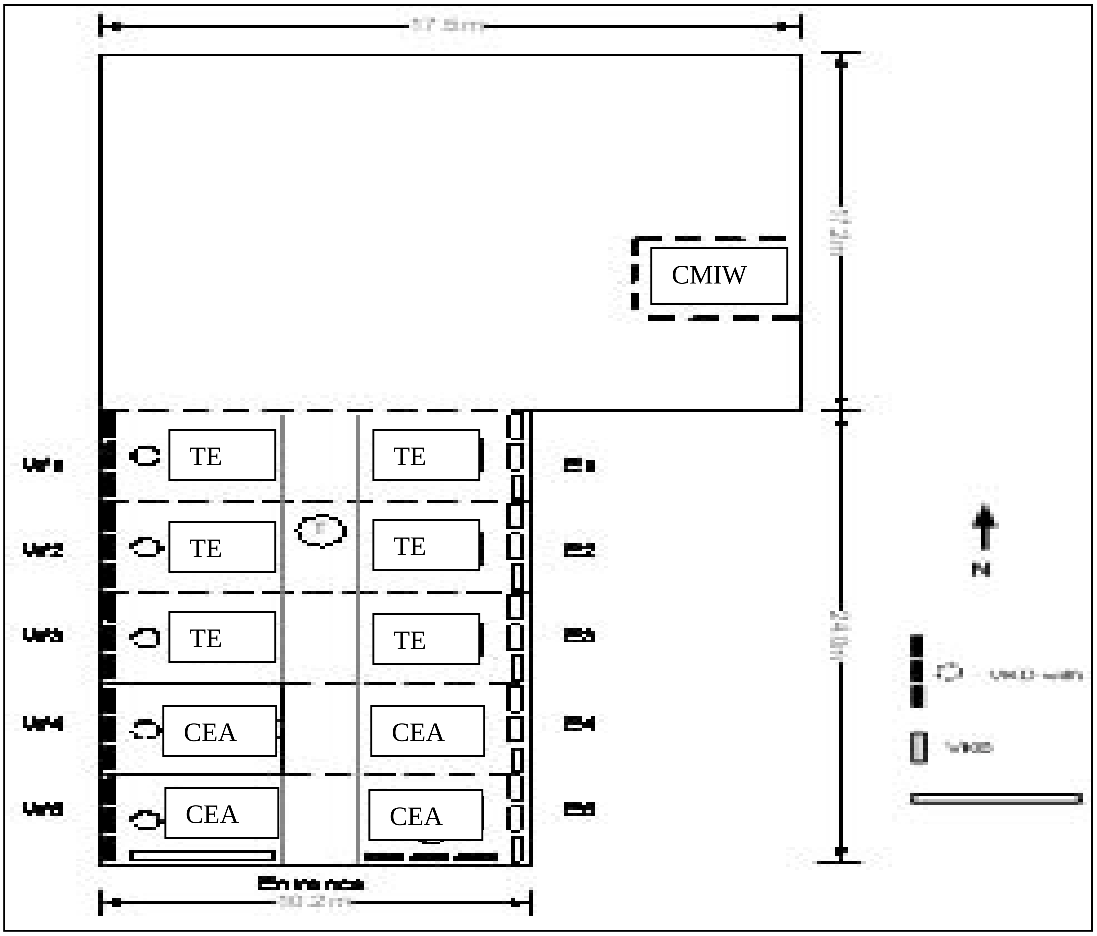

Figure 5 The proposed control system and location of each fan coil unit

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At the time of the writing of this paper Siemens has agreed to the tasks below;

- Training for two graduate students covering the design, installation, programming and daily operation of the supplied products and software.
- Eight hours of onsite assistance with by a technician at beginning of system installation: the technician will review installation requirements with installers and give guidance.
- Three copies of submittal information showing system architecture, wiring methods, part information, and user guides.
- Eight hours of onsite startup assistance by a technician after system installation is complete. This startup will provide a basic functioning "baseline system" which will allow the fan coils to properly condition the associated spaces.
- Two semi-annual visits for over two years by service technician not to exceed four hours each to review system performance and adjustments as necessary

We access to this information which constitutes the early stages of Cx. This is invaluable information for us since design intent and early design information of mechanical systems has been very difficult to document in our earlier attempts, due to the notoriously frequent loss of design information. Currently, we are working with the design teams in IW and Siemens to document this activity from design intent to occupancy.

LESSONS LEARNED

The lessons we learned from this work fall under three categories:

(1) <u>Adapting standard FPTs to specific facilities and their design intent:</u> Standard FPT descriptions are often good representations of the "normative." They describe what ought to be done under normal circumstances. Our experience with the radiant mullion system and even the fan coil system indicate that each installation has sufficient number of peculiarities to require a significant adaptation to the specific context. This is a non-trivial problem and has been the structural impediment for development of standards, not only in the Cx domain, but virtually for all other domains as well. We realize that each standard FPT should also come with rules of thumb that help its users adapt the FPT to the context in which it is being applied. Each rule would describe a variation from the overall contextual parameters of the FPT; and how the FPT would have to be modified to accommodate such variation. For example, if the FPT requires the measurement of intermediary temperature settings (between 0% and 100%), in a system where temperature variations are being achieved by changing the hot water intake temperature testing only three settings would suffice. In other cases, multiple intermediate setting would be tested.

(2) <u>Common performance retarding system defects:</u> We found that even high-end, low-energy building systems are inundated with mundane performance problems and information availability issues that hamper ECxA. In the IW's mullion system we found that some electrical installation hook-ups were faulty, some equipment had gone out of calibration, design goals were unclear to non-existent, certain factors like differential plenum temperatures were not take into account at all, and control systems were too obscure to debug. Furthermore, many of the installation stage anomalies were never resolved, even though the facility was in continuous use and under monitoring for ten years. This underscores the importance of the ECxA even for low-energy, high-tech buildings.

(3) <u>Implications for data representation in product/process models for FPT implementation</u>: The most important implication of this work for data modeling and exchange is that the bottle neck is in the exchange: that is, exchange from system to human operator, from human to data model, from data model of one phase to another phase, from owner to vendor and back. Substantial data loss (order of magnitude of 70%) is not uncommon (Wong, *et.al.*, 2004). The solution is partially on the court of information and data model builders. But the key to the entire undertaking is in the hands of the Cx agents, designers, and manufacturers of systems and control systems who make and break the standards in the field.

These problems provide guidance for understanding where the difficulties in the manual ECxA would potentially lie. How this influences the computer based applications for ECxA is a future problem on which we are currently working. This effort includes validating our current data model ECx developed by Turkaslan-Bulbul (2005) against the information categories discovered in this work; extending this model to show how it covers new ECx cases; and finally demonstrating that such expansions are achievable with relatively little effort and will cover a diminishing number of attributes or objects per new cases included in the data model.

This paper does not presume to address the added value afforded to the field by our approach or similar ones. This is clearly an important issue which must be tackled but not within the limited scope of this conference reporting.

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