SPECIFICATION AND IMPLEMENTATION OF IFC BASED PERFORMANCE METRICS TO SUPPORT BUILDING LIFE CYCLE ASSESSMENT OF HYBRID ENERGY SYSTEMS

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ABSTRACT

Minimising building life cycle energy consumption is becoming of paramount importance. Performance metrics tracking offers a clear and concise manner of relating design intent in a quantitative form. A methodology is discussed for storage and utilisation of these performance metrics through an Industry Foundation Classes (IFC) instantiated Building Information Model (BIM). The paper focuses on storage of three sets of performance data from three distinct sources. An example of a performance metrics programming hierarchy is displayed for a heat pump and a solar array. Utilising the sets of performance data, two discrete *performance effectiveness ratios* may be computed, thus offering an accurate method of quantitatively assessing building performance.

INTRODUCTION

There have been significant advances in building technologies and control strategies in recent years. However, these advances, coupled with the introduction of tighter building codes have done little to stem the poor energy performance in commercial buildings. As a result, Directive 2002/91/EC by the European Parliament with regard to the essential role of energy performance of buildings was implemented in January of 2003. The directive places demands on owners to quantify the energy usage of their buildings against benchmarks set by government energy/environmental agencies throughout the building life cycle by 2006. This directive places a new onus on the AEC community; to design, construct and operate buildings with improved envelopes and HVAC strategies, to provide adequately ventilated spaces while taking into account outdoor climatic conditions as well as indoor climate requirements and cost-effectiveness.

Unfortunately the fragmented nature of building performance assessment is currently hindering this goal of attaining high levels of building performance over the life cycle. Initial building performance assessment is carried out at the design stage utilising various simulation tools. Further assessments are carried out in the form of commissioning tests, but there is little or no monitoring or feedback once the building is occupied.

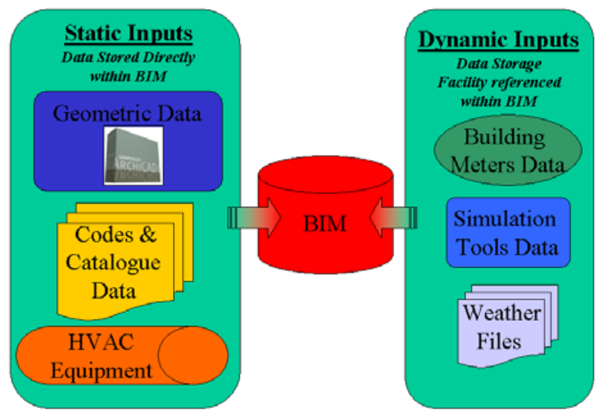

Figure 1 – Schematic of BIM storage facility

Numerous assessment frameworks are being developed to assess the performance of buildings over its life cycle in the US and Europe including ICC (ICC 2000) and BREEAM (BREEAM 2003). However, these frameworks are merely an overall indicator of the building's environmental performance. With virtually every decision made over the life cycle of a building having long and short term performance and environmental consequences; the decision makers require information to assess the consequences of each decision in a timely, cost effective, and practical way. Performance objectives and metrics must be archived in order to offer a means to scrutinise these decisions and provide feedback to the AEC community.

Therefore, the future of sustainable 'performance-based' buildings lies in a 'performance-based' approach to all stages of the building life cycle. A performance-based common building model is developed in order to accurately store the life cycle operation of the building. The paper describes a Building Information Model (BIM) that stores or references building-specific data from various sources (see Figure 1). All BIM data are stored utilising the latest version of industry foundation classes (IFC 2*x*2) data model format. This promising solution offered by International Alliance for Interoperability (IAI), serves as an object orientated description of BIM data to ensure software interoperability in the building industry (IAI 2003). The data model with its standard set of rules for data storage, data exchange and protocols provides an ideal framework to set simulation and energy monitoring requirements of a building.

This paper discusses a strategy for defining a generic set of guidelines for defining performance metrics (in the absence of a standardised set) for unconventional or uncommon systems. These performance metrics are intended to explicitly represent the performance objectives for a building project using quantitative criteria in a dynamic structured format and they are archived in the BIM. The performance metrics coupled with interoperable building simulation tools will enhance building performance by facilitating information transfer throughout the building life cycle. Despite the tools being individually optimised, they are linked by the shared information infrastructure in the form of IFC's with a single overall BIM shared by all participants in a building's design, construction and operation.

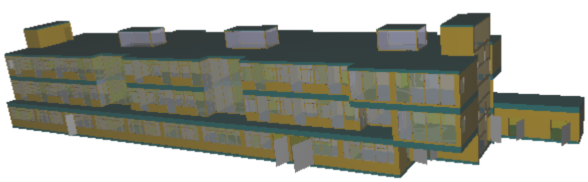

Figure 2 – ERI building

The focus of the research is centred on the operation of University College Cork's "under-construction" Environmental Research Institute (ERI) building in Ireland (see Figure 2). This green building is being designed and constructed with the intention of

- Becoming a flagship low energy building, providing invaluable research information that will contribute to the design of future green buildings in Ireland;
- Acting as a low energy research facility with its design and mechanical services providing the perfect platform to perform intensive energy analysis of a green building;
- Incorporating renewable energies with traditional means of mechanically servicing a building.

The building began construction in March 2004 and final completion is expected in February 2005. It is envisaged that the building will act as a pilot framework for monitoring, analysing and controlling a building's performance throughout the building life cycle. The building will also be used as a pilot demonstration prototype for the processes of performance metric tracking with model calibration.

In keeping with Green Building methodology, the building structure's three floors housing labs, offices and lecture rooms, will reduce energy consumption in two ways:

- Using low energy features such as passive solar architecture, improved insulation levels, improved thermal bridging details, attention to reducing infiltration levels, quality natural lighting and ventilation, and incorporating materials with minimal impact on the environment whenever possible;
- Increased use of renewable energies facilitated by incorporating state of the art ICT, sensor and BMS technology such as a heat pump based heating system, underfloor heating, individual room controls, BMS monitoring system, air heat recovery system, aquifer water system, high frequency lighting, advanced lighting controls and solar thermal collector systems.

DATA STORAGE FRAMEWORK

The framework utilised for this paper is referred to as the Building Energy Monitoring, Analysing and Controlling (BEMAC) framework (O'Sullivan et al 2003). This non-proprietary integrated environment for obtaining, formatting, storing, retrieving and controlling data associated with the building's energy usage is employed due to its interoperability between varying software tools. The Standard for the Exchange of Product Model Data (STEP) and IFC's are employed for transfer and storage of all building related information. This open transfer of data between the BIM and the various analysis tools that communicate with the BIM presents the ideal opportunity to execute building life cycle assessment.

Initial population of the database (Figure 3) begins with input of the building's geometry into the model. This 3-D model is instantiated in the IFC 2*x*2 format and investigated for errors using Solibri's Model Checker™. This powerful inquiry tool prepares the model for intensive simulation by validation of building geometry. The resulting geometric representation of the building may now be instantiated in the BIM.

The next step is to perform an energy simulation for the building. For the purposes of the ERI, this is done via Energy**Plus**™, which is a building energy simulation program for modelling building envelope structure, heating, cooling, lighting, ventilating, usage and other energy flows (US-DOE 2004). The geometric description for the simulation is imported from the BIM using BS Pro COM™ server and its Energy**Plus**™ client. This middleware package simplifies complex IFC geometry definitions into a simpler form in order to communicate with non-CAD tools such as Energy**Plus**™. In describing the HVAC systems, schedules, loads, for Energy**Plus**™ all definitions are input in the text format of *Input Data Files* (IDF).

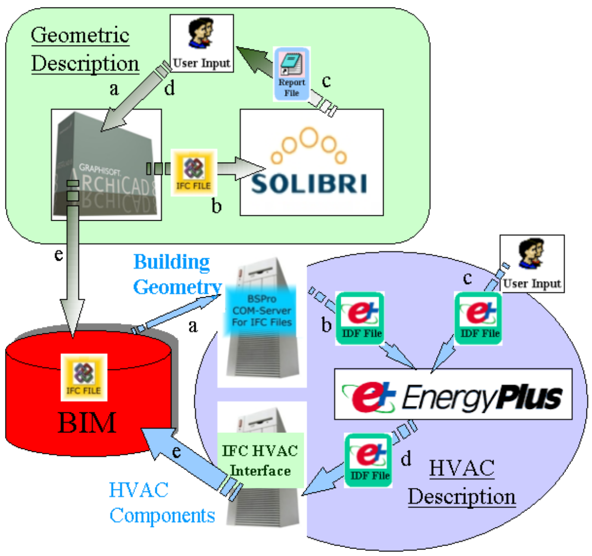

Figure 3 – Instantiating the BIM

Once the simulation model is completed and fully calibrated, it can be utilised to populate the BIM with HVAC descriptions. This is done via an 'IFC HVAC Interface for Energy**Plus**™' (Bazjanac and Maile, 2004). This middleware interface facilitates translating Energy**Plus** input files (IDF) into IFC2x2 files. Finally, storage of the building's performance history must be instantiated in the BIM. This paper describes the procedure for storage and analysis of rich performance history datasets.

PERFORMANCE ANALYSIS TOOL

In order to visualise and display these rich sets of performance data, a performance indicating software tool must be utilised. For the purposes of this work, efforts are focused on development of a beta version of BuildingPI (O'Donnell et al, 2004). This software tool, currently under development, will offer the user a 'view' or a direct visualisation of the performance data for a building that is instantiated in the IFC 2*x*2 format.

BuildingPI is being developed in order to improve decision making at all stages of the building life cycle. This software tool builds on the groundwork and the principles of Metracker™. The underlying concept is that, "to better assure the intended performance of a building, it is necessary to establish a baseline for expected performance and periodically compare actual performance to this baseline. This process requires a standardised yet flexible format for archiving performance data, and sharing these data between various software tools and their users across the building life cycle. Ideally, these performance data are archived with, and related to, other information about the building" (Hitchcock et al, 2003). Utilising IFC's to their full potential, one may prepare a direct quantitative link between design decisions (e.g. selection of system component) and building performance (e.g. minimum energy use). The purpose of BuildingPI is to capture this 'link' and display the associated performance for critical analysis.

As mentioned before, all development work is centred on the BEMAC framework, The hub of this framework is focused around the BIM, as it offers the user a fully interoperable and non proprietary database that may store building specific information and is capable of being queried at all stages of the building life cycle. BuildingPI will be integrated into the BEMAC framework and offer a seamless means of accumulating large quantities of performance data from various sources and prepare a concise report format for ease of analysis. The performance analysis will be achieved by querying an archive of performance objectives and performance metrics that are programmed within the BIM. Once the user has selected the performance metrics, a critical analysis may be performed for all related design decisions and management operations. This will be done through intensive scrutiny of the output, which will be in the form of performance graphs and effectiveness ratios.

Table 1 – Performance Metrics Stored in the BIM

Type of Metric	**Benchmark Metric**	**Simulated Metric**	**Measured Metric**
Source of Data	Building Codes & Manufacturer's Catalogues	Simulation Package(s)	BMS

As illustrated in Table 1, three discrete definitions of performance metrics data are to be stored and referenced within the BIM. This leads to large sets of data that must be elicited at various stages and from various sources. Due to the dynamic nature of performance analysis, these rich sets of data need to be accumulated and stored in a structured and easily navigable facility. In the author's opinions, storage in a single IFC 2*x*2 database would lead to a model that would be oversized and unmanageable. This would hinder the framework's adoption among the AEC community. Performance metric data will be broken up and separated from the main model with storage occurring in XML 1.0 files. These data description files are dynamic in nature and fully extensible. Historically, electronic document formats can and do become outdated. The authors argue that, because of the open nature of XML, the evolution of this schema should not invalidate the previously defined entities and they may be queried at any stage, even as the IFC schema versions evolve. This major benefit dictated the use of these files for performance data storage. As seen in Figure 4, the XML files may be referenced within the BIM and their associated sets of data may be elicited from a database in order to analyse the performance of the building.

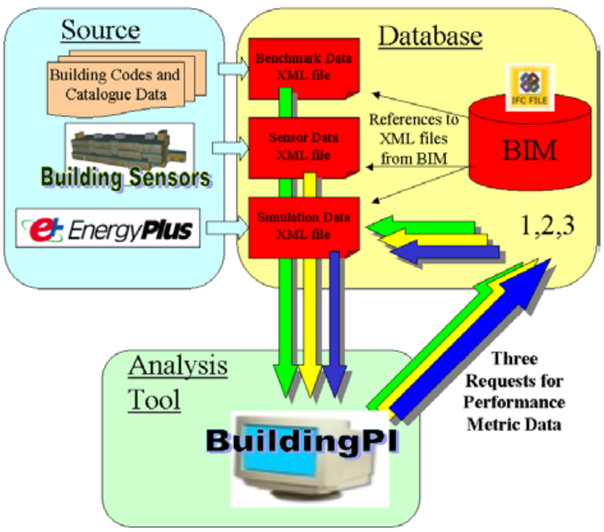

Figure 4 - Conceptual model of framework surrounding BuildingPI tool

EFFECTIVENESS RATIOS

Historically, the most common performance metric for whole building energy consumption is 'energy use intensity' (EUI). However this metric with its mean or median value tends not to be a discriminating metric for comparison of buildings (Federspiel et al 2001). Federspiel et al propose model-based benchmarking for lab facilities and introduces effectiveness ratios for comparison work that penalise buildings with inefficient systems. These ratios however, tend to be biased towards lab buildings incorporating low percentage of non-lab space. This is due to the assumptions and imposed penalties made during the computation process, which include 'no energy storage' and 'no conduction between spaces'. While this assumption is valid in large lab spaces, it is not applicable for the ERI building or buildings that incorporate large areas of non-lab space contained within the floor plan.

As illustrated in Table 1, three unique sets of performance metrics are to be stored and may be elicited in order to quantify the performance of the building. The first set of performance metrics serves as benchmark metrics. These data values are computed from an energy simulation package such as Energy**Plus**™. They are code-compliant with adequate thermal comfort; representing the minimum amount of energy required to meet the basic functional requirements of the building over a typical climatic year. The individual zones are sized and these simulation outputs are HVAC-independent. In order to compute the first of our effectiveness ratios, a second set of performance metrics are required in the form of the actual energy use. These performance data are elicited from building sensors via the BMS. With these two performance metrics in place, the first effectiveness metric ratio may be computed. It is the Idealised Effectiveness Ratio (I_r), which is computed by dividing the benchmark metric by the measured metric (Table 2). The resulting benchmark metric is fundamentally different from the model-based benchmark introduced by Federspiel et al. The building as a whole is analysed and it is unconstrained by percentages of lab and non-lab space. All building and zone-specific codes regarding adequate ventilation, lighting levels etc for each specific area may be applied for the model. This effectiveness ratio can be used across the industry for comparison with effectiveness ratios of other buildings incorporating comparable performance monitoring techniques.

After initial comparison of the building with various other buildings, one may wish to improve on-site systems performance. The Idealised Effectiveness Ratio (I_r) does not reflect to what extent the installed systems are performing. The method of baselining may be incorporated, which involves a comparison of current energy use with historical energy use for the building. However, it is difficult to measure the extent of inefficient system performance due to changes in climatic conditions, zone operation, plug and load, lighting levels, ventilation requirements etc. This highlights a requirement for a system-dependent performance effectiveness ratio, thus the second effectiveness ratio (Performance Effectiveness Ratio (P_r)), is computed by dividing the simulated metric by the measured metric (Table 2). The data used to populate the simulated metrics are elicited from a calibrated simulation package that emulates the building and its components. These performance metrics *are* HVAC-dependant and they offer the idealised energy performance level available for the installed systems. This new ratio is solely used as an indicator of the installed HVAC component's performance. This effectiveness ratio (P_r) can be used as a management tool that may be utilised to incorporate improved thermal building management as the set of simulated performance data offers the idealised performance level for the installed components. It should be noted that this technique is not baselining due to the fact that it uses real-time weather data input for the simulation model. Higher values depict levels of higher performance, and the values should range between 0 and 1. New management operation techniques may be incorporated and tested in the simulation model using this technique, resulting in an efficient form of management analysis.

Table 2 – Computed Performance Ratios

Name	Symbol	Source
Idealised Effectiveness Ratio	I_r	$\frac{BenchmarkMetric}{MeasuredMetric}$
Performance Effectiveness Ratio	P_r	$\frac{SimulatedMetric}{MeasuredMetric}$

With these improvements, the activity of benchmarking different buildings using comparable techniques will have a large impact on performance and lead to increased profitability for businesses that use efficient HVAC systems with improved operation management. The 'Idealised Effectiveness Ratio' offers the ideal building, which can be used for comparison purposes; the 'Performance Effectiveness Ratio' offers a means to attain this ideal through efficient scrutiny of the installed systems.

PERFORMANCE METRICS

As mentioned before, design intent is usually represented in a qualitative form and appears as a series of performance objectives that are initially generated during the early phases of design and may be revised or altered to reflect the life cycle variations of the building. However, these text-based documents tend to gather dust or get misplaced as the building's life cycle evolves. This makes it difficult to compare energy use in varying buildings given the variety of building-specific, code-specific and location-specific services. Thus there is a need for the objectives to take on a quantitative form of performance metrics with target values for the system. These performance indicators are stored within the BIM for ease of retrieval and reference. All system components may be associated with archives of performance objectives and performance metrics in order to assess the performance of their related design and operation decisions. Standardised performance metrics offer a clear and concise manner of depicting a wide set of performance objectives and facilitate analysing the success of HVAC design decisions along with the overall performance of the building and meaningful comparison of building performance with other dissimilar buildings.

Defining Performance Metrics for Unconventional Systems

Despite recent efforts to develop sets of performance metrics (A-Team, 2001), many system components remain without standardised sets of performance metrics. Therefore, in some buildings where unconventional or unique components are incorporated into the system, design teams must program sets of performance objectives and performance metrics in a dynamic and structured manner to facilitate system performance analysis.

The procedure of breaking down generic and abstract objectives into sub-objectives and performance metrics is referred to as programming. A base performance metric must:

- Measure, reflect or significantly influence a particular performance objective;
- Be useful across the entire life cycle of a building;
- Be either predictable or measurable at various stages of the building life cycle;
- Be limited to a concise set of data that are easy enough to collect but robust enough to emulate the objectives in their entirety.

A standard of 'one metric per objective' is adopted for ease of clarity. This is not a rule set by IFC's (multiple performance metrics per performance objective are permitted), however, in the authors' opinions, multiple performance metrics per performance objective could be abused and lead to an un-navigable BIM where clusters of performance metrics become unrelated to it's parent performance objective.

The goal of programming is to define a set of quantitative targets to accurately define the desired performance so that any decisions made in the design or retrofit process may be tracked and scrutinised. Therefore, the following methodology is incorporated while programming:

1. Decide on a set of applicable objectives for the building in consultation with the architect and the engineer;
2. Program (break down) the objectives to a hierarchy that is self explanatory and easily navigable (note: a performance objective is not

necessarily a sum of its constituent performance objectives or performance metrics);

3. Associate a performance metric to explicitly represent each base performance objective using quantitative data.

The methodology will not be adopted across the industry unless the performance metrics are limited to clear and concise sets. In order to assess the measured metric; all additional metering for the HVAC equipment should be modest to avoid unnecessary inflated system's installation costs. However, it should be noted that these sets of sensors offer a means of attaining a fully calibrated model. The process of 'fine-tuning' a model to accurately emulate the actual building is a tedious one. Among the main problems encountered in calibrating energy models is the lack of system component specific indicators. Historically, when modelling a building, if the observed energy use from utility bills does not match the simulation tool's energy use; a certain amount of model adjustments are made on a 'trial and error' basis. However, due to the manipulation of vast quantities of variable inputs, the model encounters a drop in credibility. Component sensor information may be used to calibrate the simulation model that corresponds to the climatic conditions influencing building operation. This component-specific fine-tuning results in a global increase in model credibility and is capable of depicting a precise set 'simulated performance metrics'.

PROGRAMMING EXAMPLE

For the design of the ERI building, there are two HVAC components that currently lack sets of standardised performance metrics, namely an open source heat pump and a solar array. An overall performance objective for the heat pump and the solar array might be that the "Heating Equipment Operate Efficiently". However, in order to achieve this very generic statement, the objective must be programmed into subsets of multiple performance objectives and metrics that influence the statement's overall satisfaction.

For the heat pump, the coefficient of performance (COP) is the best performance indicator. The heat pump is an open source heat pump that uses an aquifer as a heat source. The COP is the ratio of heat delivered to the building and the electrical input, (i.e. 'heat out / electrical in'). The percentage of time that the heat pump is being used is also of importance when analysing the benefits of incorporating this green technology into the HVAC system.

For the ERI building, the control strategy for the solar array is slightly more complex than the heat pump. First priority is given to domestic hot water. Any spare heat is allocated to preheating the aquifer water for the heat pump. However, sometimes, during the colder periods in the Irish climate, the heat generated may also be utilised when there is not enough heat at a high enough temperature to heat the domestic hot water, therefore a small preheat may be initiated for the heat pump. We will use the overall energy gathered by the panels (kWh/m^2) as the solar panel's performance. The high temperatures leaving the solar collectors will induce large heat losses, the ratio of 'collected energy / utilised energy' gives a good indication of how well the collected energy is being utilised in the system. We would also like an indication of the solar panel efficiency using the ratio of 'total solar radiation at the panel angle / total collected'.

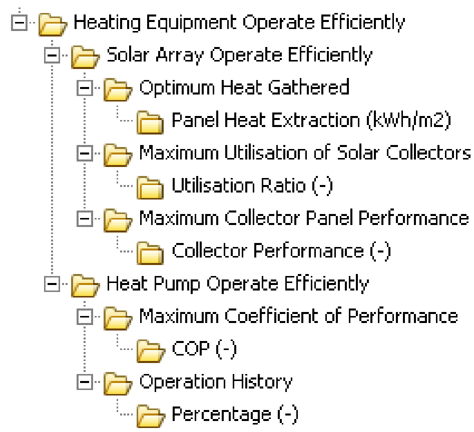

Figure 5 – Performance Objectives and Metrics Programming for the Heat Pump and Solar Array

Due to the large sets of data that will require generation and prior elicitation from the sensors and the simulation tools, programming in this case is confined to five performance metrics. The defined data is robust enough to quantify the performance of both components.

PERFORMANCE DATA IN THE IFC DATA MODEL

The IFC data model is divided into four layers containing definitions that represent not only the tangible elements such as walls and doors, but also concepts such as schedules and constraints. In the IFC 2*x*2 data model, the notions of type, occurrence and performance history were introduced in the building services model architecture. Type and occurrence data are static data; they describe the manufacturer's data along with the local placement and connections within the system (Bazjanac 2002). The dynamic data associated with the performance history entity is used to store state-specific properties that are updated continuously at regular and irregular intervals from the BMS and simulation packages.

The performance data schema provides the specification of constraints that can be applied to objects so as to limit or bound their values (e.g. a pump, chiller, heat pump etc). Constraints may be applied to objects or properties in the model using relationships and associations. The definition of a constraint consists of:

- The name of the constraint;
- A description that may apply additional information about the constraint (optional);
- How the constraint applies (i.e. advisory, hard, soft etc);
- Source of the constraint such as BMS or Energy**Plus** (optional);
- The person or organisation that has created the constraint (optional);
- Time when the constraint was instantiated (optional).

The definition of an objective inherits the constraint's definition along with:

- A list of any benchmark metric values used for comparison purposes (optional);
- A list of any resultant values used for comparison purposes (optional and used for simulated or BMS data);
- Enumeration that qualifies the type of objective constraint (e.g. code compliance, design intent etc);
- A user defined description that qualifies the type of objective constraint (optional).

Like the definition of objectives, the definition of an IFC metric inherits properties of constraints along with:

- An enumeration that identifies the type of benchmark data (e.g. less than, greater than, equal to etc.);
- Reference source for data values (optional);
- Value with data type defined by the data type enumeration.

Using this definition logic, it is possible to update the performance objectives and metrics in the BIM and link them to their respective system occurrences in the model (Figure 6).

By associating a reference within the IFC file with the base performance metric, rich sets of data may be accessed in XML files. A particular performance metric referenced from IFC's is explicitly 'tagged' within the XML file. These tags contain time stamps along with the associated value. They also contain a tag reference for all the system components influencing the performance metric in order to aid systems analysis.

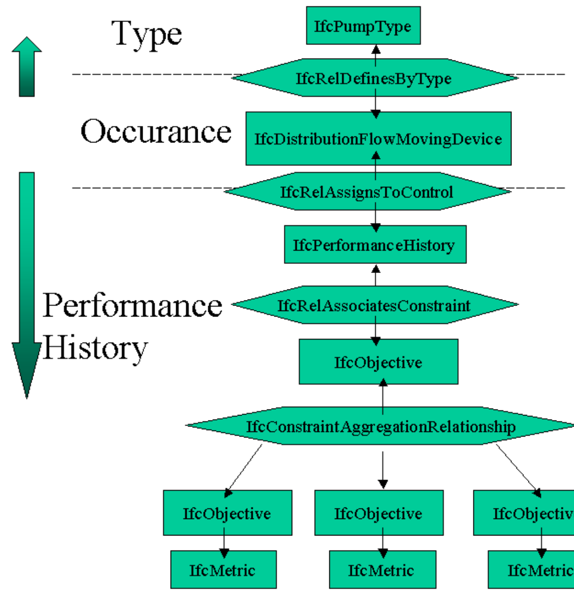

Figure 6 – Low-level example of applying dynamic Performance Data to the static entity of a Pump in an IFC 2x2 data model

CONCLUSIONS

Performance metric tracking offers a clear and concise opportunity to capture design intent in a quantitative form. With virtually every decision made over the life cycle of a building having performance and environmental consequences of both long and short term, the decision makers need information to assess the consequences of each decision in a timely, cost effective, and practical way. The tracking of these performance metrics is the key to sustainable design and offers a linkage of information as the building life cycle evolves. The IFC based BIM serves to document myriad assumptions behind these design decisions.

In the absence of standardised metrics for a component, a personal set of performance objectives and metrics may be programmed and instantiated in the data model offering the ability to archive and share performance and product data for improved building management and thus minimising energy use.

In order to assess the performance of the building, one can consult effectiveness ratios. These building effectiveness ratios offer two distinct methods of scrutinising the building's performance. Since the functional requirements for the building are incorporated into the Idealised Effectiveness Ratio (I_r), it is possible to compare the performance of dissimilar buildings. The Performance Effectiveness Ratio (P_r) completes the set of tools required to improve operations management, as it is system-dependant. Various operations techniques for the installed systems may be tested in the calibrated simulation model, resulting in an efficient form of management analysis and an overall increase in building performance.

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