Product and Process Modeling in Cx: A Significant Challenge for Digital-Cx

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ABSTRACT

In the next decade, *digitalization* of commissioning (Cx) is likely to be a key advance, in the field of AEC. This requires that as much of what we do manually, through word-processing and spreadsheets can be done through sophisticated computer applications to enhance Cx productivity. The first step in achieving this is the creation of reliable, persistent, accurate, just-in-time, and easily accessible Cx information. Towards this end we are building a proof-of-concept prototype for functional performance tests (FPT) that can help Cx agents derive *product models* through specifying *process descriptions*.

SCOPE OF WORK

On its website (ANNEX-47, 2008), the ANNEX-47 initiative of the Energy Conservation for Building Commissioning Systems (ECBCS), International Energy Agency (IEA) is defined as seeking "to enable the effective commissioning of existing and future buildings to improve their operating performance. The commissioning techniques developed will help transition the industry from the current intuitive approach to building operation to more systematic operation that focuses on energy savings."

The three year work plan for the ANNEX-47 contains three major tasks: (1) initial commissioning of advanced and low-energy building systems; (2) commissioning and optimization of existing buildings; and (3) commissioning cost effectiveness and persistence. The first task involves three subtasks: a) definition of the information flow in the commissioning process; b) definition of an information model that supports the input and output of information within this flow; and c) the definition of a series of Functional Performance Tests (FPT) for the various systems of low energy buildings, such as heating systems, lighting systems, ventilation systems, etc. The plan is to clearly define the necessary data *inputs* to perform the FPTs and the data *outputs* produced in conducting the FPTs. As part of the process of developing this information flow, it is necessary to define the need to exchange these outputs with other parts of the information flow, thus creating a digital model for Cx information processes.

Using the experience we have gained in building the *Embedded Commissioning* (ECx) approach to HVAC commissioning (Turkaslan, et.al., 2006), we propose to define the information models necessary to support the exchange of information as FPTs are conducted and model a significant set of FPT processes as applications based on the ECx model. When creating this model, we will use knowledge of the FPT inputs and outputs for a number of FPTs and seek to create a generalized representation from these specific cases.

As the Industry Foundation Classes (IFCs) are a data exchange standard that has seen extensive investment and development in the AEC industry, ANNEX-47 must seek to take maximal advantage of this standard and influence the extension of the IFC standard to better support the information that needs to be exchanged concerning these FPTs. Thus, we are also exploring the ways in which IFCs need to be extended to support the exchange of the information contained in the developed information model for supporting the FPTs.

In a previous paper (Akin, et.al., 2007), we described our findings on product modeling and interoperability of FPT protocols, including testing standard FPT with equipment resident in our test-bed, the Intelligent Workplace (IW), review of the literature in Product-Process Mapping (PPM) research, and forging a new approach to PPM.

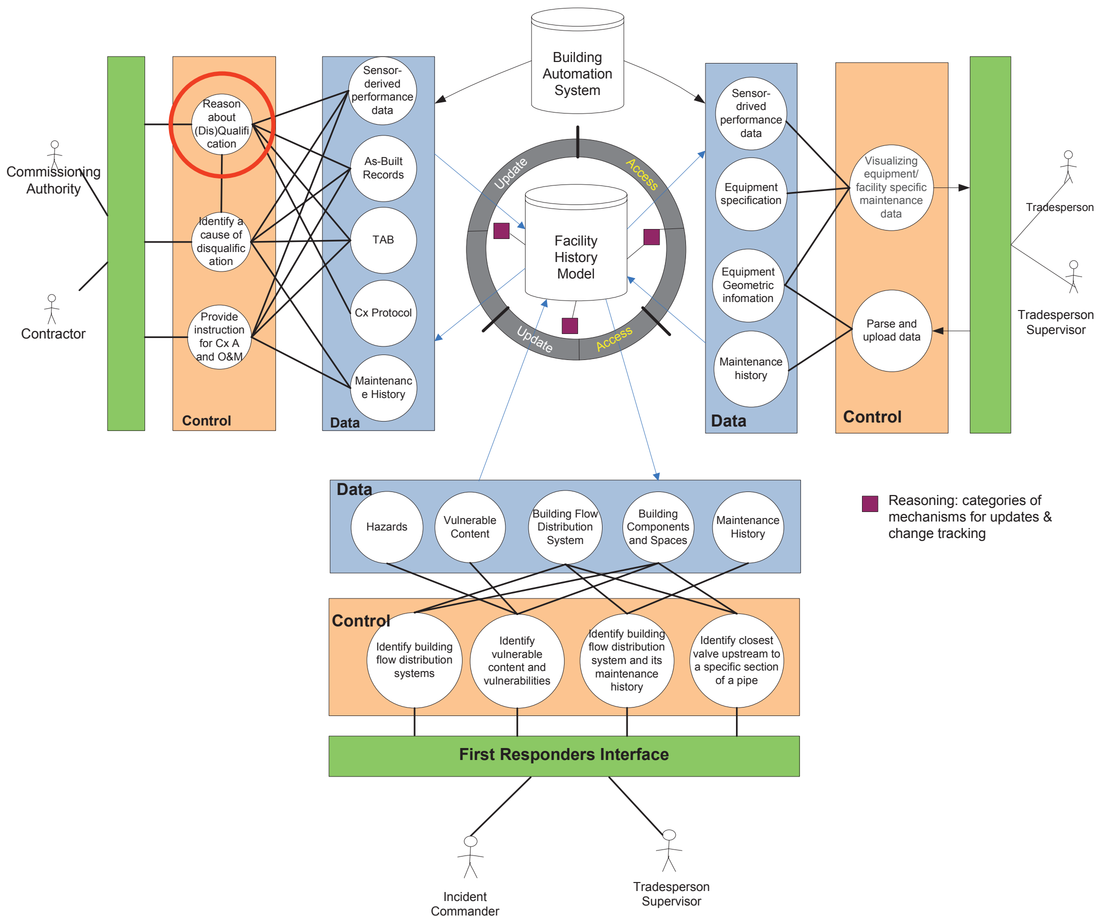

Figure 1: Our larger research project vision

We conduct this work within the framework of a larger vision that integrates a variety of modules, including as ECx, operations and management (O&M) and first response assistance systems within a robust and integrated system of product-process representations (Figure 1). Each module has three layers: a user interface object layer, a control object layer, and a data object layer, which are based on the Model / View / Controller software architecture (Akinci, et.al. 2007). While, in this paper, we describe only the ECx work, we consider the collaboration between these research projects a positive contribution to both the specific research project goals, and to the intellectual development of our research group.

In Figure 1, the Facility History Model database is intended to support operation and maintenance history, daily maintenance service, any information relevant for the emergency response, and the ECx module. For example, during the commissioning of a radiant mullion system, described in a previous paper (Akin, et.al., 2007), one of the valve actuator was found to be missing. The part was removed to be repaired but never returned and no one remembered that it was missing until the commissioning work was conducted. In this case, the maintenance history was essential to complete the ECx process successfully. It is also necessary to record the maintenance work during ECx. This often occurs when equipment is replaced or recalibrated during Cx, and it is decided not to include the fix-up in the Cx report to avoid unnecessary book keeping and promote a less adversarial relationship between the parties. In our case studies, we found many examples for this category, such as a loose power supply line for a valve actuator.

CURRENT APPROACH

We developed a vision for the ECx assistance tool based on the analysis we summarized above and parallel efforts in the O&M field, first response events, and data updating work. Currently, we are also continuing to work on the comparison of the classes of objects derived from all FPT adapted to the IW case study, namely a radiant mullion system, fan coil units, and a roof top (SEMCO) unit. The IW is an advanced, low-energy system laboratory building at Carnegie Mellon University, which provides a suitable test-bed for us. These test cases are the basis of the software development in which we are currently involved.

Our research approach involves conducting detailed case studies, identifying functional requirements and the data items that are needed to support building commissioning, developing prototype systems to validate the usefulness of the identified data items in streamlining the building commissioning process, and to evaluate how current state of the art, widely-accepted data exchange standards support the data flow within the building commissioning domain.

In this paper, we summarize the work we did for (1) formally representing functional performance test procedures (FTP) using IDEF3 diagram format, (2) formally representing the syntax of individual FTP process statements using BNF notation, (3) modeling the semi-automatic process of mapping FPT statements to BNF syntax notation, and (4) modeling the process of semi-automatically building syntactically correct FPT statements based on computable primitive ECx lexicon. In order to formalize the Cx process, we intend to derive the product model from the process model (Figure 2). In doing this, we emulate some of the features we found in the Georgia Tech Product Process Mapping (GT-PPM) work for the precast concrete domain (Eastman, 2002).

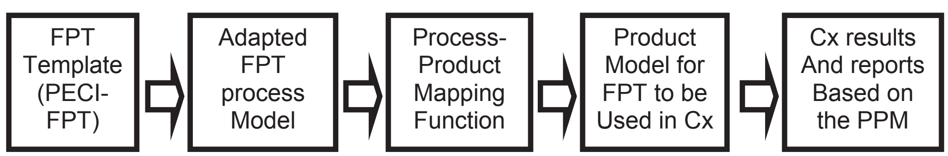

Figure 2: The General Process to Product Mapping model in commissioning

The GT-PPM technology has been used in the pre-cast building sector with considerable success (Eastman, et.al., 2002). In our work we adopted some of the features we found in the GT-PPM approach to the Cx domain. Our approach starts with specifying the process semantics required to elicit process and information necessary and sufficient to derive a product for ECx. We used the Portland Energy Conservation Inc (PECI)-FPT protocols and the standards being developed in ANNEX-47 to obtain a comprehensive scope definition for ECx. We re-codified this information in a machine-readable and computable format. Next, we started building a lexicon for a formal language to capture the semantic information contained by the components in each statement (box-1, Figure 2).

Since manual effort is needed to build-up the various dictionaries and the syntactic notations, we are also developing a semi-automatic approach towards parsing and compiling grammatically well-formed FPT statements, developing syntactic-semantic nets needed to parse process descriptions, and constructing strategies for deriving product models (box-2, Figure 2).

In our next step, we will semi-automatically derive the product models that correspond to the ECx process models, using the lexicon and formal representations developed in the previous step (box-3, Figure 2). We plan to develop and find a way to automate this process using case-based reasoning. Through this approach, a product model representation tailored to each case at hand will be derived (box-4, Figure 2). Finally, we will develop the formatting and mapping functionalities to generate the appropriate documentation for FPT implementation, field instructions, field data records, Cx diagnosis and analysis, and Cx reporting (box-5, Figure 2).

In a nutshell, we start with specifying the process semantics required to elicit process information necessary and sufficient to derive a product description for ECx. We use FPT defined by PECI protocols and the standards being developed in ANNEX-47 to develop a comprehensive definition for Cx products and processes. To date we have re-codified this information in a machine-readable format. Next, we will automate the mapping tasks in order to ease the burden of creating the syntactic-semantic nets needed to parse process descriptions and construct product models. We will test this prototype with practicing Cx agents and refine its features as part of our future work.

Formally Representing FPT Logic Using IDEF-3 Diagrams

An FPT consists of several procedures to check if the system is working as intended, by manipulating the parameters of the equipment. There are sequences described by each procedure that the Cx authority has to follow in order to obtain the expected result. However, as we experienced in our case studies, this sequence of procedures or an individual procedure itself might be modified by the Cx authority according to the specifics of the equipment situated in a new context. In order to accurately specify this modification process in a format suitable for computation, it is important to capture conceptual dependencies between individual statements and automatically represent at least some of the meaning of the FPT procedure. Moreover, the digital tools should express the domain experts' knowledge adequately in order to support the method of modification to be used by the Cx authority.

The IDEF-3 process description is a suitable method for capturing and documenting the FPT procedure (IDEF, 2008). It provides a mechanism adequate to the task of capturing the knowledge a Cx authority may possess. Test procedures and expected or actual responses in FPT contain *precedence* and *causality* relations. The IDEF-3 can show these precedence and causality relations between events in sufficient detail to model the logical basis of each statement.

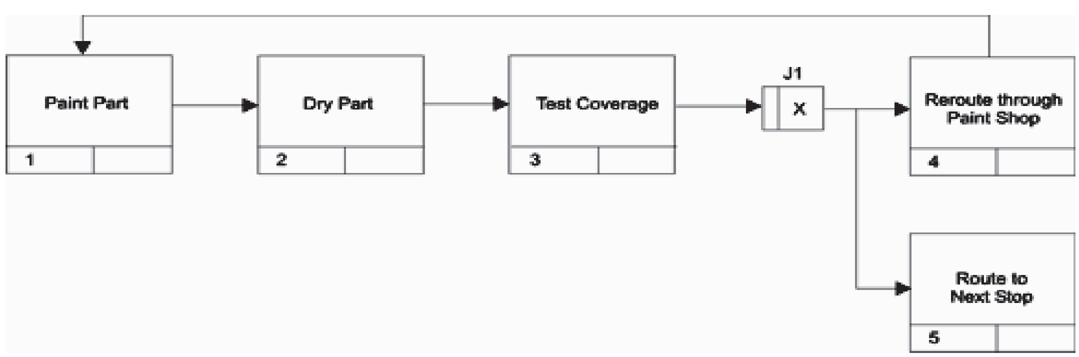

Figure 3. IDEF3 Process Description Diagram

There are two types of IDEF-3 schematics: the process flow description (PFD) and the object state transition network (OSTN). The PFD model captures, manages, and displays knowledge of “how things work” in the process (Mayer et al, 1995). Additionally, the PFD helps domain experts and analysts communicate knowledge by providing a graphical diagram (Mayer et al, 1995). In Figure 3, three IDEF-3 symbols used to express the PFD are illustrated: Unit of Behavior (UOB): labeled boxes describing activities, processes, events; Links (arrows): tie the boxes together, define the logical flows; and Junctions (smaller boxes): mechanisms to specify the logic of process branching.

Alternatively, an OSTN diagram describes processes from the object-centered point of view, which shows all object transitions throughout a process (IDEF3, 2008). Figure 4 is a similar example of the paint shop shown in Figure 3 except in the OSTN diagram format.

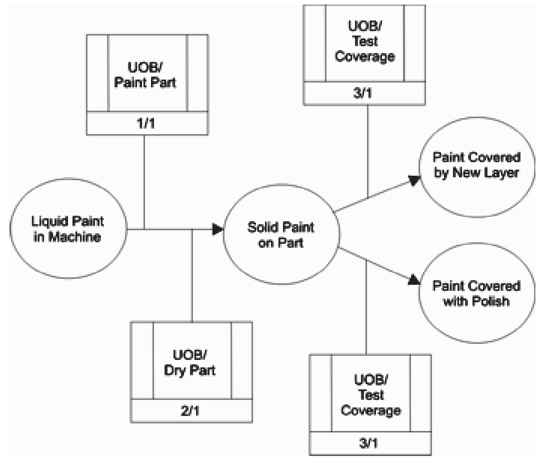

Figure 4. IDEF3 Object State Transition Network Diagram

Table 1. The PECI fin tube FPT protocol

Proced. # & Spec. Seq. ID	Req ID No	Test Procedure (including special conditions)	Expected and Actual Response (write ACTUAL response or circle)	Pass Y/N & Note #
1		<u>General Sequencing.</u> a. With boilers in normal mode and ON, increase space setpoint 20Fof TU- ______ (interlocked to the fin tube). If OSAT is not > 40F, overwrite it to be > 40F. Overwrite space temp to be 3F below main setpoint (cooling) ______F and observe in BAS that there is heating deck flow and cooling flow goes to minimum. Observe that the fin tube or radiant panels remain OFF. b. Change the space temp. to be 5F below main setpoint (cooling) ______F and observe the radiant panels or fin tubes remain OFF. c. Change the OSAT to be < 40F. Observe that the radiant panels or fin tubes start heating. Return all parameters to normal.	a. TU goes into heating mode. Fin tube HCV’s remain closed. b. TU remains in heating mode. Fin tube HCV’s remain closed. c. TU remains in heating mode. Fin tube HCV’s open.	
2		Lower space setpoint to 20F below space temperature of TU-______.	TU goes into cooling mode. Fin tube heating valve closes equally with TU heating command (TU HCV or dual duct heating damper).	
3		<u>Valve Leakage Test.</u> After 1 hour or more with fin tube heating valve closed, verify that no hot water is leaking through valve by feeling fin tube 3 feet from valve.	Tube should be near room temperature.	
4	--	Return all changed control parameters and conditions to their pre-test values	Check off in Section 2 above when completed	

In our research, we do not expect to rely on OSTN diagrams since our focus is not the state descriptions. In this process, we envision that the first step is to read the predefined commissioning protocol, such as the PECI protocol in Table 1 for the fin tube radiant system which needs to be adapted to a radiant mullion system, and to parse it into distinct statements describing sequential steps.

Figure 5 shows the four distinct steps of the fin tube FPT protocol of Table 1, in IDEF-3 format. Test procedure "a" of "Procedure 1," in Table 1 expects that the TU (test unit) goes into the heating mode and the fin tube HCV's (heating coil valve) remain closed. Each sentence or phrase in this text can be semantically interpreted and all procedural statements can be parsed into syntactic constructs. The resulting structure for a complete FPT procedure can be formally represented in the IDEF-3 format and used to automatically create various ECx documents, including the final ECx report.

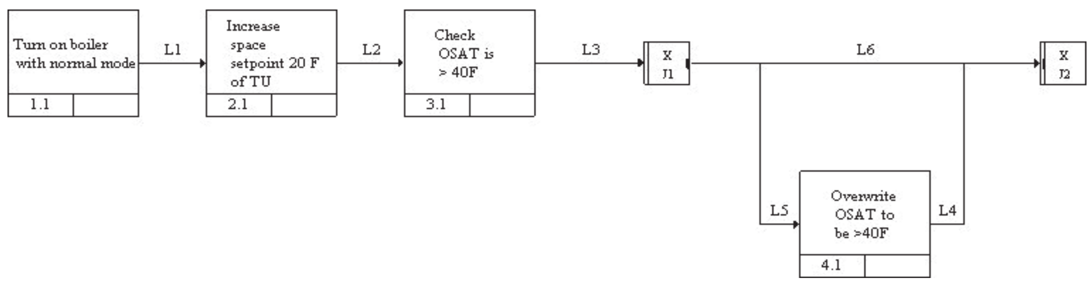

Figure 5. The FPT procedure implementation into IDEF3

For example, in Figure 5, the first sentence of Table 1 "With boilers in normal mode and ON, increase space set point 20Fof TU" was parsed into "With boilers in normal mode and ON" and "increase space set point 20Fof TU." In order to describe the activity in the unit of behavior box, in IDEF-3, "With boilers in normal mode and ON" can be mapped into "turn on boilers in normal mode." After that statement, an "if" statement ("if OSAT is not >40F") is mapped into IDEF-3 nomenclature by using a link and junction to show the logic flow of the process as exemplified. In The smaller boxes containing "X" (Exclusive Or) is the transition junction (for instance, J1) that indicates the choice of exactly one path among several possible paths in an occurrence. The other steps of the fin tube FPT can be interpreted in a similar manner.

Formal notation of the FPT process statements using BNF

This syntactic analysis still leaves unresolved a significant problem – that of formalization for the computer: interpreting each phrase contained in each of the boxes of the IDEF-3 diagram (Figure 5). For this we utilize the Backus-Naur Form (BNF), which is a formal notation to describe the syntax of natural language statements, as well as the grammar of computer programming languages and communication protocols. The role of the BNF notation in our research is to build the ECx lexicon of a formal language for capturing the semantic information of FPT statements (formally shown in the boxes of IDEF-3 diagrams in Figures 3, 4, and Table 1) for each individual system component.

The process models represented by FPT procedures consist of a list of "Test_procedures" followed by a list of corresponding "Expected_result" (Table 1). "Test_procedures" consists of an "Action" that changes the value of attributes in equipment or parts of equipment. This might also involve a "Condition" to set a situation of action or a "Qualifier" to supplement the "Action." The "Expected_result" verifies the expected "Value" of "Attributes" in the equipment based on the “Test_procedures.” This also involves an “Action” to check the result of a test or a “Condition” to satisfy a certain situation. Below we provide an example of a BNF that is developed for the FPT of the fin tube shown in Table 1.

- ProcessModel ::= {Test_Procedure} {Expected_Result}
- Test_Procedure ::= [Condition],<,>, <Action>, Predicate, [Qualifier] , <.>
- Expected_Result ::= [Action], Predicate, [Condition]
- Condition ::= <Preposition>|<if>|<When>, Predicate
- Predicate ::= [Equipment], [Status], {AVP}
- AVP ::= {<Attribute>}, <Value>

  where { } = repetitive; [ ] = conditional; < > = terminal node

Based on above BNF syntax notation, we are developing a commissioning term dictionary, or an ECx lexicon. The prototype application we are developing will initially read a pre-defined protocol, such as the “PECI fin tube protocol.” Then it will parse the protocol into the “Test_procedure” part as distinct from the “Expected_result” part. Then each sentence in “Test_procedure” and “Expected_result” will be parsed as shown below.

- *test procedure ::= boilers in normal mode and ON, increase space setpoint 20F of TU*
  - *if OSAT is not > 40F, overwrite it to be > 40F*
  - *overwrite space temp to be 3F below main setpoint (cooling) ______F and*
  - *observe in BAS that there is heating deck flow and cooling flow goes to minimum*
- *expect and actual result ::= TU goes into heating mode*
  - *Fin tube HCV’s remain closed*

The system will check if there is a “preposition,” “if” or “when,” which can indicate a [Condition] or [Qualifier]. An “And” or “Or” parses the compound sentence into two or more sentences. The punctuation “.” is recognized as a separator between sentences. If a “,” (comma) is encountered at the end of a phrase or a clause, that phrase or clause is considered as a “Condition.” Otherwise, it is categorized as a “Qualifier.”

For example, the first sentence in the fin tube FPT is parsed as shown in Figure 6. The system picks up the word according to the BNF notation and assigns it into each category (item 1 in Figure 6). Then the system checks for errors of commission, which are indicated by changing color or style of font (item 2 in Figure 6). In order to correct this error, the *librarian* (a computer system developer type, who is responsible for creating libraries of properly formatted product models) or *system developer* manually adds the left out phrases into the lexicon (item 3, Figure 6). Since the librarian monitors and corrects the entire decision support process for ECx, we call this a *semi-automatic* process of mapping FPT statements into the BNF syntax notation.

The final results create a Cx term dictionary for the FPT protocol, based on BNF notation as shown in Table 2. Afterwards, the librarian can define each item further by adding a synonym or description in order to develop an organized dictionary.

Table 2. The ECx term dictionary for the fin tube FPT

Equipment	**Status**	**Action**	**Attribute**	**Value**	**Punctuation**	**Preposition**
Boiler Test Unit Fin tube Radiant panel Heating coil valve	goes into should change shut off	increase overwrite observe change	space setpoint OSAT main setpoint	ON 20F normal mode OFF	, (comma) . (period)	with only after below after

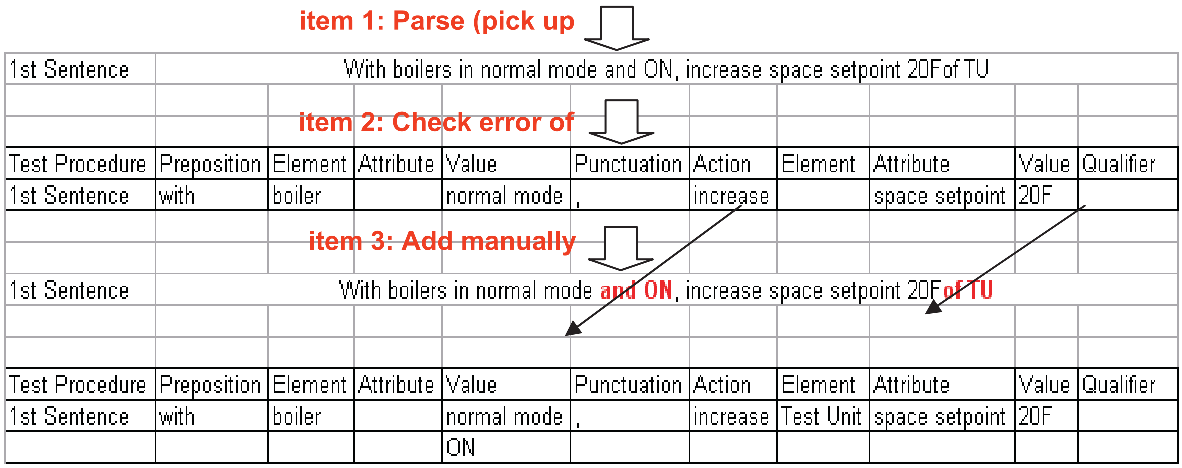

Figure 6. The process of parsing and building a lexicon

Building well formed FPT protocols from computable ECx lexicon

We assume that a computable ECx lexicon can be established from pre-defined FPT protocols, such as the PECI protocols. Using such a lexicon, a Cx authority, or a stakeholder can build his/her own FPT protocols. On the other hand, from the system library, one may retrieve pre-defined, IDEF-3 formatted FPT and modify them using the ECx lexicon.

The potential first step in this process is to select of the values in the *attribute-value-pairs* (values and their parameters like T = 90F) that are changed during the test procedure. For the expected procedure, the Cx authority or the stakeholder chooses the expected value of the attributes. The next step is to identify the equipment of the attributes selected in the previous step. The entire series of steps is shown in Figure 7.

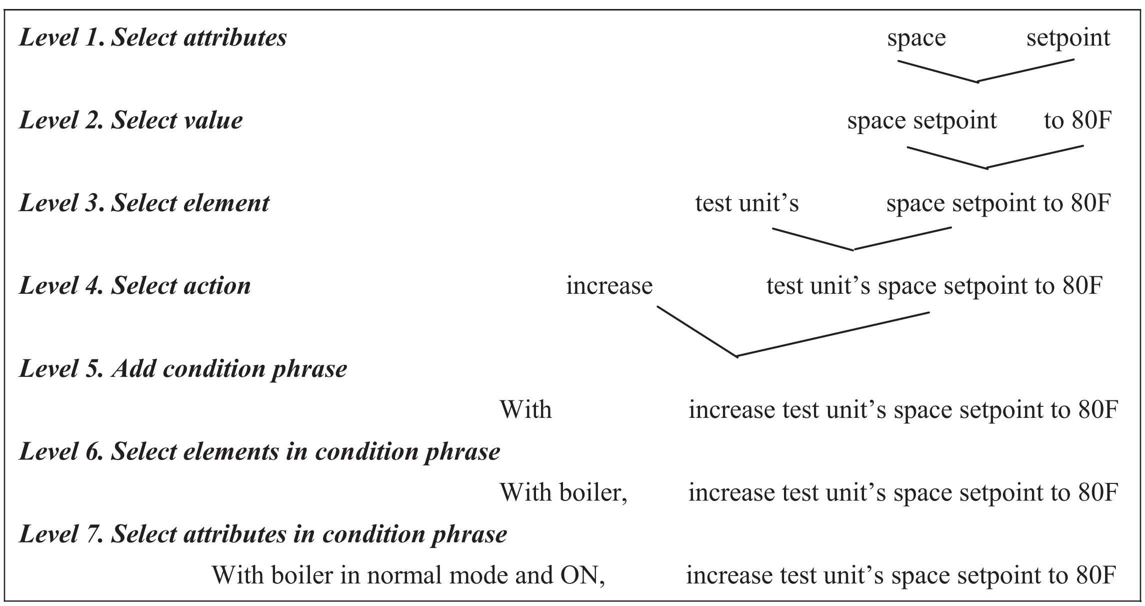

Figure 7. The process of building a Cx procedure from scratch using a Cx term dictionary

Conversely, the user may select elements intuitively from each category in an ECx term dictionary. Since the structure of each category would have been predefined in BNF notation, the manual process of making sentences would tend to be intuitively correct. Otherwise, the errors can be corrected to match the normative syntax of the FPT statements as shown in Figure 8.

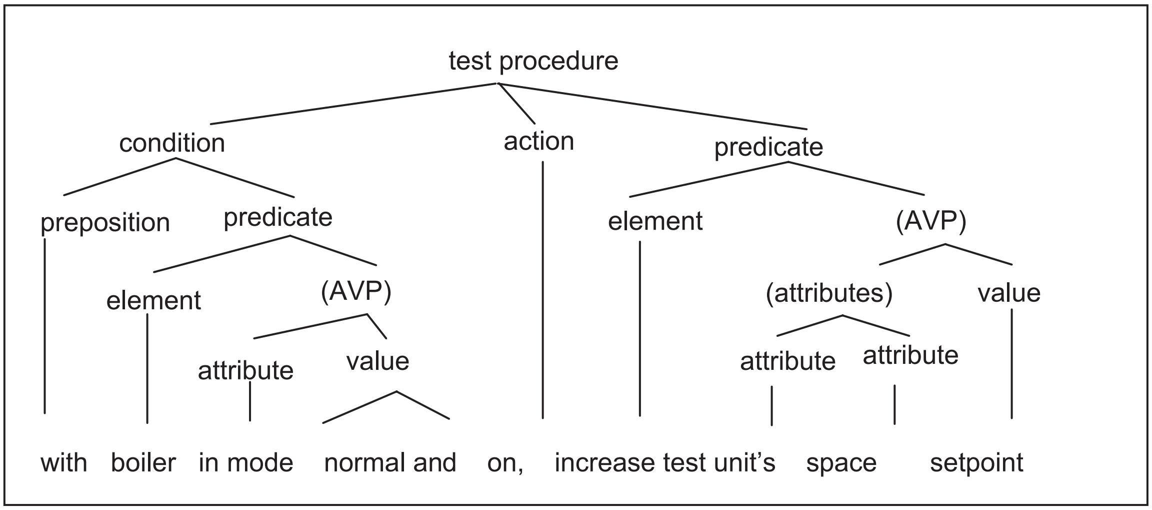

Figure 8. The Structure of an FPT statement using a BNF notation

FUTURE WORK

To date we have defined the critical aspects of making the FPT procedures in ECx operational and computationally represented. We also demonstrated in detail how this goal can be achieved in the case of a specific heating system through actual commissioning. Finally we developed two representational approaches (IDEF-3 and BNF) to forging a technological (semi-automated) solution to making this process operational.

Our future work will utilize the prototype system(s) to be developed to perform validation studies. These studies will target validating the coverage of the prototype to be developed and the usefulness of the approach in streamlining FPT procedures as well as test the exchangeability of our product models with IFC. Given the case studies we developed to date, we will utilize those studies in our prototype application(s) to validate our approach, retrospectively. In order to do this we will:

1. Build a functioning prototype that will enable the Cx authority to construct FPT protocols and corresponding product models in the digital medium.
2. Test the prototype with expert Cx agents constructing new FPTs as well as adapting existing ones for given ECx problems; and build corresponding product models that can automatically produce ECx forms and reports.
3. Diagnose problems and shortcomings of the prototype and its compatibility with international BIM standards like IFCs.
4. Redesign and improve the prototype to overcome the shortcomings discovered.

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