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Author(s)	Blanes, Luis M.; Foncubierta, Juan L.; Costa, Andrea; Keane, Marcus M.
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EDVE: An Energy Diagnosis Visualization Environment

Luis M. Blanes Restoy[a,b], Juan L. Foncubierta[c], Andrea Costa[a,b], Marcus M. Keane[a,b]
[a]IRUSE. Informatics Research Unit for Sustainable Engineering
National University of Ireland, Galway
[b]Ryan Institute for Marine, Environmental and Energy Research
[c]iiTer. Grupo de Ingenieria Termica. Universidad de Cadiz. Spain
Corresponding author: Lmblanes@gmail.com

Abstract
In this paper we describe the motivations, development and results of EDVE: the Energy Diagnosis Visualization Environment that helps to quickly visualize faults and anomalies in energy consumption at the whole building level. EDVE relies in visual comparisons against predicted benchmarks using calibrated building models plus a set of predefined performance metrics. In this paper EDVEs development process is explained and a framework to evaluate web technologies prior its adoption is proposed. The underlying methodology of the tool is also described alongside an example of use. In this example, a data set generated by a modelling software where different faults have been forced is visualized. The effectiveness of different benchmark metrics to assist on fault analysis and diagnosis tasks is discussed. Finally, potential shortcomings and challenges ahead are outlined.

Keywords: Visualization, Energy Management, Simulation

1. Introduction

It is estimated that buildings consume between 20% and 40% of the global energy, 50% of which is associated with HVAC systems. [i] These systems perform rarely as intended in practice. Energy diagnostic tools and Fault Detection and Diagnosis methods are a means to reach an enhanced performance of HVAC systems by improving energy efficiency in the operational period. By adopting recommissioning of HVAC systems it is calculated that energy efficiency can improve up to 20% - 30% of the overall system performance.[ii]

Building Managements Systems (BMS) started its development during the 1970s and have evolved from basic pneumatic control systems to highly sophisticated tools using machine learning algorithms to optimize systems operation. During the later years, data acquisition and storage capabilities have multiplied their capacity, and data sets have become increasingly complex. These advances are driving the market towards tools and services provided through the Internet. New paradigms as the Semantic Web, Software as a Service (SaaS), or the Internet of Things (IOT) are already prominent, and will influence next generation of energy management tools.

Energy consumption monitoring and supervision of HVAC systems can be performed nowadays using these advanced technologies. Modern BMS handle vast amount of data displaying a myriad of parameters and generating comprehensive data sets. However, much of the capabilities of these tools are not fully maximized due to poor design, lack of client acceptance or lack of integration with operations and maintenance in practice. Problems with the translation of data into actionable information have been highlighted by Duarte et. al [iii]. Lack of appropriate skills on using BMS tools and have also been demonstrated by Piette et. al [iv], and acceptance barriers blocking a site-wide adoption of energy monitoring technologies was detected by Ulickey et al. in the US [v].

Moreover, the use of calibrated building energy models has proven to be a valuable instrument for energy management, providing useful benchmarking data and a test bed for operation's optimization. A definitive solution that integrates data acquisition, on-line control monitoring of energy systems, building energy simulation and integration with operations and maintenance remains a challenge. BMS systems, traditionally have integrated control and monitoring of mechanical and electrical systems and more recently alarm handling and schedule optimization. The capabilities to diagnose faults is starting to attract attention among industry stakeholders. Some systems have incorporated Fault Detection and Diagnosis (FDD) techniques embedded into BMS. Nonetheless, FDD tools are in an early stage of development within the HVAC sector.

A clear distinction between “Advanced Energy Information Systems” (EIS) and “Fault Detection and Diagnosis” (FDD) tools has been widely documented in the US [v]. EIS tools operate using a top down approach, discordances between benchmark energy consumption values are compared against real energy consumption, but there is no indication of the origin of a fault. FDD tools differ from EIS tool in that they provide diagnosis capabilities following a bottom-up approach: faults are detected at the system or component level, and diagnosis are provided to the user.

EDVE tool can be considered within the first category. It is primarily focused on energy anomaly detection at the whole building level (top-down approach) and also provides ways to visualize additional information to track the possible cause of a fault. The ultimate vision of EDVE is to provide energy managers with an easy to use environment that leverages existing databases by applying simple and effective data transformation methods thus facilitating users to compare data efficiently. EDVEs targets visualization of energy in both existing and new buildings.

In this paper, the development of the tool is described in section two, exposing an overview of the multiple alternatives and technologies available. A comparison between two widely used solutions is described and a framework for evaluating application tools is proposed. EDVEs methodology, workflow and the predefined performance metrics are also presented. In section three, an example showing how modelling and visualization techniques are applied using the tool is explained. Next developments of the tool are described in section four. To finalize, in section five, conclusions and lessons learned are accounted for.

2. Application development

The key concept before the start of the development was to explore the possibilities of using visualization techniques applied to energy management. From initial discussions a preliminary brief with basic requirements was issued. Rapid Application Development (RAD) principles have been applied, involving a number of so-called sprints, that is, iterative releases of the solution that are tested and further developed as packages. This approach was preferred instead of performing long and uncertain requirements gathering, design specifications and other more comprehensive and structured approaches to software development.

The technical approach focused on using web application frameworks rather than high level coding. A framework combines low level web technologies to make the development easier and faster. The initial requirements were simple: an easy to use/easy to deploy tool to quickly visualize time series and provide easy comparison of data. After the initial idea, an investigation of the different technologies available was conducted. A summary of technologies for web development frameworks is summarized in Fig 1. showing a big deal of complexity. This can pose a substantial barrier to early practitioner as it is difficult to asses which technology to use, and what are the trade offs of any pathway. Engineers with programming skills can overcome these issue by using web frameworks. These schemes allow programmers to build applications and make use of different technologies without having to explicitly dive into different high or mid-level software and languages or deal with the assemblage of different code pieces where compatibility issues may occur. As an example, a framework uses HTML and JavaScript languages but it is not required to explicitly learn and master these languages as the framework provides an easy and robust way of rapid design and prototyping a web-based application.

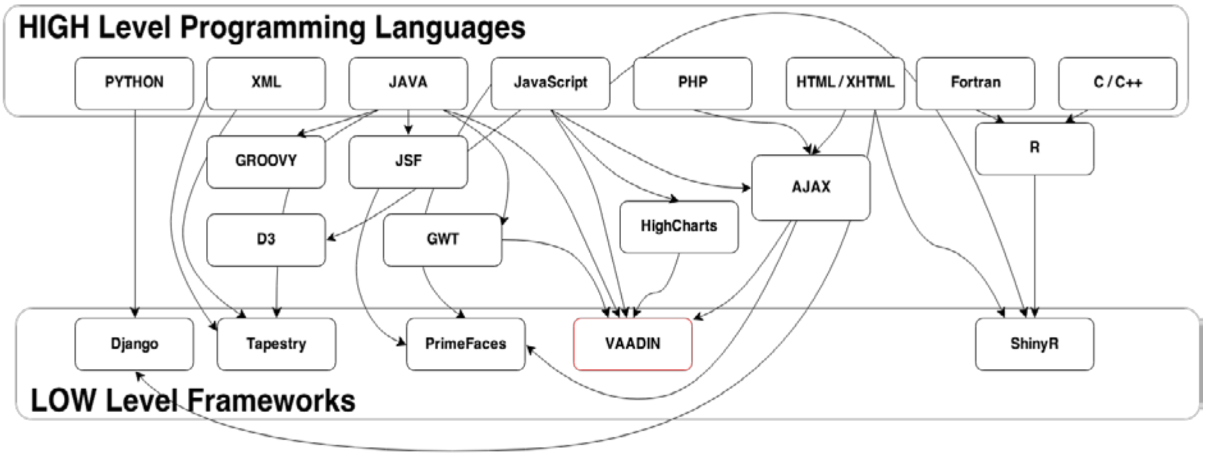

Fig 1 – Tree of analysed web technologies

Finally, two alternatives were tested: (1) Web development based on R statistical package deployed on ShinyR server, and (2) Rich Internet Application (RIA) using Java™ based framework VAADIN™ and JavaScript libraries. A set of features and performance indicators was firstly established and then two alternative were tested against them. A simplified test involved handling a noticeable big data set containing half million data entries was also performed. A summary of this analysis showing the best fitted solution for all the assessment indicators is shown in Table 1. A more detailed explanation of this comparison can be consulted in Appendix 1. Finally, Vaadin offered a more reliable option to start the design and development of the EDVE tool.

Table 1 Summary of Vaadin and R performance

	Vaadin	R
Execution Speed	•	
Time of development		•
Flexibility	•	
Compatibility	•	
Data Source	•	•
Learning Curve		•
Programing Language	•	
IDE	•	

Web Technology	•	
License	•	
Documentation		•
State of Development	•	

2.1. EDVEs Graphical User Interface (GUI)

EDVE main window is divide in three parts: (1) a left column where user select the graphs to visualize, the period of study and others options, (2) the central window where graphs and visualizations occurs, and (3), the left panel where the database selector tool and the faults engine are placed. An additional event logger frame is displayed within an horizontal banner at the bottom part of the application. The layout is shown in Fig 2. So far the tool is in prototype version, and a final Beta version will include more functionalities and will be tested using real building as demonstrators.

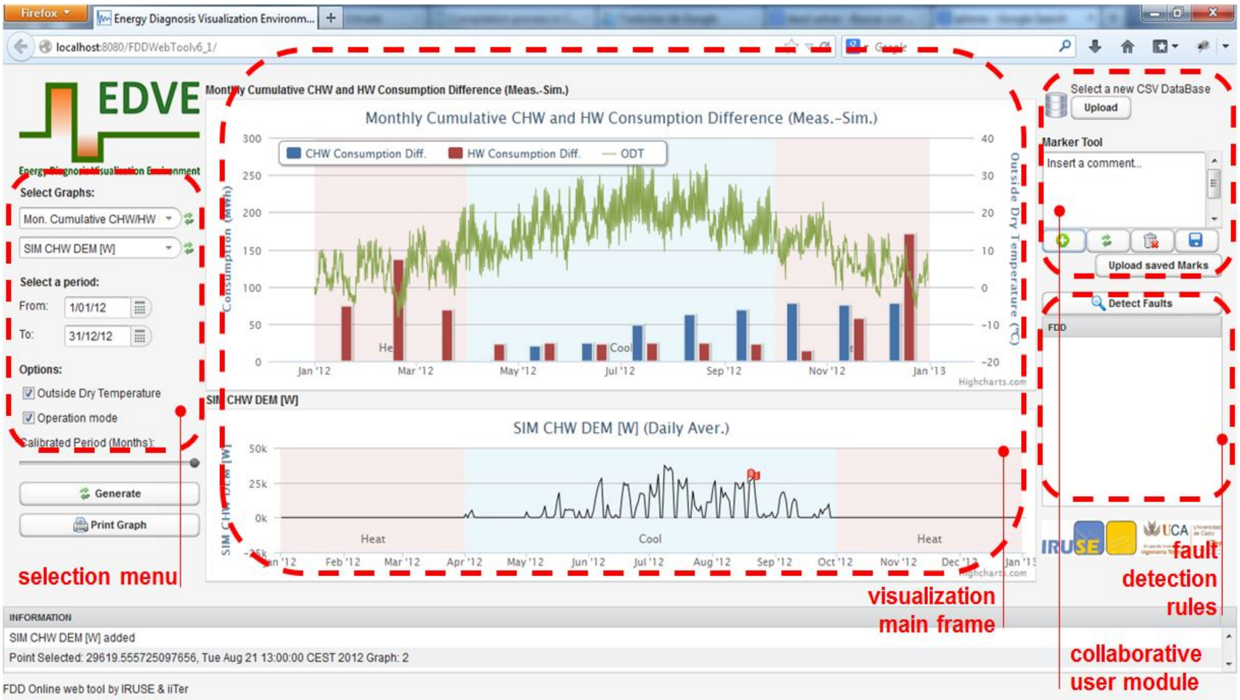

Fig 2 - Overview of EDVEs GUI

2.2. EDVEs Architecture and Data Flow

EDVE is platform independent. Whereas the core of the tool is developed in JAVA language, the final user interface is deployed in a web browser without necessity of any plugins, thus can be used by a variety of users online. To illustrate these concepts, Fig 3 shows the server-client architecture and data flows. The application resides in the server side and interaction takes place using a web browser as an ubiquitous interface.

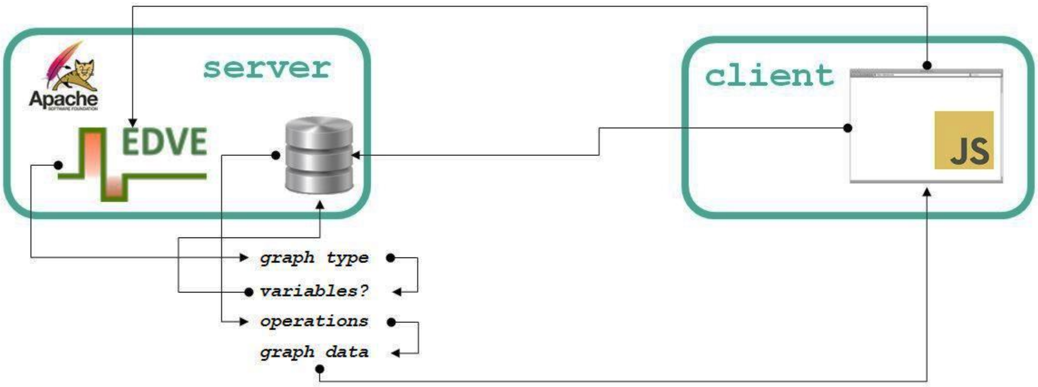

Fig 3 - EDVE server-client architecture

EDVE will be implemented as an online Software as a Service (SaaS) tool. This way different stakeholders can make use of it remotely on demand. SaaS concept is becoming commonly used as it provides a number of advantages in contrast with traditional software distribution models. Typically, visualization tools like EDVE can be conceived as part of a more comprehensive strategy within an organization to serve the purpose of energy efficiency (i.e. ISO 50001 Action Management Plan). In this line, three types of potential users can be identified: (1) Energy Managers. They are responsible for carrying out the energy review, energy planning and identifying of improvement opportunities. EDVE can help them monitor energy performance, using simulation to study the impact of energy conservation measures, establishing the energy baseline and tracking down the effectiveness of actions undertaken, (2) Technical Financial Officer. This user can use EDVE to help quantify energy investments, translating energy savings into monetary savings, and (3) Operations and Maintenance Personnel can make use of visualization tools on a daily basis, their duties are the day to day monitoring of BMS alarms, to execute scheduled maintenance activities and address emergency requests. Visualization of energy anomalies and troubleshooting can be supported by EDVEs capabilities using time series analysis.

2.3. EDVEs methodology

As highlighted previously, EDVEs use relies on the visual comparison of simulated energy versus real performance. Using EDVE requires a number of steps, as depicted in Fig 4:

1. Select, analyse and develop a whole building performance simulation (WBPS) of the building and systems of interest;
2. Calibrate the model using a tested calibration methodology [vi] [vii];
3. Build a data set according to EDVEs convention;
4. Visualize faults making use of different predefined benchmark metrics;
5. Explore the data set assisted by the EDVE tool to find correlating values and infer root causes.

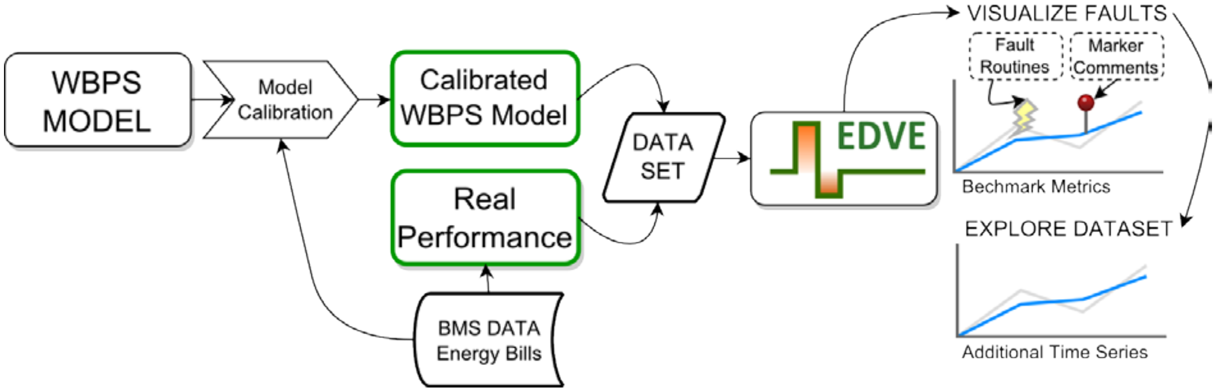

Fig 4 - EDVEs Methodology

2.4. Benchmark Metrics

Assessment of whole building energy performance and/or HVAC systems need reliable benchmark to use for constant comparison. These benchmarks can be understood two ways: (1) constructed empirically from energy consumption data or, (2) as baselines generated by simulation software representing "design intent" or "fault-free condition".

In the first case, sources and methods for benchmark of buildings are available, being the EPBD Framework in Europe [xxi] and Energy Star Portfolio Manager [xxii] tool in US the most significant. Both instruments are based in the concept of "reference building", that is, a set of calculations and indexes constructed upon existing building stock data.

In the second case, a baseline is generated using calibrated building models. Methodologies for modelling and calibration have been developed by Raftery et. al [vii]. Once the baseline model is established it is used as benchmark to either compare in search for energy anomalies (FDD) or to verify improve performance as it is required by ISO 50001 energy management standard and IPMVP protocol.

A third approach can be the use of DOE benchmark models for commercial buildings developed in Energy Plus [xxiii], this are ready to use building models based on statistical data. Assumptions and simplifications of these models are fully documented and form the base of ASHRAE analysis and development of energy standards.

More specifically, HVAC systems lack of a consistent database for benchmarking. This challenge is being addressed by EU FP7 project iSERV [xxiv] that aims to build a database of at least 1,600 HVAC systems across Europe and use it as an online tool for continuous monitoring and benchmarking.

EDVE predefined metrics are based on comparison of measured versus simulated and are based on already proven methods developed by Lee, Painter and Claridge in US [vi]. Comparison between predicted energy consumption and real energy consumption is performed in various ways. The parameters of study are Hot Water (HW) and Chilled Water (CHW) instantaneous energy rate (W). CHW and HW are measures easily available at the whole building level normally from metered data stored by BMS. EDVE can handle data coming at different intervals (e.g.: BMS typically logs data at 7' 30'' intervals or in 15' intervals, or even hourly data). The application can also handle sparse data sets (mostly with “empty”, “NULL” or “0” values). The values are integrated automatically to account for the absolute energy consumption (KWh or MWh) within the time period of interest. Once net energy consumption is worked out, the benchmark metrics are constructed.

The metrics defined are three: (1) Monthly differences (MD), (2) Daily normalized differences (DND) and (3) Cumulative Differences (CD). These metrics are constructed both for heating energy and cooling energy and can be visualized jointly in the same graph or separately.

Monthly differences are expressed in Equation 1. This is the difference between the monthly energy consumption of the measured period and the simulated energy consumption for the same period. Energy consumption is calculated as the sum of the daily energy consumption for each month. This is expressed in bar charts showing positive or negative values. Positive values account for abnormal increase on energy consumption and vice versa. This metric shows absolute differences.

$$\Delta \boldsymbol{E}_{\boldsymbol{monthly}_{\boldsymbol{k}}} = \sum\nolimits_{\boldsymbol{j}} \left(\boldsymbol{E}_{\boldsymbol{measured}\,\boldsymbol{j,k}} - \boldsymbol{E}_{\boldsymbol{simulated}\ \boldsymbol{j,k}}\right) \tag{1}$$

Where:

$E_{measured} = daily\ measured\ energy\ consumption$

$E_{simulated} =\ daily\ simulated\ energy\ consumption$

Daily normalized differences is shown in Equation 2. This metric express the daily difference of measured versus simulated daily energy consumption. This measure is then normalized against the same day of the calibrated period. It is expressed as a percentage.

$$\boldsymbol{E}_{\boldsymbol{day}} = \boldsymbol{100}\left[\frac{(\boldsymbol{E}_{\boldsymbol{measured}} - \boldsymbol{E}_{\boldsymbol{simulated}})}{\overline{\boldsymbol{E}}_{\boldsymbol{calibration}}}\right] \tag{2}$$

Where:

$E_{measured} = daily\ measured\ energy\ consumption$

$E_{simulated} =\ daily\ simulated\ energy\ consumption$

$E_{calibration} = daily\ simulated\ energy\ (same\ day\ but\ of\ the\ calibrating\ period)$

Finally, the Cumulative Differences metric shows the cumulative difference between the expected “right” performance od the building and the real performance can be seen in Equation 3. The difference accumulates throughtout the period of study. Visualization of this metric can be seen as the “energy penalty” of the buiding along its history, whereas the slope of the line can be interpreted as a representation of on going performance for a given day. This way a positive slope means “increasing penalty”, horizontal “performance as expected” and negative slopes as “improved performance”.

$$\Delta \boldsymbol{E}_{\boldsymbol{cum}\,,\boldsymbol{n}} = \sum\nolimits_{\boldsymbol{i=0}}^{\boldsymbol{i=n}} (\ \boldsymbol{E}_{\boldsymbol{measured}\,,\boldsymbol{i}} -\ \boldsymbol{E}_{\boldsymbol{simulated},\boldsymbol{i}}) \tag{3}$$

Where:

$E_{measured,i} = daily\ measured\ energy\ consumption$

$E_{simulated,i} = daily\ simulated\ energy\ consumption$

3. Example of Use

A previously developed model of an airport building [xix] was used as a case study for a primary assessment of the visualization metrics proposed. The model was developed using EnergyPlus [xiii] and comprises both the building envelope, zones and materials plus the HVAC system. Air is conditioned by a Dual Duct Variable Air Volume (VAV) Air Handling Unit.

A calibration period of 12 months was established as “fault free” performance. Secondly, a number of energy faults were induced within the simulation for the following three years of operation. The faults forced in the simulation are based on typical faults found in HVAC systems in some studies [viii]. The strategies for modelling faults in Energy plus have been documented by Lee and Yik [x] and Basarkar et al. [xi]. An example of a typical fault is a VAV box damper stuck to open or to the closed position. To simulate this fault, the *“Air Terminal: Dual Duct VAV / Zone Minimum Air Flow Fraction”* object was modified and fixed to the maximum value, being in this case the sizing value for the VAV box, calculated by Energy Plus. A more detailed description of all the faults generated is listed in Appendix 2. Faults have been spread throughout a time span of three years and have been induced one at a time, so no concurrent faults were modelled. Each fault has been modelled for different possible scenarios: winter, summer, hot duct and cold duct. Some faults have been considered as abrupt changes (e.g.: stuck damper), while another faults were modelled as degradation (e.g.: temperature sensor offset). The data set was loaded into the EDVE tool and graphs were generated. The main visualization window displays the predefined benchmark measures whereas the secondary frame below shows additional time series data.

In Fig 5 the MD graph is shown for the 4 years of the simulated period.

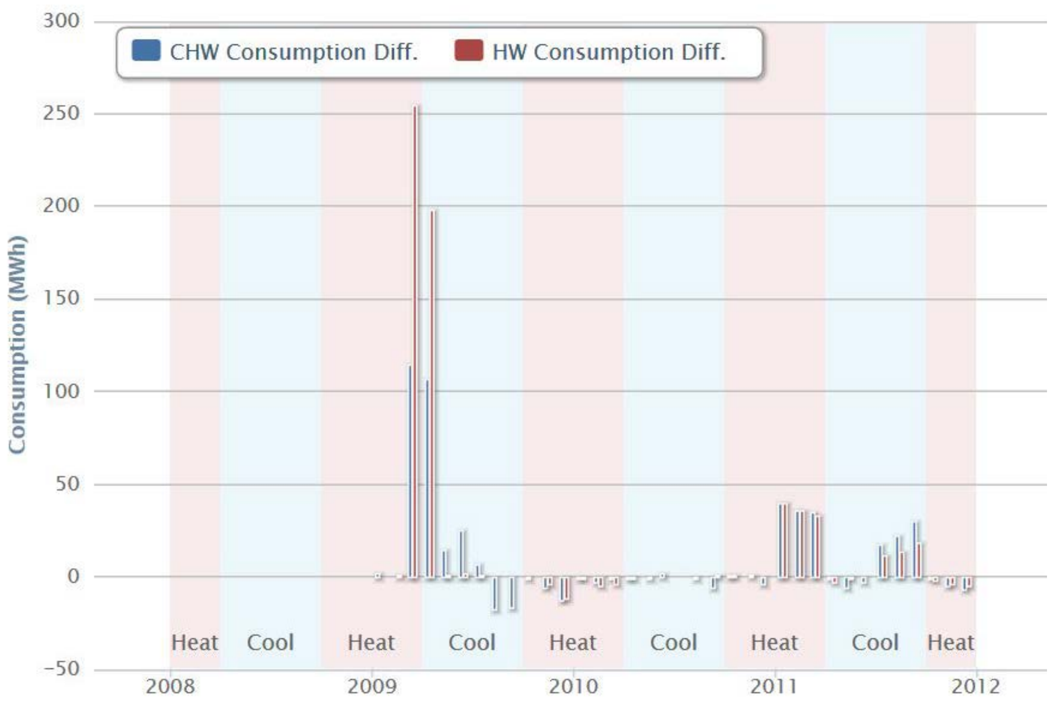

Fig 5 - Monthly Differences (MD) graph

The graph shows the impact on energy consumption for each month throughout the four years of the data set. There more noticeable increase takes place during March and April 2009 (F1). The periods January-March 2011(F2) and July-September 2011 (F3) show also a difference in energy consumption for both CHW and HW.

Monthly differences work well as soon as the data available is sufficiently big to spot significant differences between different years and there are illustrative benchmarks assisting the users on finding out the relative importance of the differences observed. Otherwise, absolute data comparison doesn't adds much more information regarding the severity of the difference encountered.

In Fig 6 the DND graph shows more specific information for the same period as it can be relatively compared with the reference year by looking at the Y axis, where relative percentage for the same day of the reference year are shown. DND graphs shows that for fault one (F1) during March to April 2009, represents increases in energy consumption varying from 50% to 20% of an optimal performance in the case of HW. The same fault also triggered an significantly less important increase in CHW, approximately of a 5% more, and constant for all the period of the fault. The decrease in the impact of the fault on HW suggests a relationship with weather related variables, as it evolves towards the summer.

At this point, EDVE can assist to work out potential causes of this using the additional frame to find correlations with other parameters contained in the data set. For instance. The data set can contain a wealth of data streams, from temperatures at different points of the system, to setpoint or feedback damper position.

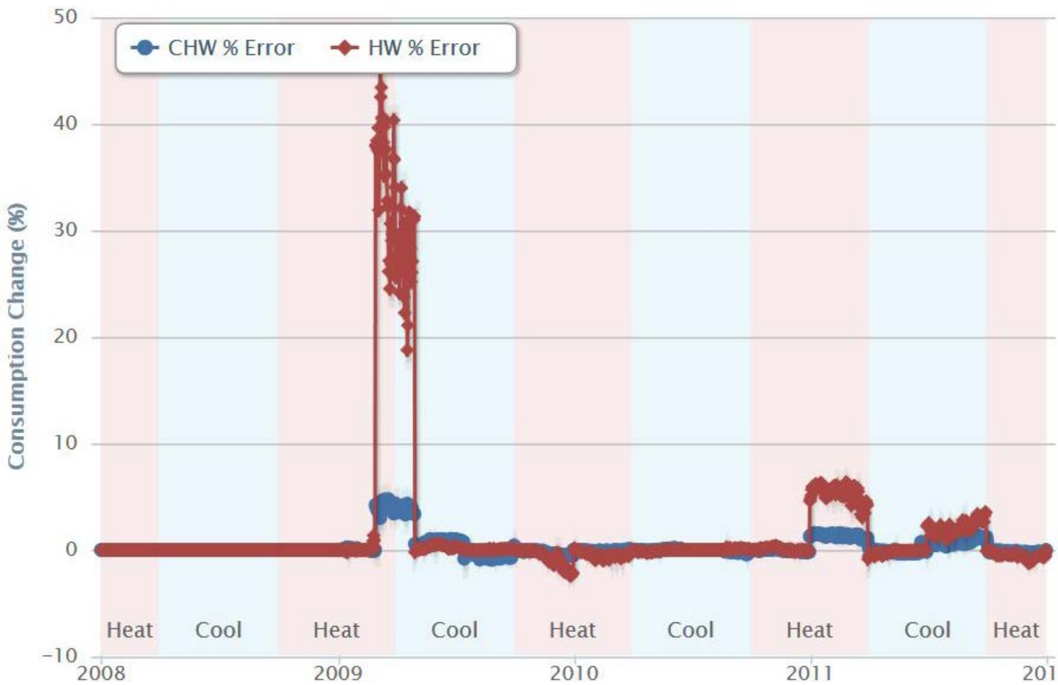

Fig 6 - Daily Normalized Differences (DND) graph

An observation of the position of the dampers in Fig 7, during the fault period mentioned, demonstrates an abrupt change in position to 50% that is correlated with the increase of energy consumption for the exact period. Abnormal operation of this damper is also correlated with F2 and F3 period, but this time less consistently as there are some fluctuations during both periods. It was found that comparison of different graphs is useful for reasoning and troubleshooting on diagnosing faults. Nevertheless, it is up to the ability, skills and engineering knowledge about the system of interest to accurately conclude with a reliable diagnosis that is not possible to find out at first sight. For instance, while different graphs point out F1 as caused by a stuck damper, that damper effect was actually caused by a change in the Outdoor Air Ventilation settings to a higher rate (one of the forced faults).

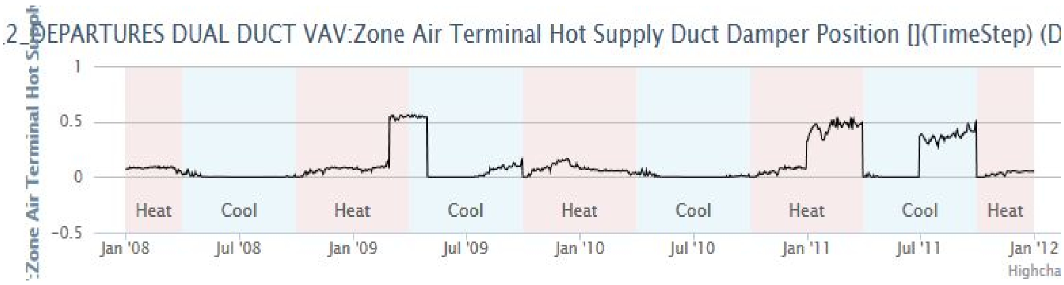

Fig 7 - VAV Hot duct Damper position

In Fig 8 the CD graph shows a clear representation of the faults induced for the different periods. As mentioned before, this graph conveys an abstracted representation of the HVAC performance during a period of time. We can clearly see that due to F1, nearly 700 MWh of energy was wasted. This metric represents more intuitively the net increase of energy consumption in relation to the optimum performance, it is hence very straightforward to establish a relationship between the temporal dimension and the net impact on the building performance. Comparison among different faults and periods become evident. For instance, F2 and F3 can be easily assessed as having an impact of approximately 150 MWh and 80 MWh, without any further calculation. On the other hand, impact on energy consumption due to energy conservation measures would be equally visible but featuring as decreases and easily highlighted by the negative slope.

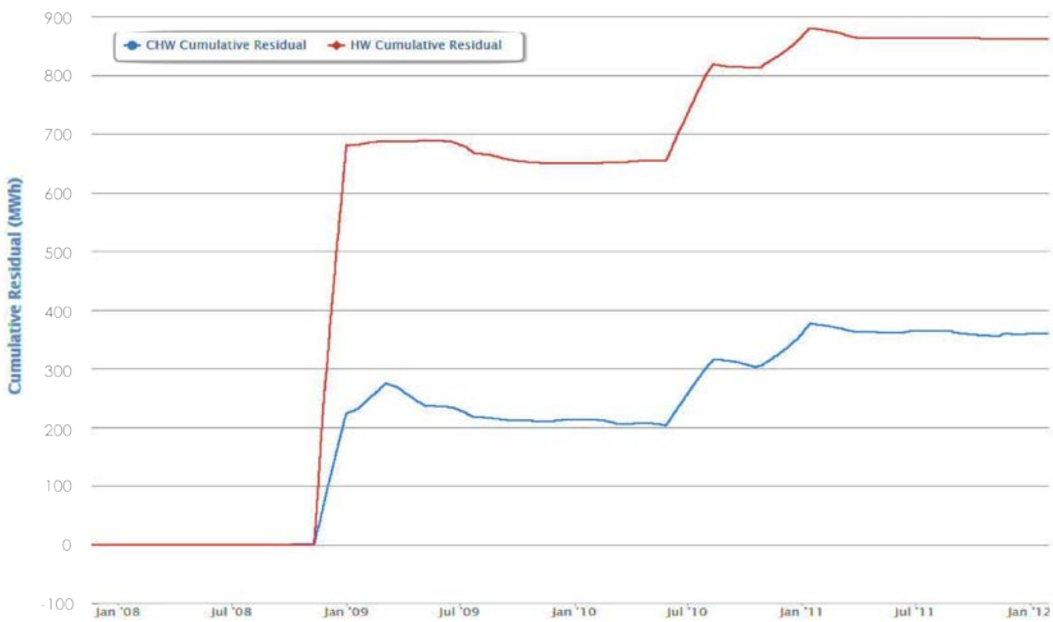

Fig 8 - Cumulative Differences (CD) graph

Additionally, a more common graph used for FDD is the scattered plot of daily energy consumption versus outside dry bulb temperature presented in Fig 9. The abnormal patterns due to faults are shown. As this graph is plotted for the whole four years period, it is difficult to ascertain what are the causes of the fault. However, EDVE can help identify the period of the fault by using a clickable legend, finding the period for the specific abnormal patterns, and performing a more narrowed search.

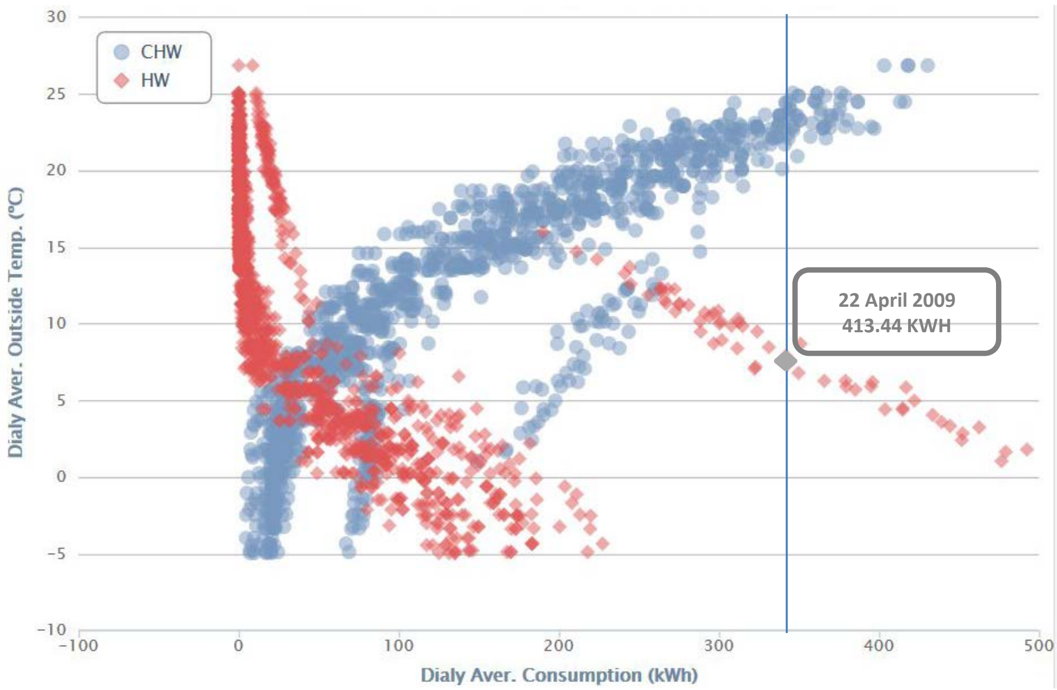

Fig 9 - Daily Consumption Vs. Average Daily Outside Dry Bulb Temperature

3.1. Potential energy savings

So far in the previous examples artificial faults were forced with a limited duration. In real systems, however, faults tend to extend in time an remain unobserved until a major failure occur or discomfort complaints arise. An early detection of this faults and a subsequent translation into actionable information can lead to substantial energy savings.

Survey studies in US [v] have illustrated the main factors, barriers and benefits of already adopted energy monitoring tools ranging from simple dashboards to advanced FDD software. Heavy reliance on the human factor was also identified as the main setback related to the real effectiveness of these tools. Adoption of structured energy management framework such as the one proposed by ISO 50001 is meant to facilitate the realization of energy savings.

Regarding quantification of energy savings, Irish researchers have recently documented the results of a pilot implementation where different faults have been detected on a set of Air Handling Units (AHU), demonstrating cost-effectiveness of the solution [xvi]. To give an example, a single fault in one AHU similar to as one of the simulated in this paper such as a stuck damper was calculated to impose a penalty of €18,000 to if run unnoticed during one year (as it was confirmed by the data recorded), this can jump to €48,000 combined with other common faults as passing heating/cooling valve actuator.

4. Future development

The next subsections describe the planned stages of the development of EDVE. Future uses of the tool will comprise the development of simplified models calibrated to actual monitored demonstrator buildings with a known history of faults. EDVE revealed also as an effective instrument to test different simulation strategies targeted at Fault Detection.

4.1. Integration with database.

Energy monitoring applications based on data manipulation need to tackle the interoperability with existing databases. One way of solving this problem is the creation of higher abstraction layers of information by introducing a taxonomy for conveying meaningful information to the otherwise raw data. Examples of this have been analysed in Ireland introducing the DataWarehouse concept [xii], which is a holistic "*Ndimensional*" information management system that stores, integrates and analyse complex data sets. Another way of solving this problem is to create a meaningful model representation of knowledge using a metadata layer based on the concept of ontology [xiii]. Researchers in Austria have also developed a monitoring systems toolkit (MOST) with a vision on ultra connectivity between a broad range of network platforms [xv].

4.2. Data Manipulation.

Another interesting feature to further develop is the capability of loading data that are format independent. Users will load a data set and interactively will be asked to point at the specific streams for CHW and HW consumption, whether the file is formatted according to specific standards, and other features. Identify two different sources of data (simulated and real data) will be also studied. Previous knowledge of the database structure, data quality and availability is always required from the user side.

4.3. Addition of new visualizations.

Additional capabilities for interactive visualization and exploration of new libraries will be explored. The capability to generate "small multiples" that facilitate comparison of multivariate data by enforcing comparisons of changes and differences among objects will be analysed.

4.4. Automation of fault detection routines

The process of Fault Detection can be enhanced by applying data mining algorithm that search for frequent patterns, associations and correlations among the stream of different time series.

4.5. Enterprise user system and applicability

So far the EDVE tool is installed in a local server and can be accessed by a variety of users. An enterprise application architecture will provide an scalable and modulable platform that can handle concurrent access, multi-users and user customization. This way, the platform can be used independently and deployed permanently for remote access.

Although the paper focuses on HVAC as main energy consumer in buildings, energy monitoring based on visualization, simulation and time series analysis can be applied as a generic tool to a wide range of energy systems provided simulation techniques and calibration methodologies are sound and sanctioned by practice. This can be said for instance of CHP plants, where simulation libraries has been developed widely by Razak [xvii] and effective methods for FDD of coolant systems make consistent use of time series visualization [xviii]. Another important field of application for EDVE can be the renewable energy systems (RES). Fault detection methods applied to RES have been thoroughly summarized by Al-Sheik and Moubayed [xix]. In contrast with the case study illustrated in this paper that focuses on large time extents, FDD methods targeted to PV panels, PEM fuel cells and wind turbines use narrower time windows [xx].

Equally important to simulation and FDD methods is also the existence of adequate data acquisition and storage capabilities. Insufficiently sensed devices can also be a costly barrier to FDD implementation.

5. Conclusion and Recommendations

In this paper the EDVE tool was described. Different technologies were compared against a set of proposed benchmarks and the benefits of using low level frameworks for engineering applications was highlighted. An example of use was illustrated: a data set generated by a simulation tool where faults have been induced was visualized and possible causes of error were tracked down. From the three graphs presented it can be concluded that DND and CD were in general more effective to transfer meaningful information, and had a better perceptual representation of energy performance and fault impact. It can be concluded that enhanced visualization tools are becoming more present for developers and scientist due to huge increase of the community and tools available, boosted by the open source model. These new technologies will influence the way data is transformed into actionable information and will assist also in representing novel concepts, as for instance, the one generated by FDD tools. Development and testing of new applications using real case scenarios, and active involvement of stakeholders becomes crucial to build robust effective tools that avoid unnecessary complexity to the final user.

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Appendix 1

Table 2 - R Vs. Vaadin

Concept	Indicator	Value
Execution Speed	Time Reading a 525600 rows and 33 column data base, and processing a cumulative sum operation.	**R:** 2'15'' **Vaadin (Tomcat 7 server):** 39''
Time of development	Code Length	**R:** 60 lines **Vaadin**: 300 lines
Flexibility	Number of GUI components	**R:** up to 15 built-in components and 1 main layout. **Vaadin:** up to 30 built-in components with 3 totally configurable combinable main layouts and more than 367 third parties components.
Compatibility	Web server OS Compatibility	**R:** Shiny server only for Linux. **Vaadin:** Tomcat 7 All platforms (or any application server like Glassfish, JBoss…)
Data Source	Data format that can be read	**R:** Excel, CSV, SQL, Oracle, MSSQL, MySQL, SPSS, Hadoop, Cassandra, MongoDB, XML, JSON **Vaadin:** All Java supported.
Learning curve	Time to deploy first application	**R:** 1 time unit. **Vaadin+Tomcat:** 2 time units.
IDE	Feature List	**R:** R Studio **Vaadin:** Eclipse, NetBeans
Programing Language		**R:** R scripting **Vaadin:** Java
Web Technology		**R:** JavaScript **Vaadin:** Java, GWT, Ajax, JavaScript
License		**R:** GPL 3.0 **Vaadin:** Apache 2.0
Documentation	Manuals, books and community activity.	**R:** Official Manual and wide variety of third parties books. Wide community in forums and online groups. **Vaadin:** Official Manual. Wide implementation examples. Not many third parties books. Wide community of add-ons developers and users.
State of Development	Date of the first stable version and actual version.	**R:** since 2000. Last version: 3.0.1 **Shiny app server:** Beta version 0.6 **Vaadin:** since 2002 Last version: 7.1.0 **Tomcat app server:** since 1999 Last version: 7.0.41

Appendix 2

Table 3 - Faults generated in E+

	Status (Faults)	Type	Simulation Strategy in E+	From	To
	Ventilation set to 8l/person-second	BASELINE	Set *DesignSpecification:OutdoorAir* to 0.008m3/segperson	01/01/2008	31/12/2008
1	Negative Room Air Temp. Sensor Error (Winter)	Degradation	Change Thermostat Setpoint (Schedules) (zone 12_2)	01/01/2009	31/01/2009
2	Positive Room Air Temp. Sensor Error (Winter)	Degradation	Change Thermostat Setpoint (Schedules) (zone 12_2)	01/02/2009	28/02/2009
3	Ventilation fixed to 5ACH	Operational	Set *DesignSpecification:OutdoorAir* to 5ACH	01/03/2009	30/04/2009
4	Negative Room Air Temp. Sensor Error (Summer)	Degradation	Change Thermostat Setpoint (Schedules) (zone 12_2)	01/05/2009	15/07/2009
5	Positive Room Air Temp. Sensor Error (Summer)	Degradation	Change Thermostat Setpoint (Schedules) (zone 12_2)	16/07/2009	30/09/2009
6	Negative Air Supp. Temp. Sensor Error (Winter) Hot Duct	Degradation	Change Setpoint Schedule 42	01/10/2009	31/12/2009
7	Negative Air Supp. Temp. Sensor Error (Winter) Cold Duct	Degradation	Change Setpoint Schedule 44	01/01/2010	31/03/2010
8	Negative Air Supp. Temp. Sensor Error (Summer) Hot Duct	Degradation	Change Setpoint Schedule 42	01/04/2010	16/05/2010
9	Negative Air Supp. Temp. Sensor Error (Summer) Cold Duct	Degradation	Change Setpoint Schedule 44	17/05/2010	30/06/2010
10	Positive Air Supp. Temp. Sensor Error (Summer) Hot Duct	Degradation	Change Setpoint Schedule 42	01/07/2010	16/08/2010
11	Positive Air Supp. Temp. Sensor Error (Summer) Cold Duct	Degradation	Change Setpoint Schedule 44	17/08/2010	30/09/2010
12	Positive Air Supp. Temp. Sensor Error (Winter) Hot Duct	Degradation	Change Setpoint Schedule 42	01/10/2010	16/11/2010
13	Positive Air Supp. Temp. Sensor Error (Winter) Cold Duct	Degradation	Change Setpoint Schedule 44	17/11/2010	31/12/2010
14	VAV Box damper stuck OPEN (Winter)	Abrupt	Change *AirTerminal:DualDuctVAV/ZoneMinimumAirFlowFraction* to the autosized value for VAV box of zone 12_2	01/01/2011	31/03/2011
15	Outdoor Air damper stuck OPEN (Summer)	Abrupt	Change *Controller:OutdoorAir Minimum/Maximum Outdoor AirFlow Rate* according to Stuck Open,Closed or Percentage % Relative to the autosized value	01/04/2011	30/06/2011
17	VAV Box damper stuck OPEN (Summer)	Abrupt	Change *AirTerminal:DualDuctVAV/ZoneMinimumAirFlowFraction* to the autosized value for VAV box of zone 12_2	01/07/2011	30/09/2011
16	Outdoor Air damper stuck OPEN (Winter)	Abrupt	Change *Controller:OutdoorAir Minimum/Maximum Outdoor AirFlow Rate* according to Stuck Open,Closed or Percentage % Relative to the autosized value	01/10/2011	31/12/2011
18	Sutck/Leaking coolin valve (CC) (Winter) (80%open)	Abrupt	Change *Minimum/Maximum Actuated Flow* according to Stuck Open,Closed or Percentage % relative to the autosized value	01/01/2012	31/03/2012
19	Sutck/Leaking coolin valve (HC) (Summer) (80%open)	Abrupt	Change *Minimum/Maximum Actuated Flow* according to Stuck Open,Closed or Percentage % relative to the autosized value	01/04/2012	30/06/2012
20	Sutck/Leaking coolin valve (CC) (Summer) (80%open)	Abrupt	Change *Minimum/Maximum Actuated Flow* according to Stuck Open,Closed or Percentage % relative to the autosized value	01/07/2012	30/09/2012
21	Sutck/Leaking coolin valve (HC) (Winter) (80%open)	Abrupt	Change *Minimum/Maximum Actuated Flow* according to Stuck Open,Closed or Percentage % relative to the autosized value	01/10/2012	31/12/2012