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| ***Authors(s)*** | Corry, Edward; Pauwels, Pieter; Hu, Shushan; Keane, Marcus; O'Donnell, James |
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# A performance assessment ontology for the environmental and energy management of buildings

Edward Corry[a], Pieter Pauwels[b], Shushan Hu[a], Marcus Keane[c], James O'Donnell[a]

[a] *School of Mechanical and Materials Engineering,*
*Electricity Research Centre,*
*University College Dublin, Belfield, Dublin 4, Ireland*
[b] *Department of Architecture and Urban Planning*
*Ghent University, J. Plateaustraat 22, 9000 Ghent, Belgium*
[c] *Informatics Research Unit for Sustainable Engineering,*
*National University of Ireland Galway, Galway, Ireland*

## Abstract

Narrowing the performance deficit between design intent and real-time environmental and energy performance of buildings is a complex and involved task, impacting on all building stakeholders. Buildings are designed, built and operated with the use of increasingly complex technology and throughout their building life-cycle, produce vast quantities of data. However, many commercial buildings do not perform as originally intended.

This paper presents a a dual strand approach to the performance gap problem, describing how heterogeneous building data sources can be transformed into semantically enriched information. This data can serve as a data service for a structured performance analysis approach, at the enterprise level. A performance management framework is described which builds on the semantically enriched information. The performance framework is an approach to performance management which describes performance in a series of objectives which can be evaluated against performance data. The demonstrator illustrates how heterogeneous data can be published semantically and then interpreted using a cross life-cycle performance framework approach.

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*Email addresses:* `edward.corry@ucd.ie` (Edward Corry), `p.pauwels@uva.nl` (Pieter Pauwels), `shushan.hu@ucd.ie` (Shushan Hu), `marcus.keane@nuigalway.ie` (Marcus Keane), `james.odonnell@ucd.ie` (James O'Donnell)

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## 1. Introduction

Energy is a key issue in a global context and buildings account for roughly 40% of global energy use [1]. Buildings do not operate efficiently [2]. There are very strong economic [3], social [4], environmental [5] and legislative [6] mandates to improve the environmental and energy performance of the existing building stock and to ensure new construction meets more stringent performance requirements.

A recognised performance gap exists between design intent and actual performance in the architecture, engineering and construction industry (AEC) [7] and performance often deviates from design intent by a factor of 2 [8, 9]. Buildings specifically designed to perform optimally regularly fail to meet expectations [10].

One of the key factors affecting building efficiency relates to information management and use throughout the building life-cycle (BLC). Building data is usually retained in domain and application specific data formats. A cornerstone of improved building efficiency is improved data interoperability, the ability of data and applications to interact and a strong case has been made for the use of cross domain data [11, 12].

Hitchcock characterised the BLC as a long-term decision making process [13]. From the initial planning decision to the final decommissioning stage, choices are made which impact on the building. He described how a decision making process which involves diverse participants, changing objectives and a long time-span, required systematic information management and yet the flow of information was generated and transformed in the context of disconnected islands of information.

A data explosion is taking place, with 90% of all digital data having been produced in the past two years, with most of it unstructured [14]. Many of the devices which produce this data are found in buildings or are portable in nature and used by building occupants. In terms of creating, capturing and transforming digital data, the buildings industry is at a tipping point, where it can now transform data in ways that were not even imagined a decade ago. Cross-domain analysis of data is beginning to emerge and new technologies and ideas such as Semantic Web, Big Data, the Internet of Things, Cloud computing and Machine to Machine communication have the capability to deal with and transform these and other types of data in a useful manner.

This research illustrates how a greater use of the available data sources in a building can lead to improved efficiency levels and illustrates how some of the barriers to improved cross domain data use might be overcome. Buildings are not operating effectively, despite a generation of research into the issue and buildings are consuming an enormous and ever growing amount of energy. As was the case 20 years ago [13], decisions are still made in the absence of key information, throughout the life-cycle and the full impact of decisions is often unclear [15, 11, 16].

This paper describes a path to a more holistic building performance management structure, based on key cross life-cycle analysis techniques, driven by a focus on semantic data sharing. Based on this research, cross life-cycle metric analysis is now possible, providing measurable key performance indicators from design to demolition.

The paper is structured as follows:

- The case for semantic web technologies in building performance management is made in section 2;
- The publishing of AEC data using Semantic Web Technologies is described in section 3;
- A concept implementation is provided in section 4.

## 2. The case for semantic web technologies in building performance management

Significant issues surround the transfer of data in the AEC industry. AEC data tends to be restricted to heterogeneous data silos and is rarely used outside its original domain [17]. The lack of interoperability in the industry is felt throughout the building life-cycle. The interoperability problem manifests itself in different ways, including financial [17], communication and ultimately building performance.

The Building Information Modelling (BIM) approach has addressed the interoperability issue in some ways, particularly during the design and construction phases, but operation has yet to be addressed in detail. BIM can be seen as a central repository of building data, for use by all project stakeholders, across the project life-cycle. However, within the wider-context of the organization BIM is only one silo of information and other relevant information must also be utilized to optimize both the building and organization itself [18].

The performance gap is a significant issue which in part emerges from poor data interoperability.

### *2.1. Performance Gap*

A number of studies illustrate the multi-faceted nature of the performance gap problem. The PROBE studies describe how predictions can be unrealistically low [19], due to inaccurate design assumptions and modelling tools, while issues surrounding management and controls, occupancy behaviour and build quality can lead to poor actual performance levels.

The CarbonTrust [20] have listed some of the common faults experienced as inadequate predictions at design time, poor communication of performance intent from the design team, inadequate testing of design, overly complex building systems and controls, poor construction practice, inadequate commissioning, poor measurement approach and incorrectly operated buildings. These issues span the entire building life-cycle.

The ZeroCarbonHub [21] identified similar issues in the area of new low carbon home construction. Acknowledging a lack of study in the area, an undeniable issue existed, caused by insufficient technological understanding, industry culture, poor integration of energy and carbon performance in the design phase and poor feedback mechanisms amongst others. Bordass [22] points to the gap resulting from slippage occurring throughout the development life-cycle from initial design assumptions, ending in a poorly performing building a distance away from the original assumptions. De Wilde, in the most recent review of this area, suggested the performance gap was evident throughout the BLC [7]. ARUP describe the issue similarly, as a gap that increases throughout the life-cycle and suggest solutions must take the form of a feedback loop, feeding back to design and feeding back to operation [23].

A key observation from these studies is the absence of a cross life-cycle performance management approach in the AEC industry. The Performance Framework has been proposed as a holistic approach to building performance and is discussed in the following section.

### *2.2. The Performance Framework*

The holistic management and maintenance of facilities is a multi-domain problem encompassing financial accounting, building maintenance, facility management, human resources, asset management and code compliance, affecting different stakeholders in different ways [18]. Breaking performance down into a series of measurable components and employing a comprehensive continuous commissioning strategy has been shown to improve building performance dramatically [24, 25].

The performance framework is an approach, which describes a clear relationship between a specific building objective, an associated metric and data stream. The approach has been described in greater detail in [26, 11]. A quantifiable metric can be described to evaluate a particular aspect of performance and that metric can be explicitly linked to a relevant data stream. In this way, overall building performance can be broken down into constituent parts and measured. The scenario modelling technique is built on the concept of performance being broken down into quantifiable metrics, which can be evaluated across the life-cycle.

The concept is illustrated in figure 1. The image describes how specific performance measurements can be assigned to performance metrics and then related to building objects, such as zones, rooms, HVAC equipment and so forth. These metrics can then be evaluated against actual or simulated performance, providing the building manager with focussed, relevant information about building performance at a granular level.

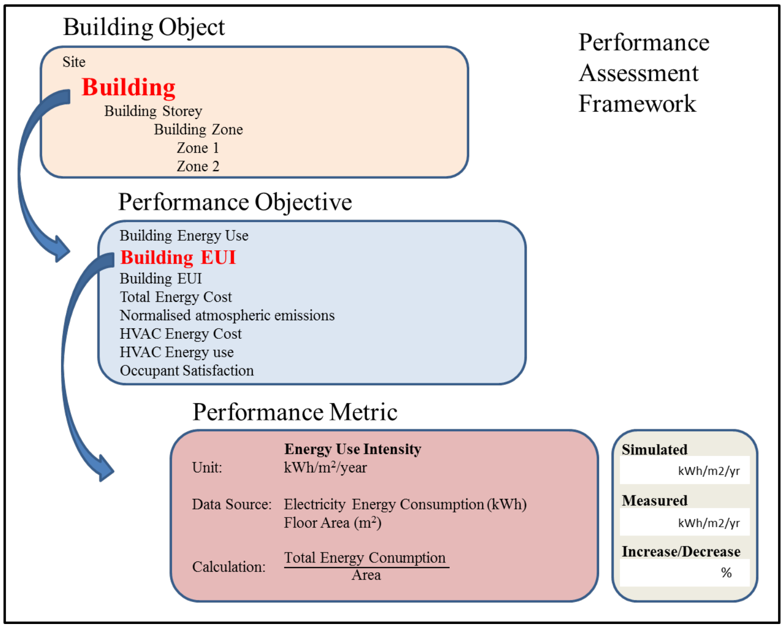

Figure 1: Performance objective linking specific building object to a measurable objective and associated data streams. The performance assessment application combines several of these objectives into a scenario model in order to holistically interpret performance

Several examples of the performance framework in use are available in [11, 26] and a general description of performance metrics is provided by [27, 15, 28].

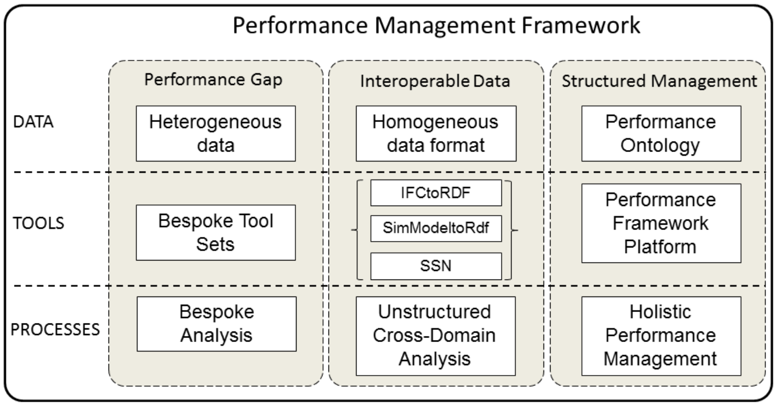

Figure 2: Concept diagram illustrating the transition required to move from the current AEC data management approach to a performance framework approach capable of driving cross-domain data analysis efforts.

### *2.3. Using the semantic web to drive performance management*

Figure 2 describes the transformation in data required to move from a current situation of heterogeneous data sources and piece-meal performance analysis efforts to a more holistic interpretation of building performance, based on homogeneous data sets. The first stage of the transformation requires the conversion of AEC data into resource description framework (RDF) format [29], using a series of data adapters. A semantic web based performance framework builds on these homogeneous data sets to provide a more holistic interpretation of building performance.

## 3. Publishing AEC Data using Semantic Web Technologies

Currently, it is possible to describe a range of AEC data in RDF. Much of this data is originally described in native data formats and can be converted to RDF using a range of data converters currently available. For the purposes of this research, we focused on three key adapters and ontologies:

- IFCtoRDF data service [30]
- SIMModelToRDF conversion service [31]

- Semantic Sensor Network ontology [32]

Each of these approaches defines how certain AEC data should be defined semantically. These adapters allow AEC data to be described homogeneously, at the data level, separate from applications and tool-sets.

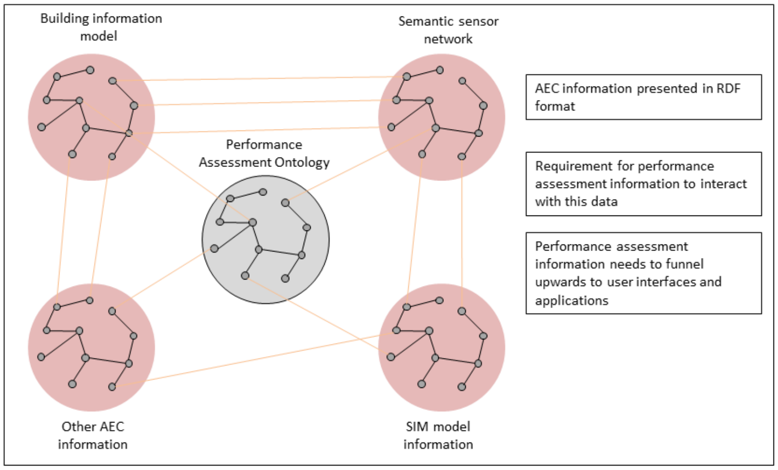

Figure 3: Linking separate homogeneous data sources using a performance framework ontology

Figure 3 illustrates how these separate domains or data sources, presented in RDF format, using a domain ontology can be accessed using a performance framework ontology. In the performance management area, we are interested in accessing information about the building geometry, the building HVAC systems, scheduling information, sensor information and so forth. The circles in figure 3 represent separate AEC data sources, previously described natively, in application dependent, heterogeneous data formats. It is now possible to represent these sources homogeneously.

Performance assessment and management can be driven by key life-cycle performance assessment metrics, but this approach was restricted due to the nature of often inaccessible, heterogeneous data sources. Figure 3 describes how such a performance management structure can now be implemented more effectively, using homogeneous data sources.

### *3.1. The performance assessment ontology and the semantic web*

The scenario modelling process can be considered an enterprise level data integration and analysis function, building on homogeneous data sets. One solution to aid this integration process is to avail of an ontology to define the performance assessment domain and subsequent relationships with other ontologies. The performance assessment ontology describes the assessment domain, detailing how metrics can be defined and related to specific objects of interest. In this work, we are interested in linking various subsets of AEC data together using the performance framework technique. While an ontology such as this is unusual in the AEC domain, the world of business and BPM, in particular, makes use of similar ontologies to drive business performance assessment efforts. This work builds on some of these ideas [33, 34].

### *3.2. Performance Metric Ontology*

Metrics can be considered the most elementary aspect of the performance framework. Pedrinaci described how a metric might be implemented in an ontology [34], albeit in a business process assessment context. Defining the metric is the key element of the performance ontology, from which the remaining elements of the performance framework evolve.

In the performance framework ontology, the metric is the basic building block. The ontological representation of metrics can be categorised into two groups [34], functional metrics and aggregation metrics. Functional metrics are metrics which can be evaluated over a fixed number of inputs or parameters. Aggregation metrics are intended to take an arbitrary number of individual inputs, of the same kind [34], for instance, an average, maximum or minimum, of a set of sensor readings.

Aggregation metrics are computed over a population in order to obtain an overall perception of some aspect of interest such as the maximum temperature reading, achieved using a population filter. The aggregation of data semantically is an extremely difficult proposition and perhaps futile, in that considerable resources are available which can achieve this already. By retaining the aggregation construct, or functional construct associated with a metric in RDF, software algorithms can be used to perform the associated calculation outside of RDF.

Pedrinaci allowed aggregation metrics to have a nested definition where a given function metric could be evaluated over each instance of the population prior to the computation of the aggregation function. This structure allows metrics such as the maximum of the average temperature readings in a facility. An example of a functional metric being used to populate an aggregation metric would be the average daily thermal comfort level in a space. The functional metric is used to compute the thermal comfort level at a given moment in time, while an aggregation metric is used to derive an average of the comfort levels throughout the day.

Performance metrics are used to evaluate performance objectives and these objectives then form the scenario. Quantifiable elements of performance are a necessary component of performance management. Specifically, we are interested in performing calculations on performance data in a repeatable manner, requiring an explicit link to specific data sources. In order to evaluate each metric, a metric assessment relationship needs to be defined, illustrating the links between the metric and associated data. Figure 4 represents the initial placement of the performance assessment framework with respect to sources of data in the wider AEC domain and these relationships are now explored further.

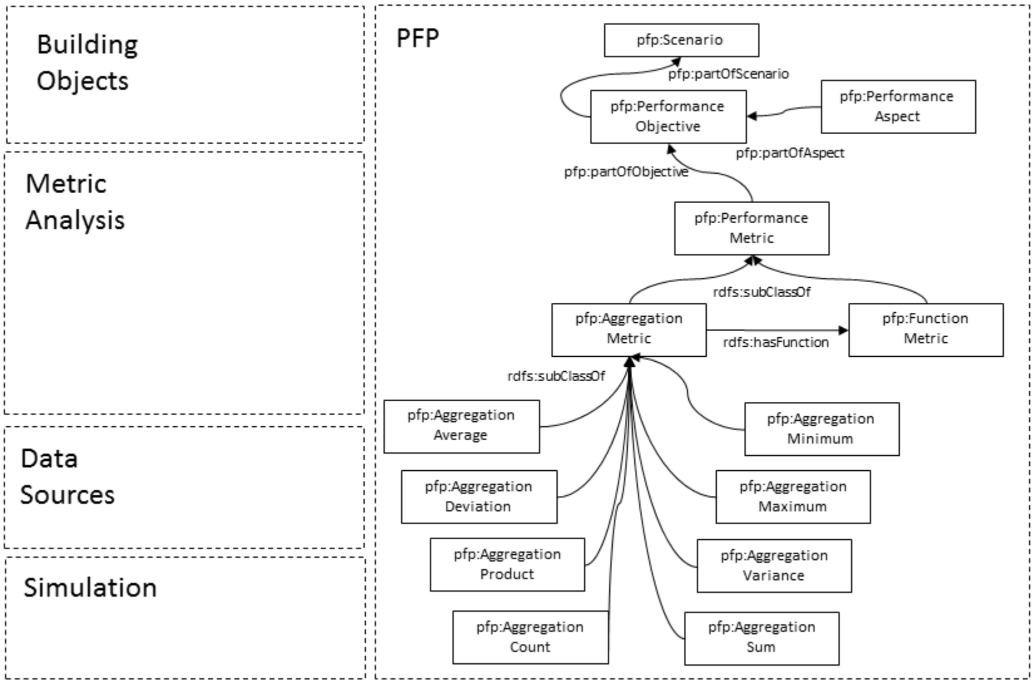

Figure 4: Performance framework ontology and the wider AEC domain

Performance metrics are described in terms of their inputs and the nature of the evaluation required on these inputs. In the case of a functional metric, the associated function is described as a property of the metric, while for an aggregation metric, the type of aggregation is recorded. These metrics are then interpreted and evaluated using the Performance Framework Platform.

List 1 describes on a pseudo-code level, the algorithm used by the performance framework platform to compute the metric. A functional metric might call for some element of calculation to be carried out, based on input parameters, leading to a single value output. An example might be the calculation of an EUI figure for a building. This calculation requires energy consumption levels and building area as inputs (List 1). In this case, the calculation is retained as a property of the metric and evaluated using the Java based PFP. Several performance metrics are defined as part of this work and are referred to in the following sections. Each of these metrics describe a calculation common in the domain, such as the calculation of thermal comfort, energy usage intensity, etc.

Listing 1: Metric associated with energy usage intensity. This metric requires multiple inputs and provides a single output

```
Building Energy Usage Intensity
Input: Total Energy Consumption
Input: Floor Area
Calculation: Total Energy Consumption/Floor Area
Output: Energy Usage Intensity
```

The second type of metric is an aggregation metric, which can be specified to describe a particular aggregation function to be performed on a set of data. In this case, we are typically dealing with sensor output data. The key consideration here is that the data is all of the same type, in the form of a list. A data filter is defined, which filters a sensor data stream, based perhaps on date or time parameters. This filtered stream is linked with the metric instance and associated with the performance metric (List 2).

Listing 2: Aggregation metric associated with total energy use. This metric is required to perform an aggregation function on a list of data, returning a single output.

```
Total Energy Use
Input: List of energy use by source
Aggregation: Sum
Output: Total Energy Use
```

The metric structure, integrated with the performance framework platform, allows for the interpretation of specific sets of numerical data in a structured manner. Interpreting a list semantically is extremely difficult. We can achieve the desired outcome by retaining key information about the data we wish to analyse in the performance metric instance and then evaluating this using the performance framework platform tool.

If we consider a collection of data points gathered in a typical building, say daily dry bulb temperature and we wish to find the average of these data points, we might structure the metric similarly to list 3. In this case, the metric retains a link to the data source in question and a time period. The performance framework platform software interprets these inputs and returning a list.

Listing 3: Aggregation metric associated with average dry bulb temperature. This metric determines an average from a list of data, returning a single output.

```
Average Daily Dry Bulb Temperature
Query Input: Data source
Query Input: Time period
Query Output: List
Data Filter: List
Aggregation Metric Input: List
Aggregation Metric Output: Value
```

Pointing metrics at the data sources involves linking to other areas in the semantic web. The next section describes how metrics, defined using the performance ontology can be linked using the SSN.

### *3.3. The performance ontology and other ontologies*

The observation value used to describe an observation outcome in the SSN ontology serves as an basis for the evaluation of performance metrics intended to measure sensor data in some fashion. Linking to sensor data modelled using the SSN ontology allows us to access all manner of defined properties relating to sensors. The observation value is linked to the performance metric. The nature of this link is relevant. A simple functional metric, with a single input and single output, can be easily modelled, with the metric linking directly to the observation value. A more complex metric, involving a list of data requires the use of a filter, to group population values into a list. This list can then be linked to the relevant aggregation metric. At this stage, there is a clear link between the performance metric, clarity on the nature of the metric and an explicit link to data sources. The scenario modelling endeavour requires further links to be made to other domains of data and these are now explored further.

The performance framework is concerned with relating performance objectives to specific building objects. It is important that objectives can be associated with a particular building object and that data sources are also associated with particular objects or spaces. For instance, for a given zone, we would like to explicitly link to available sensors in that zone. This type of interaction allows for the interpretation of building performance at a much more granular level. A key requirement of the performance framework is that explicit links can be created which illustrate the location of specific devices in the building. For example, if you wish to understand the thermal conditions in a space, you would be interested in the sensor data for the space, the scheduling data for the space and the physical expression of the space. The framework is intended to break down building performance into defined, measurable components or objectives.

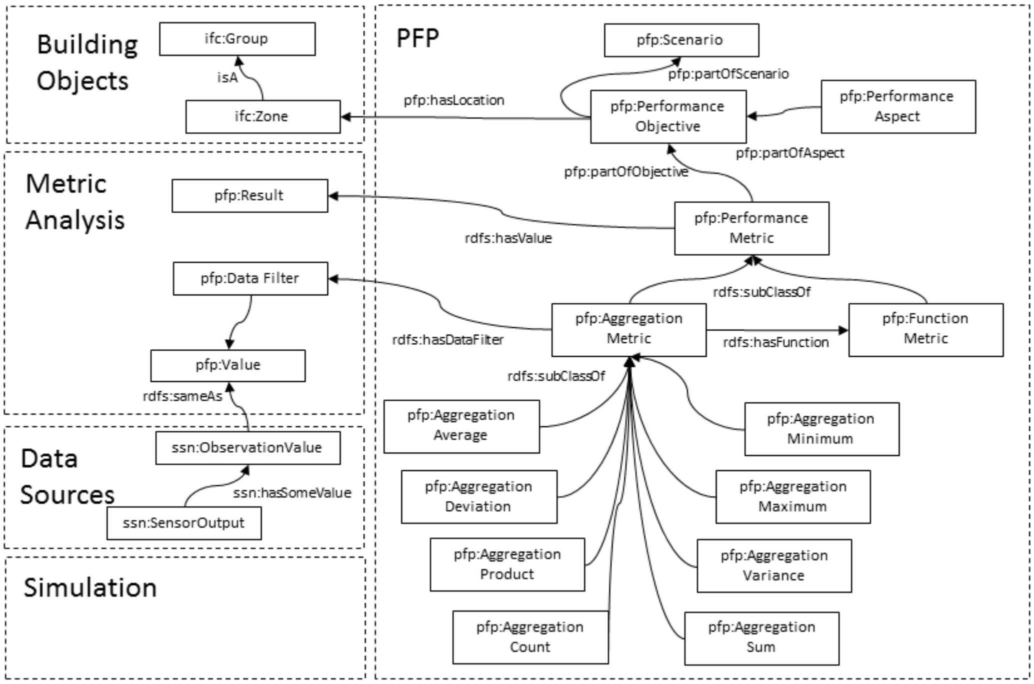

Figure 5: Building objects related to the PFP ontology

We would like to relate specific performance objectives to a relevant building object. The IFCtoRDF ontology exists to enable the description of building information modelling data semantically. For instance, a building zone is particularly relevant in the performance management context. The performance ontology needs to interact with other data sources as a matter of course and this is illustrated in figure 5.

## 4. Demonstration

This section presents an implementation of each stage in the transformation described in figure 2, from heterogeneous, restricted data silos to homogeneous data and a structured performance management implementation. This presentation considers some of the AEC data around the area of thermal comfort and illustrates how this information might be used to provide a greater level of interpretation for the building manager, in a performance management context. The approach outlined in this example provides a more holistic level of performance awareness for the building manager, but the broader cross-domain approach allows for homogeneous data to be used as a service for many different types of cross-domain data analysis. Key information can be provided to other stakeholders at the enterprise level also.

### *4.1. Thermal Comfort*

This demonstration draws on results derived as part of a wider thermal comfort experiment, conducted at the National University of Ireland, Galway [35]. The thermal comfort of a building is considered a key stakeholder requirement in most organisations. We use the scenario modelling technique to create performance objectives around the comfort levels of the space and use the data linking techniques mentioned to access relevant data to evaluate these objectives.

The PMV and PPD thermal comfort indices form the basis of the ISO 7730 thermal comfort standard [36] and are used to predict the mean response of a large group of people to thermal conditions. PPD and PMV readings provide a useful indicator of stakeholder satisfaction with thermal conditions in a space. The PMV is an index that predicts the mean value of a large group of people on the 7-point thermal sensation scale.

### *4.2. Demonstration space*

The new engineering building at the National University of Ireland, Galway is a 14500 m$^2$ faculty building, containing lecture theatres, laboratories, offices and research areas. The building was completed in 2011 and is a highly instrumented facility, with a range of innovative environmental systems, including a climate facade and natural ventilation throughout the building. Managed by a BMS, a number of systems need to operate in sympathy with each other to satisfy operational objectives. The study was conducted in a computer suite at the south west corner of the building.

### *4.3. Description of data*

This section describes the initial data transformation process, illustrating how building data can be converted to RDF, using a series of data adapters, providing a homogeneous collection of data sets. A sample building information model was constructed of the room to illustrate the geometric properties of the space. The model contained one zone and was created using the ArchiCAD tool and was stored in the Industry Foundation Class (IFC) data format. The IFCtoRDF conversion service uses an OWL ontology which maps each IFC entity to an element in the OWL ontology [37]. List 4 is an RDF representation of the BIM following conversion. The outputted graph can then be uploaded to a triple-store type application such as the Virtuoso server [38], and SPARQL queries can be run against the data-set.

Listing 4: An RDF representation of a BIM model following conversion by the IFCtoRDF converter service

```
<component>
    <Vevent>
        <IfcBuildingStorey rdf:about="http://ninsuna.elis
           .ugent.be/IFC-repo/Room/AWS-3_Ar15#
           GUID037fa3d473bae4cf3aab377a65e793">
        <compositionType rdf:datatype="http://www.w3.org
           /2001/XMLSchema#string">_ELEMENT_</
           compositionType>
        <containsElements rdf:parseType="Resource">
            <rdf:first rdf:resource="http://ninsuna.elis.
               ugent.be/IFC-repo/Room/AWS-3_Ar15#
               GUID0fb9b3c97d02f4eddae71cd551e94b"/>
            <rdf:rest rdf:resource="http://www.w3.org
               /1999/02/22-rdf-syntax-ns#nil"/>
        </containsElements>
        <decomposes rdf:parseType="Resource">
    </Vevent>
</component>
```

The semantic sensor network (SSN) is used to describe sensors semantically [39]. In this experiment, the room has a number of sensors, which provide the BMS with data. The experiment also included a number of other sensors to measure air velocity, surface temperature and radiant temperature. The semantic web is an excellent resource when dealing with objects and relationships between objects. It is less useful when dealing with data sets and existing technology is perfectly adequate to accommodate such data. What is necessary is to illustrate how the sensor data can interact with sensor definitions. For the purposes of this experiment, we define sensors using the SSN approach and in the case of a temperature sensor, this is described (in part) by list 5.

Listing 5: An RDF representation of a temperature sensor, as provided by the web based application [40] described in [39]

```
<rdf:Description rdf:about="http://spitfire-project.eu/
   property/Temperature">
    <ns0:type rdf:resource="http://purl.oclc.org/NET/ssnx
       /ssn#Property"/>
    <ns1:measuredIn rdf:resource="http://spitfire-project
       .eu/uom/Centigrade"/>
  </rdf:Description>
  <rdf:Description rdf:about="http://spitfire-project.eu/
     uom/Centigrade">
    <ns0:type rdf:resource="http://purl.oclc.org/NET/muo/
       muo#UnitOfMeasurement"/>
    <ns1:prefSymbol>C</ns1:prefSymbol>
  </rdf:Description>
```

This RDF description provides information concerning the static information about the sensor, including location, what the sensor measures, unit of measurement and so on. It is important to differentiate between this type of static sensor information and the actual sensor output. We wish to perform various types of mathematical operations of such data and while a range of tools are available to covert say CSV data to RDF, the performance platform described in the next section is designed to integrate semantic data with various data-streams. Essentially, the tool enables the user to select sensors based on the building object in question. For example, if a zone is selected as a building object, then a list of available sensors in that space should be returned also, together with a breakdown of the static sensor information. A link can then be made to the specific output stream of the relevant sensor.

A simulated predicted mean vote (PMV) result was also generated for the space [35]. Based on various input parameters to the model, a PMV for the space was determined at around 1, indicating a slightly warm space. Typically, building energy simulations are not carried out on many buildings for many reasons, particularly cost. Unfortunately, even when a simulation exercise is carried out on a building, the data is often removed from the operative decision making process as time goes on. Simulation output is critically important to the effective management of a building and providing a building manager with predicted and actual performance data will lead to better outcomes. As the experiment progresses, more data is being made available. At the final stages of the experiment, the building manager will be presented with key thermal information from 3 sources, including the simulated PMV result-set.

### *4.4. Description of Measured Data*

The measurement data for the study came from a combination of thermal comfort metering equipment, hand-held temperature/relative humidity meters and BMS data [35]. In order to account for room temperature gradient, air temperature, $t_a$ readings were taken locally at each work station, using a hand-held thermometer. Radiant temperature, $t_r$ was recorded at a single location, using a QuestTemp 36 Thermal Comfort Meter.

| Var | Air Tem $t_{air}$ | Mea Rad Tem $t_{rad}$ | Op Tem $t_{op}$ | Rel Hum RH | Air Vel $v_a$ | Act Leve | Clo Valu | Clo Tem $t_{clo}$ | TCL | Com Vote CV | PMV | PPD |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| C | C | C | % | m/s | met | clo | C | C | | | | % |
| Mean | 24.18 | 24.14 | 24.16 | 31.76 | 0.23 | 1.10 | 0.86 | 29.06 | 28.20 | 0.8 | -0.2 | 14 |
| Min | 18.00 | 22.40 | 21.00 | 21.90 | 0.00 | 0.80 | 0.31 | 23.40 | 24.73 | -2.0 | -2.8 | 5 |
| Med | 24.00 | 23.70 | 23.80 | 32.00 | 0.20 | 1.00 | 0.82 | 29.00 | 28.14 | 1.0 | -0.2 | 9 |
| Max | 30.00 | 33.30 | 28.65 | 55.00 | 0.60 | 2.40 | 2.00 | 37.00 | 31.05 | 3.0 | 1.6 | 98 |
| Std. Dev. | 1.36 | 1.50 | 1.10 | 5.04 | 0.1 | 0.16 | 0.26 | 2.00 | 0.99 | 0.9 | 0.6 | 15 |

Table 1: Summary of measured and surveyed values for New Engineering Building Computer lab [35]

Table 1 provides a tabular description of the measured data gathered during the experiment and is described more fully in [35]. The following section describes briefly the performance framework tool-kit and how it interacts with semantic and measured data sets, and comments on how this data might be accessed and transformed, using the scenario modelling technique.

The computer suite is served by an AHU, operated on a control logic based on a series of set-points. The system is reactive in that it reacts to a certain control being triggered and supplies cold/warm air depending on the control. In the case of the computer suite, the BMS is operating effectively and as designed. The supply air, on the date of the experiment was around 11-12 C. As it passed through the frost coil, it was heated by about 4 degrees. The AHU is operating as designed, although the room is considered warm.

It is not apparent to the building manager, based on the BMS data alone, that the computer suite is being slightly over-heated, with a consequent loss in thermal comfort and energy. When viewed in conjunction with other data though, it becomes clear that the room is receiving too much heat, with a consequent energy and comfort loss. This is illustrated more clearly when a scenario is created for thermal comfort in the space.

### *4.5. Performance Framework Platform*

The PFP tool uses the RDF based building model as a basis for a performance assessment exercise. Each building object (Site, Building, Building Storey, Zone, HVAC) has a series of objectives which the object may be linked to. Once the RDF building model has been imported to the application, the user has the option to create a scenario model. Upon naming the scenario, the user is presented with a screen which lists the available performance aspects. At this point, the user can select a specific building object and an aspect to relate it to. The user is then presented with a list of objectives depending on the chosen object type. The user is able to choose from a specific list of objectives which are pre-defined (figure 6).

Having selected the appropriate objective, the user is presented with the associated metric. This metric retains an algorithm or aggregation function, based on the nature of the metric and the user can assign parameters for these functions. Possible data sets, based on those appropriate to the object chosen are presented at this stage also. The scenario can then be saved in RDF format and evaluated or modified throughout the life-cycle of the building. The scenario represents a measurable and repeatable assessment of building performance and is stored in a format which will allow greater integration with other data domains.

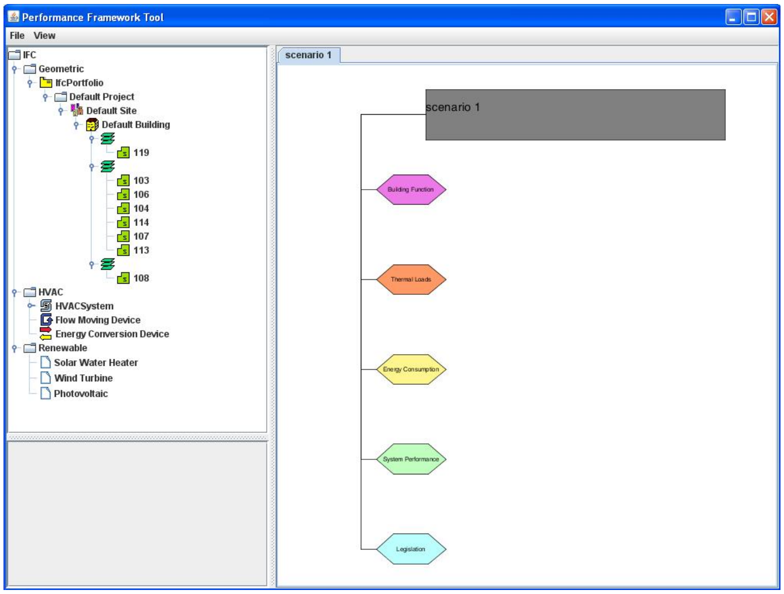

Figure 6: Main screen of the performance framework platform. The building objects are displayed in the top left hand frame, while a scenario is presented in the frame on the right. This frame includes performance aspects but no objectives have been created yet.

### *4.6. Scenario Creation and Evaluation*

For this experiment, a scenario model has been created to reflect some key concerns in the area of thermal comfort in a space. The scenario model, described in figure 7, refers to two separate performance aspects, *Building Function* and *System Performance*. Three objectives are used to describe three specific aspects of performance in the space.

Firstly, the thermal comfort objective is used to describe thermal comfort in the space and is quantified using the associated thermal comfort metric, which returns a PMV value. The metric applies the stored calculation formula to return this value. The metric also must be associated with the relevant data sets and in this case, these are provided from the measured data. This object is associated with the *Building Function* performance aspect as thermal comfort is considered a key building function.

The thermal comfort objective is also measured against simulated thermal comfort data. The data is taken from a simulated data source and this approach clearly allows the integration of design and performance outcomes in a single performance management system. A similar process is followed for the second objective, detailing temperature conditions within the space.

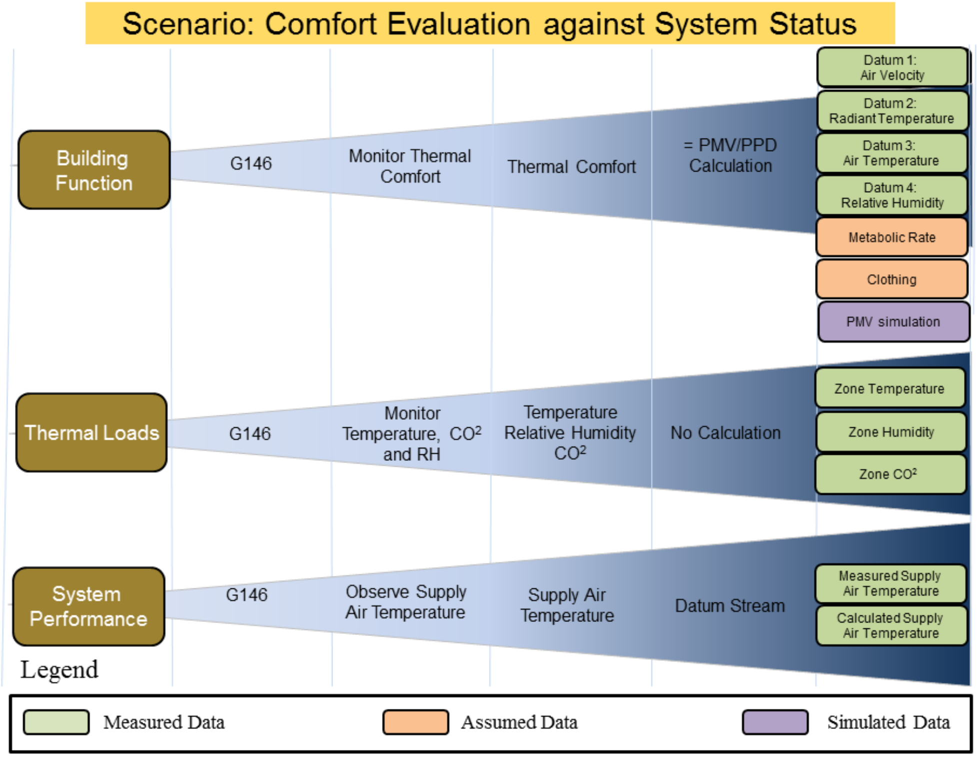

Figure 7: Scenario model, created from combination of two performance objectives. The scenario can be used to compare the thermal comfort levels in the space against the system status in the zone.

The objective is measured by a functional metric which simply returns the temperature value for the space current at that time. The objective is associated with the *Building Function* performance aspect as temperature is a reflection of the function of a building.

The third object relates to system performance and reflects the performance of the air handling system supplying the zone. The three objectives, taken together, constitute a scenario model for the zone. When the model is evaluated, a clear picture emerges of the thermal conditions in the space and how they relate to design intent. The scenario model described can also be saved in RDF.

Being able to retain this type of information in RDF allows the user to return to the scenario over time and evaluate it against particular data sets of interest. In this way, the scenario can be considered as a type of stored procedure, which can be evaluated repeatedly over time.

Capturing these measurements in an overall scenario is the essence of scenario modelling and the output is described in figure 8. This approach allows the user to consider performance from a number of perspectives in a comparative manner.

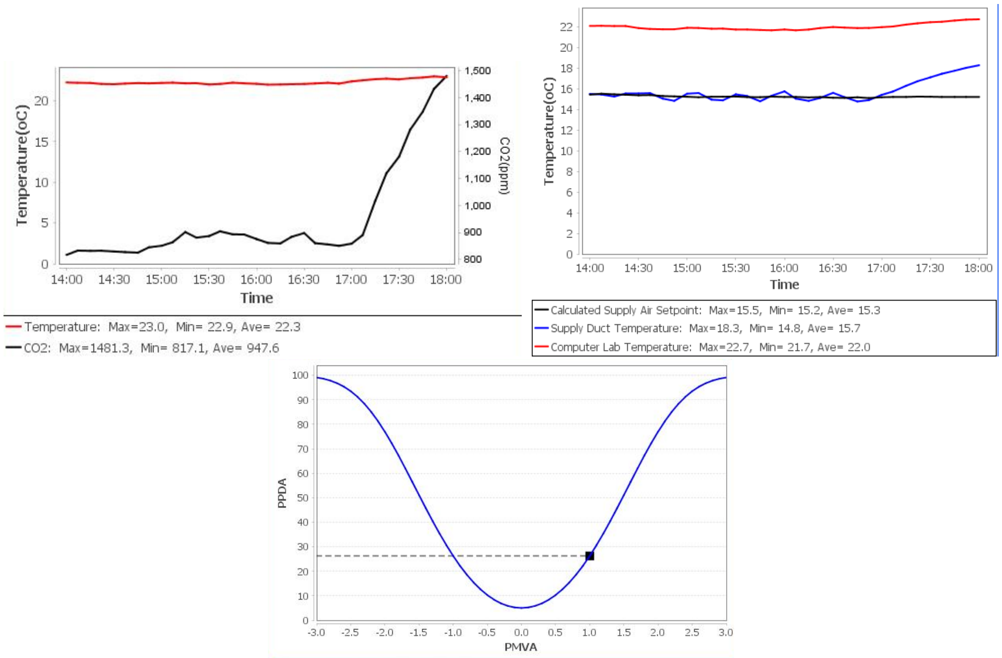

Figure 8: (a) Room Temperature (b) AHU system performance including room temperature, calculated and supply duct temperatures (c) Measured PMV

Figure 8 clearly illustrates three distinct outcomes for the space, illustrating to the building manager that although the thermal comfort reading is somewhat warm, the result is very much in line with that expected from the simulation model.

A closer look at the temperature objective and the AHU objective are the first suggest that perhaps the space is not conditioned correctly. The temperature of the space hovers around 22-23 C, while the supplied air is around 16 C. We can see from the thermal comfort reading that the space is somewhat warm. It would suggest that the AHU control needs to be modified somewhat to reduce the temperature of supplied air to the space. A further point to note is the spike in the supply duct temperature at 5 pm as the AHU is turned off. A spike is also seen on the measured $CO_2$ level for the space.

This type of scenario analysis is at the core of the performance framework approach and provides the building manager with contextualised information, based on several data sources.

## 5. Conclusion

The management of buildings is a multi-stakeholder, multi-domain problem and this paper illustrates how the semantic web can be used to manage performance holistically in buildings. Significant interoperability issues exist in the industry and this work leverages semantic web technologies to overcome some of these issues. It introduces a performance ontology which can interact with other homogeneous data sources, providing cross-domain links with other AEC data. The ontology describes a performance assessment domain for buildings semantically, allowing performance metrics to be integrated with other data in the semantic web.

A demonstration around the area of thermal comfort was described which illustrated how traditional insufficient data communication to building managers can be supplemented with a more holistic interpretation of performance, building on other available building data sources.

Future work will focus on extending the range of data sources available for interpretation and providing feedback to other key building stakeholders.

## References

[1] World Business Council for Sustainable Development, Energy efficiency in buildings transforming the market, World Business Council for Sustainable Development, Geneva, Switzerland, 2009. URL: `http://62.50.73.69/transformingthemarket.pdf`.

[2] E. Mills, Building Commissioning A Golden Opportunity for Reducing Energy Costs and Greenhouse Gas Emissions, Technical Report, Lawrence Berkeley National Laboratory, Berkeley, CA 94720 USA, 2009. URL: `http://cx.lbl.gov/2009-assessment.html`.

[3] McKinsey & Company, Pathways to a Low-Carbon Economy, Version 2 of the Global Greenhouse Gas Abatement Cost Curve, Technical Report, 2009. URL: `http://www.epa.gov/statelocalclimate/documents/pdf/mckinsey_summary_11-19-09.pdf`.

[4] R. Gasper, A. Blohm, M. Ruth, Current Opinion in Environmental Sustainability 3 (2011) 150–157. URL: `http://www.sciencedirect.com/science/article/pii/S187734351000148X`. doi:`10.1016/j.cosust.2010.12.009`.

[5] United Nations Environment Programme, Buildings and climate change: status, challenges, and opportunities, UNEP DTIE, Sustainable Consumption and Production Branch, Nairobi, Kenya : United Nations Development Programme ; Paris, France, 2007.

[6] European Union, DIRECTIVE 2010/31/EU OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the energy performance of buildings, 2010.

[7] P. de Wilde, Automation in Construction 41 (2014) 40–49. URL: `http://www.sciencedirect.com/science/article/pii/S092658051400034X`. doi:`10.1016/j.autcon.2014.02.009`.

[8] PROBE, Usable buildings trust (UBT) PROBE archive, 1995. URL: `http://www.usablebuildings.co.uk/Pages/UBProbePublications1.html`.

[9] J. A. Clarke, J. Cockroft, S. Connor, J. W. Hand, N. J. Kelly, R. Moore, T. O'Brien, P.Strachan, Energy and Buildings 34 (9) (2002) 933–940.

[10] U.S. Green Building Council, Regional Green Building Case Study Project: A post-occupancy study of LEED projects in Illinois, Technical Report, U.S. Green Building Council Chicago Chapter, 2009. URL: `U.S.GreenBuildingCouncilChicagoChapter`.

[11] J. ODonnell, E. Corry, S. Hasan, M. Keane, E. Curry, Building and Environment 62 (2013) 102–111. URL: `http://linkinghub.elsevier.com/retrieve/pii/S0360132313000346`. doi:`10.1016/j.buildenv.2013.01.019`.

[12] E. Corry, J. ODonnell, E. Curry, D. Coakley, P. Pauwels, M. Keane, Advanced Engineering Informatics (2014). URL: `http://linkinghub.elsevier.com/retrieve/pii/S1474034614000366`. doi:`10.1016/j.aei.2014.05.002`.

[13] R. Hitchcock, Improving life-cycle information management through documentation of project objectives and design rationale, Ph.D. thesis, Graduate Division of the University of California, Berkeley., 1996.

[14] IDC, The Digital Universe of Opportunities: Rich Data and the Increasing Value of the Internet of Things, Technical Report, 2014. URL: `http://www.emc.com/leadership/digital-universe/2014iview/executive-summary.htm`.

[15] R. J. Hitchcock, "Standardized Building Performance Metrics" LBNL Technical Report for CEC PIER High Performance Commercial Building Systems Program, Technical Report, LBNL Report No. 53072, 2003.

[16] E. Corry, D. Coakley, J. O'Donnell, P. Pauwels, M. Keane, in: Proceedings of the 13th annual International Conference for Enhanced Building Operations, Montral, Canada, p. 11.

[17] M. P. Gallaher, A. C. O'Connor, J. L. Dettbarn, L. T. Gilday, Cost Analysis of Inadequate Interoperability in the U.S. Capital Facilities Industry, Technical Report NIST GCR 04-867, RTI International and Logistics Management Institute, 2004. URL: `www.bfrl.nist.gov/oae/publications/gcrs/04867.pdf`.

[18] E. Curry, J. ODonnell, E. Corry, S. Hasan, M. Keane, S. ORiain, Advanced Engineering Informatics 27 (2013) 206–219. URL: `http://www.sciencedirect.com/science/article/pii/S1474034612000961`. doi:`10.1016/j.aei.2012.10.003`.

[19] A. C. Menezes, A. Cripps, D. Bouchlaghem, R. Buswell, Energy Solutions for a Sustainable World - Proceedings of the Third International Conference on Applied Energy, May 16-18, 2011 - Perugia, Italy 97 (2012) 355–364. URL: `http://www.sciencedirect.com/science/article/pii/S0306261911007811`. doi:`10.1016/j.apenergy.2011.11.075`.

[20] Carbon Trust, ctg047: Closing the gap: Lessons learned on realising the potential of low carbon building design, Technical Report, The Carbon Trust, 2012. URL: `http://www.carbontrust.com/media/81361/ctg047-closing-the-gap-low-carbon-building-design.pdf`.

[21] Zero Carbon Hub, Closing the gap between design and as-built performance, Technical Report, Zero Carbon Hub, 2014. URL:

http://www.zerocarbonhub.org/sites/default/files/resources/reports/Closing_the_Gap_Bewteen_Design_and_As-Built_Performance_Interim_Report.pdf.

[22] B. Bordass, R. Cohen, J. Field, in: International conference on improving energy efficiency in commercial buildings, Frankfurt, Germany. URL: http://www.usablebuildings.co.uk/Pages/Unprotected/EnPerfNDBuildings.pdf.

[23] ARUP, The Performance Gap: Causes & Solutions, Technical Report, ARUP, 2013. URL: http://www.greenconstructionboard.org/images/stories/pdfs/performance-gap/2013-03-04%20Closing%20the%20Gap_Final%20Report_ISSUE.pdf.

[24] M. Liu, D. E. Claridge, W. D. Turner, Journal of Solar Energy Engineering 125 (2003) 275. URL: http://link.aip.org/link/JSEEDO/v125/i3/p275/s1&Agg=doi. doi:10.1115/1.1592538.

[25] C. Neumann, D. Jacob, Building EQ- WP3Requirements for Data and Measurement Equipment, Technical Report, Fraunhofer ISE, 2007.

[26] J. O'Donnell, Specification of Optimum Holistic Building Environmental and Energy Performance Information to Support Informed Decision Making, Doctorate, Department of Civil and Environmental Engineering, University College Cork, Ireland, Cork, 2009.

[27] R. Hitchcock, Metracker Version 1.5. Building Life Cycle Performance Metrics, Technical Report, Lawrence Berkeley National Laboratory, 2002.

[28] D. O'Sullivan, M. Keane, D. Kelliher, R. J. Hitchcock, Energy and Buildings 36 (11) (2004) 1075–1090.

[29] O. Lassila, R. Swick, Resource description framework (RDF) model and syntax, 1999. URL: http://www.w3.org/TR/1999/REC-rdf-syntax-19990222/.

[30] P. Pauwels, D. Van Deursen, L. Madrazo, G. Costa, L. Granholm, E. Corry, E. Curry, J. ODonnell, S. Trm, J. Oraskari, LDAC 2012 (2012) 12.

[31] P. Pauwels, E. Corry, J. O'Donnell, American Society of Civil Engineers, 2014, pp. 2271–2278. URL: `http://ascelibrary.org/doi/abs/10.1061/9780784413616.282`. doi:`10.1061/9780784413616.282`.

[32] P. Barnaghi, M. Compton, O. Corcho, R. G. Castro, J. Graybeal, A. Herzog, K. Janowicz, H. Neuhaus, A. Nikolov, K. Page, Semantic Sensor Network XG Final Report, Technical Report, W3C, 2011. URL: `http://www.w3.org/2005/Incubator/ssn/XGR-ssn-20110628/`.

[33] C. Pedrinaci, J. Domingue, in: Proceedings of the 4th International Workshop on Semantic Business Process Management, ACM, 2009, pp. 43–50.

[34] C. Pedrinaci, J. Domingue, A. K. A. de Medeiros, in: The Semantic Web: Research and Applications, Springer Berlin Heidelberg, 2008, pp. 49–64.

[35] D. Coakley, E. Corry, M. Keane, in: 13th annual International Conference for Enhanced Building Operations (ICEBO).

[36] International Organization for Standardization, ISO 7730 2005-11-15 Ergonomics of the Thermal Environment: Analytical Determination and Interpretation of Thermal Comfort Using Calculation of the PMV and PPD Indices and Local Thermal Comfort Criteria, International standards, ISO, 2005. URL: `http://books.google.ie/books?id=p3YcoAEACAAJ`.

[37] Multi Media Lab, Universiteit Gent, IFC to RDF coversion service, 2010. URL: `http://demo.mmlab.be/IFC-repo/`.

[38] Openlink Software, Virtuoso, 2014. URL: `http://virtuoso.openlinksw.com/`.

[39] M. Leggieri, A. Passant, M. Hauswirth, in: Proceedings of the 10th International Semantic Web Conference (ISWC 2011), Citeseer, 2011. URL: `http://iswc2011.semanticweb.org/fileadmin/iswc/Papers/PostersDemos/iswc11pd_submission_100.pdf`.

[40] Digital Enterprise Research Institute (DERI), inContext-sensing: LOD augmented sensor data, 2011. URL: `http://spitfire-project.eu/incontextsensing/ld4sensors.php`.