BaaS

Building as a Service

FP7-ICT-2011-6: ICT Systems for Energy Efficiency
Small or Medium-scale Focused Research Project
Grant Agreement No. 288409

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Deliverable Summary Sheet

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Deliverable D8.7: Short Description

This document is an annex of the final report which is confidential. In that sense, the publishable summary of the report may be published. The content is primarily a summary of the project with the scientific and technical objectives, results to achieve such goals and the lessons learnt extracted from the project.

Keywords: BaaS, lessons learnt, technical and scientific objectives

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Abbreviations and Acronyms

AL	Application Layer
APP	APPlication
BaaS	Building as a Service
BAC	Building Automation and Control
BACS	Building Automation and Control Systems
BIM	Building Information Modelling
BMS	Building Management System
CD	Control Design
CLL	Communication Logic Layer
DACM	Data Acquisition and Control Manager
DC	Domain Controller
DHW	Domestic Hot Water
DWH	Data Warehouse
FD	Fault Detection
FDD	Fault Detection and Diagnosis
FDI	Fault Detection and Identification
HVAC	Heating, Ventilation, and Air Conditioning
ICT	Information and Communication Technology
IFC	Industry Foundation Class
ISO	International Organization for Standardization
KPI	Key Performance Indicator
P controller	Proportional controller
PID controller	Proportional–integral–derivative controller
PMV	Predicted Mean Vote
PPD	Predicted Percentage Dissatisfied
SO2	Scientific Objective SO2: Integrated Automation and Control Services.
TABS	Thermally Activated Building Systems
TAS	Thermal Active Slabs
TBM	Technical Building Management
WP	Work Package
WSHP	Water Source Heat Pump

Executive Summary

The document is a summary of the final report where the public sections have been documented. In that sense, this deliverable is structured as follows:

- Summary of the project
- Scientific and technological objectives
- Technical results towards the project in order to achieve the different scientific and technological objectives.
- Lessons learnt extracted from the project where a set of conclusions/recommendations are given from the project experience.

1 Project summary

The BaaS system aspires to support efforts for energy performance improvement during the operational stage of non-residential buildings. Generally speaking, in the building operational life-cycle three significant tasks have to be continuously performed: data collection and assessment of the buildings' current state (identifying possible faults and inefficiencies if they exist); prediction of the effect that various decisions will have to Key Performance Indicators (KPIs); and optimized operation of systems to achieve high operational performance. Within BaaS, a generic ICT-enabled system has been developed to provide integrated services that guarantee harmonious and parsimonious use of available resources.

In short, the BaaS system comprises four components:

1. A data management component to collect, organize, store and aggregate data from various in- and out-of-building sources. An IFC-compatible Data Warehouse acting as a central persistent media for all static building data (meta-data), as well as dynamic information coming from sensor readings.
2. A service middleware platform to abstract the building physical devices, support high-level services on the cloud and facilitate secure two-way communication between the physical and ICT layers (building) with high level services (cloud).
3. Energy Analysis models for performance estimation and control services design, established on the basis of a reasonable trade-off between prediction accuracy (estimation) and computational complexity (fast-model for control design).
4. Analytics Services
   - for assessment and prediction services:
   - for building automatic and control (BAC) services. A number of model-based and data-driven approaches have been investigated towards improvement of control strategies with the goal of achieving operational efficiencies as measured through relevant KPIs; for model-based control design approaches, the energy analysis (simulation) models, acting as surrogates of the real building, incorporating sensor dynamic data, have been used to assess performance and comprehensively estimate values of relevant KPIs.

Upon verification of component interoperability, and development of a measurement and verification plan in the first phase of the project, the BaaS system has been demonstrated in real buildings and validated as an Energy Conservation Measure with Energy-Services Companies as the end-user. These buildings are located in Valladolid, Spain (CARTIF offices), Kassel, Germany (Fraunhofer offices) and Granada, Spain (Sierra Elvira school), which cover different climate zones in order to increase the replicability of the BaaS solution. There, the ECM (i.e. BaaS platform as a whole) has been applied in the buildings and the evaluation has been carried out under IPMVP Protocol (International Performance Measurement and Verification Protocol), a well-established standard for Measurement and Verification purposes.

The results from BaaS project reach a wide range of stakeholders. The target of public covers: Building and construction companies, Process and systems integration engineering at buildings, Building Automation and Building Management Systems companies, Software developers, IT Services and networks providers, Energy providers and utilities companies, Facility managers, Energy Services Companies, Public Authorities and Regulatory Bodies and Building Owners.

2 Project context and objectives

The discussion on energy-efficiency in the building sector has become ubiquitous, as has become the effort of achieving improved operational performance along with a lower lead time from building design to commissioning, and the development of tools to support facility management and operation. The development and integration of ICT technologies can help best coordinate building design and operation and thus contribute to achieving energy performance objectives. Still despite significant advances there exist no tools that are capable of streamlining the whole process and achieving in a systematic and well-defined way design objectives. In the effort of improved efficiencies, the successes in the AECOO (Architecture, Engineering, Construction, Owner and Operator) industry are as interesting as its failures – suggesting that even with careful planning achieving good energy performance can be an elusive goal. There are two important phases in the building life-cycle: the design phase in which design decisions significantly affect subsequent performance; followed by the operation phase where the Building Energy Management System (BEMS) ensures a parsimonious and effective use of the available resources. Achieving energy efficiency requires mitigation of both design-phase and operational-phase inefficiencies.

In the design phase, issues of collaboration and information interchange are crucial for the successful orchestration of the different teams (including architects, engineers, contractors, owners, site planners etc.) and for achieving many, – often conflicting, – requirements and constraints imposed by the different teams involved. In current practice, during the initial phases of design, different tools are utilized with little or no connect between them: ineffective communication (of files and documents) and lack of standardization between the various teams involved along with incomplete information incur significant delays to the design and construction phase, and design errors are easily introduced (and overlooked) that require retroactive actions. It is estimated that in the AECOO industry there is up to 57% non-value-added effort or waste from current practices that directly contributes to increased costs – not to mention costs that are incurred in the building lifecycle due to lacklustre performance.

Mitigating design-time inefficiencies and reducing non-value-added effort, requires better information inter-change between teams involved (architects, civil engineers, mechanical engineers, etc.). Building Information Modelling (BIM) presents a viable solution for information inter-change by establishing, through accepted standards, a common language to describe architectural, structural and energy concepts in the building. It can therefore help establish a stronger (and more direct link) between various stakeholders. The Industry Foundation Classes (IFC) (currently ISO/PAS 16739 and with the new version IFC4 destined to become ISO/IS 16739) along with Green Building XML (gbXML) provide consistent frameworks, of sufficient granularity, capable of describing all pertinent details; editors capable of editing such descriptions have been developed; and the AECOO industry – typically slow to adapt to change – is starting to adopt available tools (esp. for larger Projects) and gradually is incorporating such solutions, into the overall workflow and common business practices. Change is beneficial but, even in this case, a good design is a necessary but not sufficient condition for energy performance, as operational-phase inefficiencies can play a detrimental role.

In the operation phase, designing the building monitoring system and also incorporating decision strategies is a laborious task requiring expert knowledge. Buildings viewed from a systemic viewpoint are becoming increasingly complex: they have a wealth of energy systems that have to operate harmoniously together; they have to respond to signals from the grid; the atypical availability of energy through Renewable Energy Sources (RES) has to be effectively utilized; and graceful degradation of performance has to happen in case one or more of the building subsystems fails or goes offline. The need to design the building control strategies on a seasonal basis mean that the building operation must be postponed for at least two seasons. Expert knowledge and "best-practice" recommendations offer by no means a guarantee of "good" performance. More to that, changes on the building components (through refurbishing, installation of new systems and/or sensors etc.) and characteristics (degradation of performance) during the operational life-time of the building present formidable problems in reconfiguring and updating the BEMS. And last but not least, building users largely stay out of the loop and their actions inside the building can have detrimental effect on energy efficiency and building performance.

In current practice, the increasing complexity of designing and operating high-performance buildings quickly reaches the limits of existing approaches and hinders further development. The fact that the BEMS is configured once during the initial installation along with possible reconfigurations during subsequent retrofitting phases represents a very static (and limited) view. Even more, the separation and discontinuity between design- and operation-phases seems unnatural. The availability of BIM description during the initial phases is essential for effective information interchange; but in the operational life-time of the building this description can be updated and can evolve dynamically, to describe and reflect actual changes in the building. Energy management and other services can be generated automatically using this description and can be updated automatically when small or large changes occur.

There are three important elements in the designing of energy management systems: Data collection, aggregation and management as obtained through sensing modalities in the building along with the evaluation (or forecasting) of Key Performance Indicators (KPIs) help assess performance and enhance state-awareness regarding our system; the availability of models and forecasting tools that allow us to predict the effects that various decisions will have with respect to energy performance; and the availability of model-based control-design strategies to take decisions on how to best operate the building services within the context of achieving good energy performance. Developing better tools for lifecycle analysis but, perhaps more importantly, services to optimize performance over the building lifecycle establishing a necessary and, we believe, sufficient condition for achieving energy performance objectives. Better design, standardization, and component orthogonally and interoperability can contribute to the goals of improving energy efficiency. Interoperable components – "ICT Building Blocks," (ICTBBs) – that provide such services at the building level, lead naturally to the concept of the Building as a Service ecosystem (BaaS).

Thus, the BaaS proposal aims at optimizing energy performance in the application domain of "non-residential buildings in operational stage. Within BaaS, services to optimize energy performance (associated to HVAC systems and user actions) of buildings along with a generic platform for delivering such services are provided. There are three layers in the BaaS system: the data-management and building information modelling (xBIM) layer which is used to store and aggregate all static and dynamic data regarding the building; a service middleware platform to abstract the building and its subsystems and allows transparent two-way communication between the physical and the ICT layers; and the application service layer where all the services are provided. A "separation of concerns" approach is adopted to help manage the complexity and provide a generic and widely applicable solution: data management, middleware services and the generation of building services are to be developed.

Thus, work within the BaaS project aspired to provide tools towards energy performance optimisation during the operation of non-residential buildings. Within BaaS, services to improve energy performance (associated to HVAC systems and user actions) of buildings along with a generic platform for delivering such services has been developed. There are three layers in the BaaS system: the data-management and building information modelling (xBIM) layer which is used to store and aggregate all static and dynamic data regarding the building; a service middleware platform to abstract the building and its subsystems and allows transparent two-way communication between the physical and the ICT layers; and the application service layer where all the services are provided. A "separation of concerns" approach is adopted to help manage the complexity and provide a generic and widely applicable solution: data management, middleware services and the generation of building services have been at the focus of work within the project.

At the data layer, the use of Building Information Modelling (BIM) using the open IFC standard has been used as a central repository for all building-related information. The IFC4 specification has new and consistent definitions for building systems, services and controls that we have fully utilized. A "BaaS view" of the data model is created with all pertinent to our system information and appropriate interfaces have been created for interacting with BIM information sources. In addition to static data, all dynamic-data (i.e. ones obtained through sensor measurements) are stored and aggregated in a "data warehouse" that automatically populates data from the BIM sensor information descriptions, and is able to obtain data through the middleware layer of the building. The middleware platform is a service to provide transparent two-way communication between the building and the services. It acts as a building gateway (BGW) in the individual buildings which provides a generic and well-defined interface for the communication platform to interact with a wide range of BEMS. At the application layer, services (ICT BBs) provide that given the building characteristics (as available from the BIM), and measurements (as available from the DW) intelligence to perform building management operation. These services included: KPI-evaluation services to provide insights into the building operation and data quality; fault detection and identification services towards timely identification of inefficiencies and performance degradation of building services when and where they occur; and, model-based and data-driven control design approaches to improve operation performance (as measured through relevant KPIs).

For the development of the various ingredients of the BaaS system a top-bottom approach has been taken towards identification of the high-level architecture and alignment with stakeholders needs; followed by a bottom-up approach for the development of the individual components. Unit testing has been extensively performed before component integration. The performance of the BaaS system has also been evaluated according to usual business practices of VEOLIA, along with a comprehensive "energy savings and CO2 emission reduction" measurement and verification (M&V) methodology to be adapted and used within the Project. As part of the evaluation procedure evidence of energy savings and CO2 emissions reductions will be recorded.

In summary, better services, standardization, interoperability and integration are the key ingredients for making the BaaS system an ICT-driven Energy Conservation Measure (ECM). The reliance on BIM for building description and thermal modelling along with model-based control design ensure that the system is generic and replicable. In Figure 1, a schematic is presented of the operation of the BaaS System in a real building. During normal operation the middleware platform will abstract building devices, the data warehouse will be the central data repository and the services will provided the operational intelligence. In the schematics, data exchange paths are shown.

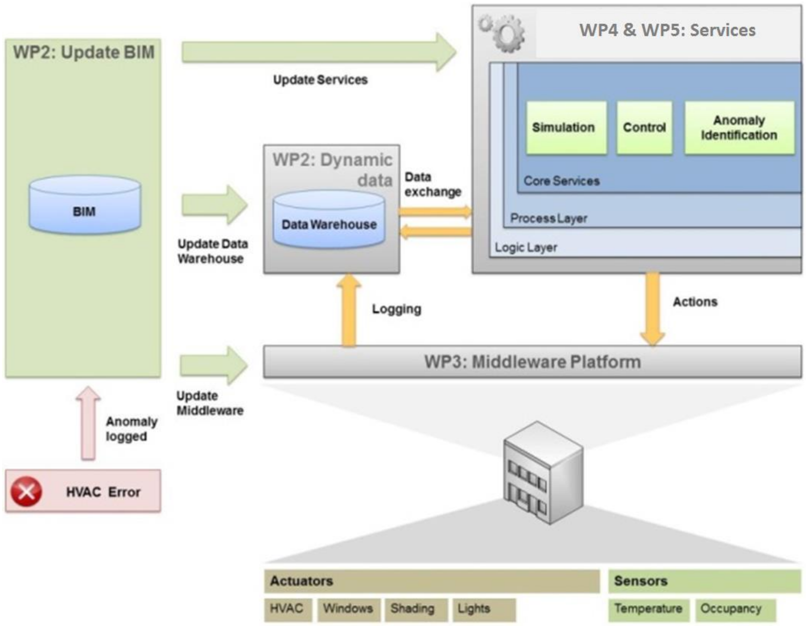


Figure 1: Schematic of the BaaS System

Based on the concise analysis presented above, BaaS has filled a number of methodological, technological and practical gaps for the development of a vertically integrated energy management solution. This major objective is pursued within BaaS via a number of multifaceted actions and S&T Objectives:

- Scientific Objective SO1: Building modelling and simulation for energy performance estimation and control design.
  - Assessment of KPIs using simulation models.
  - Integrate measured real-time data (from operation phase) along with thermal simulation models (re-design phase) to create methods to comprehensively estimate performance and compare predictions with actually measured values.
  - Modelling for simulation of the building, its subsystems and strategies (re-design phase). Model dimensionality-reduction for control and energy optimization purposes. Model identification using real-time data (operation phase).
- Scientific Objective SO2: Integrated Automation and Control Services.
  - Advanced control strategies: develop a set of holistic control strategies considering synergies between facilities and subsystems (HVAC, lighting, intelligent facades, micro-generation and storages subsystems) and Energy (Thermal & electrical) balancing into the building considering external conditions (the District Energy Management and/or

    - Utilities Power Grid control). Near Real time integration, light-weight algorithms.
    - Using thermal simulation models, evolutionary re-design nearly-optimal control strategies and based on KPI estimation select the best strategies.
    - Adaptive and self-learning control strategies considering building usage dynamics like current habitants, age of environment and facilities, changing surroundings. Continuous tuning of the building operation parameters and fully-automated fine-tuning of the controller parameters based on simulation models and in situ sensor measurements at the BMS.
    - Fault detection and Diagnosis algorithms integrating building usage dynamics based on energy performance estimation.
- <u>Technological Objective TO1</u>: Data Management: Working on existing initiatives and ongoing projects results, integrating State of the Art of extended BIM, EEB Ontologies and Standards:
    - Harmonization of near real time data for the implementation of Scientific Objectives.
    - Structural extensions of BIM: Support current IFC works. Add properties regarding Energy Efficiency and building dynamics. Standards (IFC, ifcXML).
    - Model-based knowledge management. EEB Ontology. Semantic knowledge services.
    - Development of a Data Warehouse as an integrated data management technology platform for the integration of operational near-real-time information: harmonization of near real time data for implementation of Scientific Objectives.
    - Development of a methodology for uncertainty propagation. Address inconsistencies in data.
- <u>Technological Objective TO2: Middleware Platform</u>: System Integration, Interoperability and Standards.
    - Development of an Open Service Middleware Platform to implement Scientific Objectives.
    - Utilization of Open Service Middleware Platform technologies for cloud-enabled interactive e-services specialized for integration of multiple trusted and un-trusted services of EMS stakeholders (common and interoperable to existing standards).
    - Development of an ontology-based service composition framework hosted in an open cloud-based environment.
    - Integration of SOA and EDA architectures
    - Distributed loosely-coupled functional design to enable hosting in flexible Cloud infrastructure.
    - Define communication interfaces between the communication platform, external ICT systems (e.g. on the Internet) and the building systems in a secure manner (Building Gateway).
    - Improving privacy and security in sharing data on energy consumption.

The integrated BaaS platform, along with exemplary services which have been developed within the project, have been demonstrated on three sites: the CARTIF Office building in Valladolid, Spain; the ZUB office building in Kassel, Germany; and, the Sierra Elvira School in Granada, Spain.

Figure 2: Demonstration sites of the BaaS solution

Each of the demonstration buildings has been distinctly different: in the amount of sensing equipment available, the types of building services, the building use, as well as different contextual patterns (e.g. related to prevailing weather conditions or building use).

The demonstration goals have been two-fold: to develop, test and debug under realistic conditions the components developed, and to estimate the potential to contribute to improve energy performance. The use of standard-industry practices, used by ESCOs – which is the main end-user of the project results – to estimate the capability of the BaaS set of services towards improved energy performance has led to the following understanding: energy performance improvements were obtained in all cases ranging from 10% to 24% compared to the baseline strategies – these numbers are commensurate with other reports of similar experiments in the literature; obviously the amount of energy saved should not be looked in isolation to comfort. The solutions provided managed to save energy while maintaining comfort and comparable levels, or in certain cases allowed for a controlled selection of the trade-off between comfort and energy. In addition, potential savings are commensurate to the baseline strategy (in all project buildings the baseline strategy was commensurate with that found in state-of-the-art approaches in commercial installations) and also the building sensitivity, with lightweight and not-airtight buildings being less sensitive to predictive control approaches. In that sense, the notion that a passive-first approach has been reinforced; followed by the continuous monitoring and improvement approach which is supported by the BaaS suite of tools. Also, a final conclusion is that optimisation is untimely on a building with faults. The sad reality, confirmed also for the buildings we had available in the project, is that fault-free building operation is something that is very infrequent in practice. As such the fault-detection and identification have an important role to play in the whole process of energy management, enforcing the motto: "It makes no sense to optimise something which is faulty"

For more information on detailed project results please review the project deliverables and publications, available on the project web-site: http://www.baas-project.eu

3 Towards the S&T results/foregrounds

To achieve the aforementioned Scientific Objectives, a technological infrastructure has been developed able to support:

- Real-time data management (aggregation of data from building and external sources) in a harmonized way (and make them available in near real time)
- Implementation of scientific outcomes as Services (models, simulations and algorithms).
- Privacy and security in the communication of the various components.
- Deployment possibilities in flexible Cloud infrastructure (private, public, hybrid) enabling multitude of business models.

Each of the objectives has been addressed through the collaborative work among all work packages that contributed towards results with the aim at ensuring the proper behaviour of the system as a whole. Next, each one of the objectives is detailed in terms of results and foreground generated that demonstrate its achievement.

3.1 Scientific Objective SO1: Building modelling and simulation for energy performance estimation and control design

This first SO1 is focused on the development of building models, including simulation tools, in order to provide with model-context features to the control strategies. The achievement of this objective is primarily associated to the WP4 "Building Energy Modelling and Simulation for Performance Estimation and Control" and WP5 "Advanced Automation and Control Services for Performance Optimization of Building Operation".

WP4 was in charge of creating the thermal simulation models, one of the four pillars within BaaS. With the building simulation models has been obtained simulated building behaviour used to create different control strategies for the buildings and in some cases, the results obtained from the thermal and illuminance simulations where used to evaluate a diverse family of Key Performance Indicators that only could be obtained from "virtual" measurements not able to be recorded from the real model, as could be radiant zone temperatures, thermal comfort or illuminance several working surfaces. Those exposed indicators, among others, are described in the bibliography but when these measurements are to be brought into practise within a normally occupied building, the amount on sensors needed and the reliability of the data obtained does not deliver the expected results. That reason leads us to obtain "virtual" representative values from the previously identified and validated simulations.

In this way and as it has been introduced, the simulation models contribute on the realization of the scientific objective using as basement or main starting point one of the subchapters included in the technological objective 1. The use of the structural extensions of Building Information Modelling (BIM) allowed the WP4 partners to create 3D building thermal models from IFC STEP data. The semi-automatically created building models were exported in a first step to building thermal simulation engines where the building structure and the components installed to provide heating and cooling are simulated. Within these engines, EnergyPlus and TRNSYS to name but a few — are widely used to analyse the buildings' thermal performance and predict their energy consumption with high accuracy. To this direction, the BEP simulation model must incorporate all heat transfer mechanisms, inside and outside of the building. Focusing on the building's envelope, preparation of a BEP simulation model is an effortful process, predominantly slowed down by the geometry information absence.

That is the reasoning why a methodology for semi-automated BEP simulation model creation could make this process much more expedient and as such lower the threshold for the use of such models. Concerning the building geometry information, BIM as mentioned before is a rich repository of information that could be used to streamline and expedite the collection of such information.

BIM technologies, associated to TO1 (see below), make use of standards and, in the specific case of the BaaS project, the Industry Foundation Classes (IFC) can provide static building information that include geometric configuration and material properties, but in a form that might not be directly usable for the generation of thermal simulation models due to the absence of 2nd-level space boundary information. Thus, a new approach has been developed whose streamlined process is illustrated in Figure 3, which transforms an IFC file and existing weather data to a Building Energy Performance simulation model. This process consists of different aspects need to work together. The five basic steps of the process are the following:

- A checking algorithm to detect and corrects geometrical errors, due to e.g. incorrect building designs or imperfections, of the IFC exporter software;
- CBIP, a building second level space boundary topology generation tool processes the IFC file of the building and generates the 2nd level boundaries, which are essential for the definition of the detailed thermal simulation model;
- The output of the CBIP algorithm is used for defining the System of Resistances and Capacitances (SRC) thermal simulation model of the building. SRC is an IFC compatible building thermal simulation and energy demand prediction tool, used in the Application layer of BaaS platform. SRC performs thermal and energy building simulations by forming and solving a system of ordinary differential equations (ODEs), which describes the thermal energy flows among building elements, in general. This system of ODEs is formed according to the electro-thermal analogy applied on a graph, or network of resistances and capacitances, which represents the whole building. Figure 4 shows an example application of the SRC modelling approach for the prediction of the indoor temperature and the energy demand of TUC building.
- The output from the previous processes can be utilized to generate automatically the building envelope of EnergyPlus and TRNSYS simulation models;
- For the use of the simulation model as a demand prediction tool, a local weather file is required. Here, the weather-file creation process is also performed as a dedicated, automated service, utilizing models that are used to estimate the global solar radiation from existing percentage of cloud coverage data and diffuse/direct solar radiation components from existing global solar radiation data.

Once the building energy model has been created, with the maximum level of complexity, its simulation model can be simplified to face different problems: i.e. Comfort condition in occupied zones should be simulated much more accurately than the total heating energy demand of the building where simplified building models deliver good enough results.

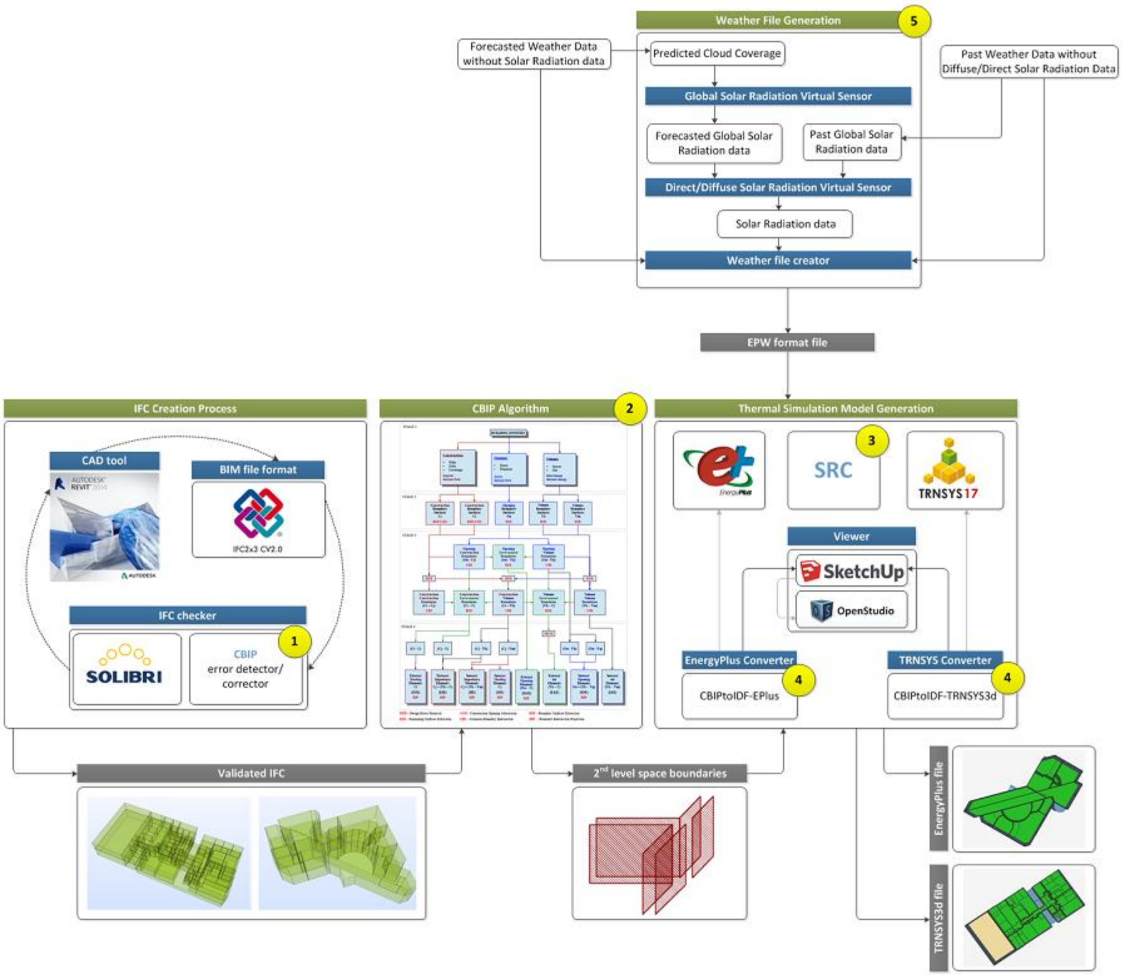


Figure 3: Transformation of an IFC file and existing weather data to a Building Energy Performance simulation model; enumerating aspects that could be performed as separate supporting services within the application layer of BaaS framework

With the results of this process, it is dealt with the possibility of integration between the simulation model and the control-design algorithms using co-simulation models. The ultimate goal of this advanced control is the energy optimization through more accuracy tools that take into account the building physics and dynamics, instead of only the ambient characteristics. In this manner, the performance is accurately and comprehensively estimated that compares real behaviour of the building with real data and the predicted energy results.

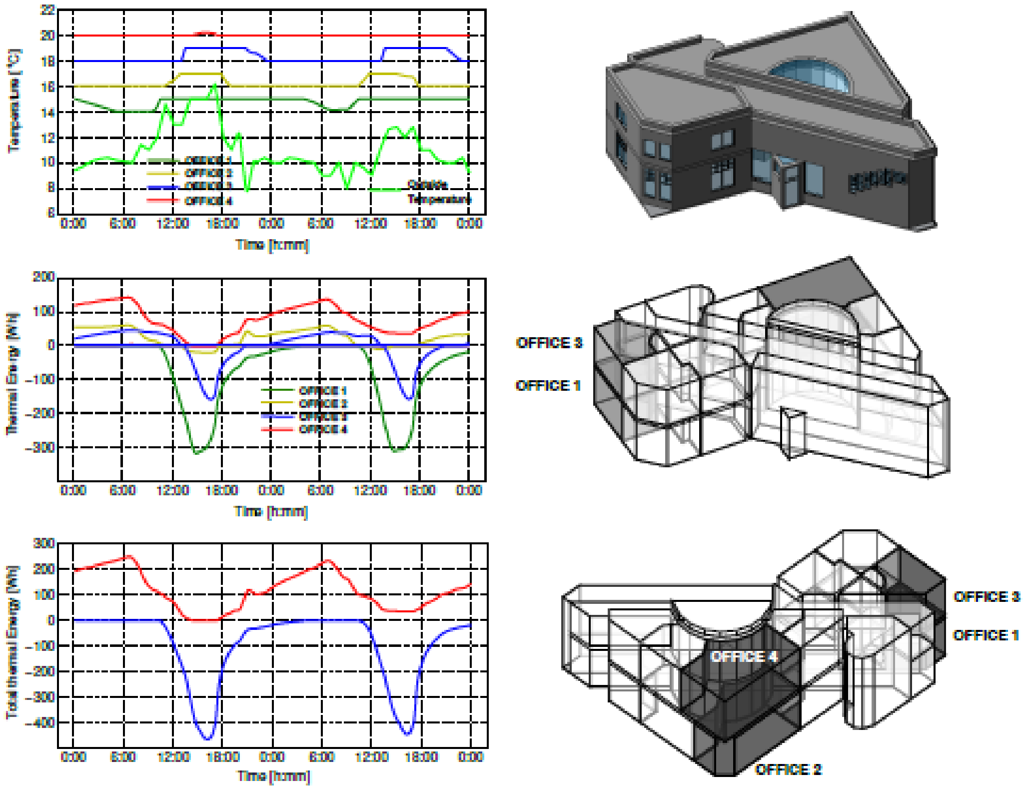


Figure 4: Temperature and thermal energy demand plots referring to four selected offices in TUC building (Two- day period: March 1st and 2nd, simulation time-interval: 10 min)

Additionally, these models are widely used for the evaluation and assessment of the KPIs by means of sets of KPIs. They are obtained both from real measurements and via simulated data such as it is highlighted in Figure 5. Considering the established framework in WP1 "Theoretical Case Studies and End-user Acceptance", which is a horizontal work package and defines the KPIs for evaluation purposes, these simulation models have led to energy and comfort evaluation. Among others, the following KPIs are used in the evaluation process of the control strategies:

- Comfort
  - Predicted Mean Vote
  - Percentage of Dissatisfied People
  - Lux level
- Energy-related
  - Net thermal energy consumed
  - Net electricity energy consumed
  - Primary energies
  - CO2 emissions

Having this in mind, Figure 6 exemplifies one of the KPIs for the Sierra Elvira School where the heat transfer is compared between the original strategy and two other different approaches. The intention is to extract comparable results and, therefore, normalized by external conditions values have been used in order to provide objective comparisons. It is also important to note here that the KPIs-based assessment has been complemented under WP6 with the application of the IPMVP protocol that conducts to the evaluation of the energy savings. For that reason, additional mathematical models have been built according to real data samples. The model represents the trend of a dependent variable (e.g. energy consumption) in relation to an independent variable (e.g. temperature). Thus, by means of adjustments, the baseline period can be extrapolated to the evaluation period under the similar conditions to compare them and extract conclusions about energy savings. An example is depicted in Figure 7.

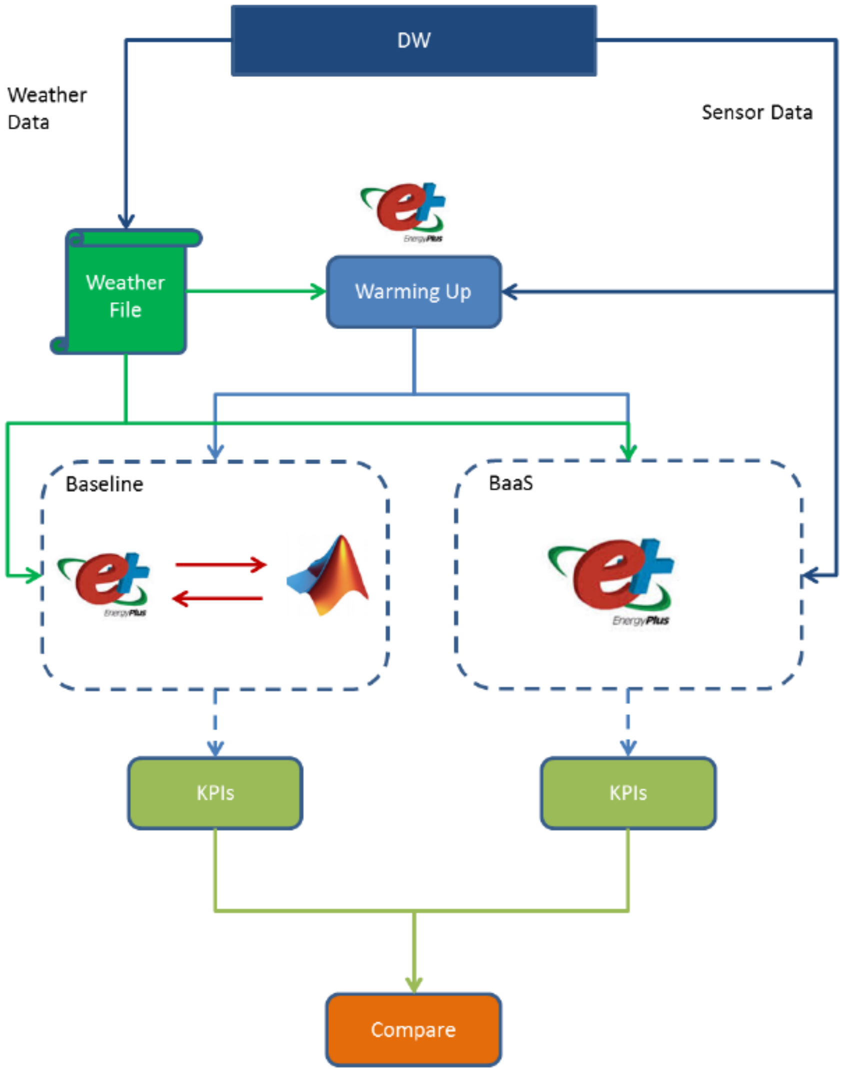


Figure 5: Evaluation process based on simulation

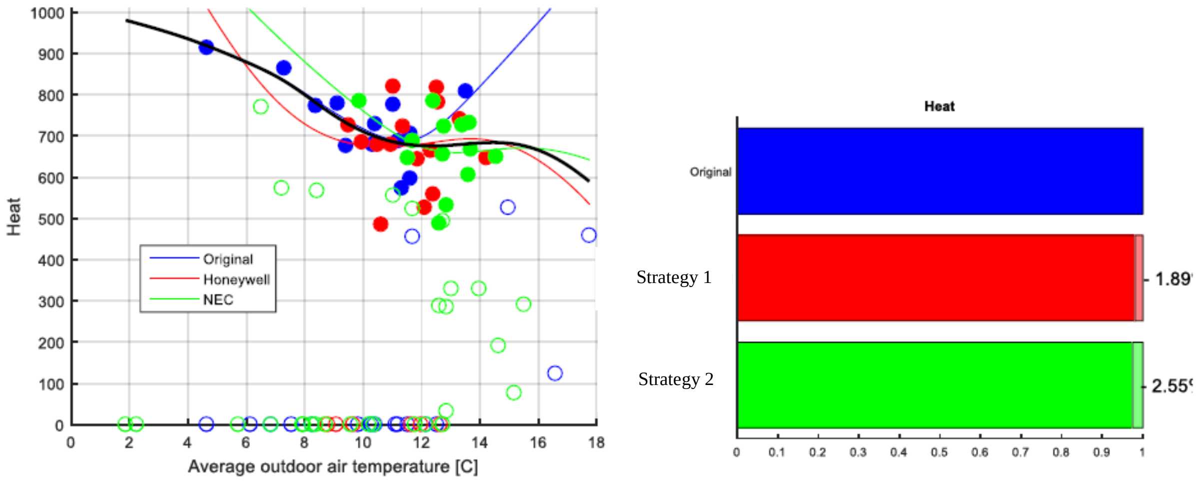


Figure 6: Example of results for Sierra Elvira School

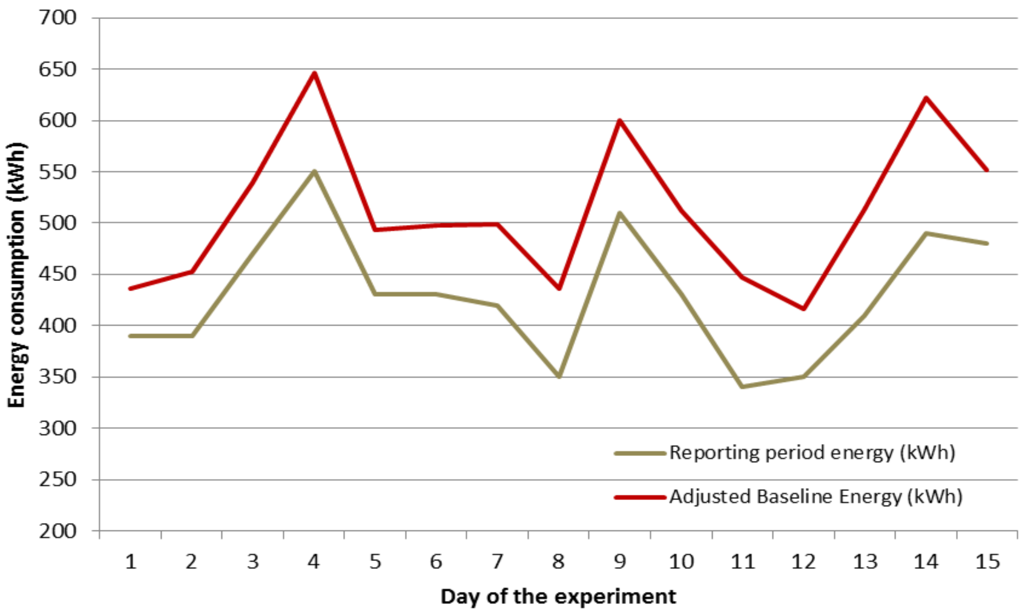


Figure 7: Implementation of the IPMVP protocol in the use case 1 in Sierra Elvira School

3.2 Scientific Objective SO2: Integrated Automation and Control Services

SO2 focuses on the high-level intelligence services. Towards the SO2 objectives, most of the work has been carried out within WP5. The work within this context focused on a number of interrelated aspects:

- Integrated Control Services, to improve operational performance.
- Technical Building Management Services, to provide functionalities related to fault- and anomaly-detection, as well as KPI evaluation.
- Integration services, which are based on an ICT service deployment and interoperability architecture, the application (APO) kernel. A topic of investigation has been the extraction, transformation and use of data obtained from structured sources, e.g. IFC4 STEP files. This is related to meta-data critical for the configuration of the services and the kernel.

For model-based services, whether they are used for control design, fault-detection or virtual sensing, the thermal models produced as part of the work towards SO1 have been utilised. More details on results and foreground generated towards SO2 for each of the aforementioned points is given in the sections below

- Integrated Control

The Building Automation and Control (BAC) functions defined in EN 15232 and ISO 16484-7 provide a comprehensive categorization of energy management services, and facilitate a generic BAC selection process suitable for many buildings, supporting common HVAC and energy systems and enabling the development of a set of control strategies considering synergies between facilities and subsystems. In the current state-of-practice, the building administrator is tasked to study historical data of the building performance and/or the occupant behaviour and manually adapt the control logic (tuning controller parameters) following common rules. It is very often the case that these decisions are not good enough: even in the case of good configurations, it is very hard to encapsulate good strategies within a static set of rules. Also, tuning of individual controller parameters might not (and probably will not) result in good performance as unintended consequences will almost always occur. The situation can be particularly egregious for buildings with complex energy concepts, where the complexity of integration becomes formidable as all the systems have to operate harmoniously together.

Within BaaS, this manual tuning process is replaced by a methodology developed following two axes:

- Predictions instead of study of historical data: here along with gathering and analysing historical data from the building to improve the efficiency of BAC functions, we also utilize (weather, occupancy, equipment gains, etc.) forecasts to determine the (near) future state (e.g. comfort conditions, demand, etc.) of the building. This allows for a constant adaptation of the control logic to the (predicted) needs of the building and the microclimatic conditions of each site, a process that needs to be repeated;
- Automated control design: since using predicted data for BAC functions optimization implies frequent design intervals (e.g. once a day), it is practically infeasible to tune all these functions by hand. Thus, an automated control design process is defined and posed as a classical optimization problem over a search space which is related to the tuneable control parameters.

Figure 8 provides an overview of the developed methodology along with a comparison to the approach as hinted upon by the EN 15232 and ISO 16484-7 standards.

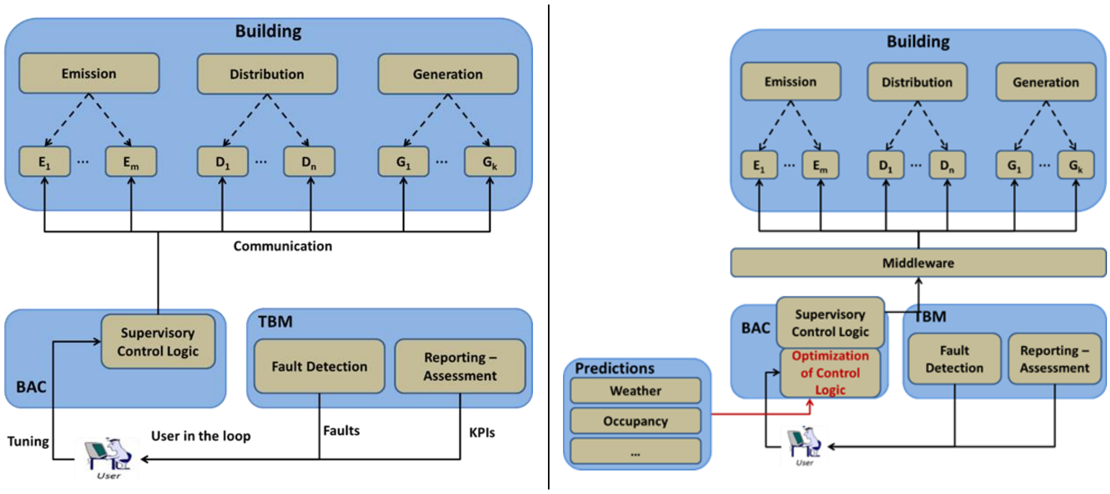


Figure 8: Left: Building Automation and Control System according to EN 15232 and ISO 16484-7. Right: Prediction-enabled control design.

➢ Model-based Control Design

While the list of BAC functions in EN 15232 and ISO 16484-7 standards describes (to a good level of detail) the control function blocks, it provides little by way of implementation on the logic behind each function. For this reason, we defined a set of parametric controllers for each controllable element of the building, based on expert knowledge. These controllers can be of various types, like e.g. linear functions of external and internal sensor measurements, Finite State Machines (FSM), etc. Some examples of such controllers are shown in Figure 9.

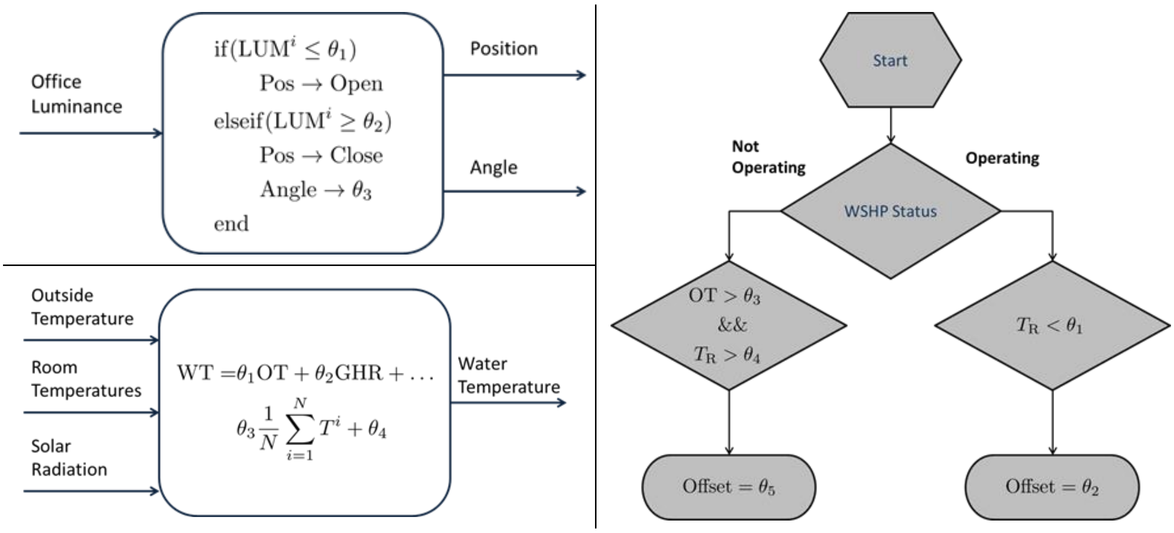
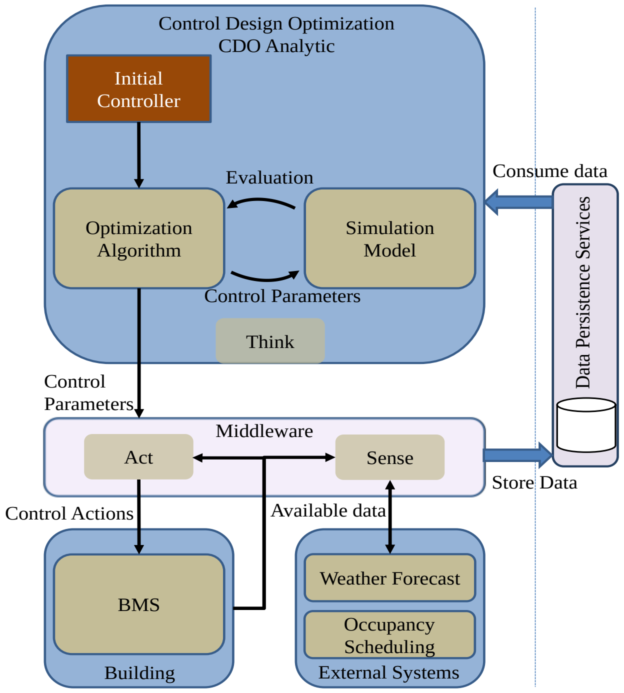


Figure 9: Different types of parametric controllers defined within BaaS

The coordinated building operation is ensured by the proper tuning of all the parameters of all the controllers simultaneously, taking into account the complex interplay between the various building sub-systems, as well as the disturbances from the weather and the occupants.

The overall Model-based Control Design process is shown in Figure 10 right. In this set-up, the control design problem is posed as a constrained optimization problem, with the cost function to be minimized a performance index – say the primary energy – while ensuring that a set of constraints – say, thermal comfort (ISO 2005, ASHRAE 2010) or visual comfort – are not violated. The information from the thermal simulation model is utilized to design control actions adapted to the forecasted thermal response of the building. Since the look-ahead period is typically a few days and depends on the availability of forecast data, the Model-Predictive Control paradigm is adopted, where the optimization problem is iteratively solved in a receding horizon manner.

In model-based control design methodology developed within BaaS, we utilize detailed thermal simulation models using thermal simulation software like EnergyPlus. While these models are able to capture all relevant dynamics and thermal phenomena in the building, they are characterized by high execution times, hindering application in cases like control design, where repeated evaluations of the model are required. To cope with the increased computational burden a surrogate-based stochastic optimization algorithm has been applied, shown in Figure 10 left, and described in more detail in Deliverables and Journal Publications available on the project web site.



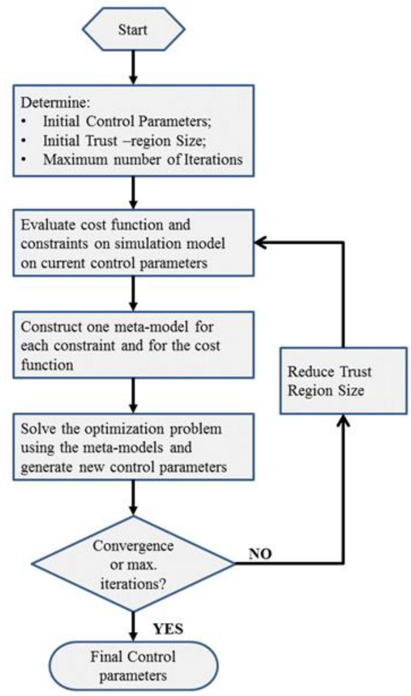


Figure 10: Left: Surrogate-based Stochastic Optimization. Right: High-level overview of the Model-based Control Design Process

➢ Adaptive, self-learning control strategies

In some cases, a model of the building might not be available and the stakeholders do not wish to invest in the development of such model. Here, optimization algorithms that rely on available data are an alternative path towards improving the performance of a building.

Two data-driven building optimization approaches have been developed and applied within BaaS: i) a methodology combining neural network predictions of the comfort conditions and the total energy consumption of the building along with genetic algorithms for optimizing the control strategy to be applied; and, ii) a reinforcement learning approach, based on a variant of the Fitted-Q Iteration (FQI) algorithm. Both approaches were applied to the SE school pilot, where a model was not readily available.

In the first approach, the following steps were followed:

- An approximation of the microclimate of the area of the building is performed, based on forecasted weather data;
- Neural network models have been trained using historical data for predicting the indoor temperatures in each zone and the total energy consumption of the building, based on the forecasted weather conditions, the expected occupancy and the control strategy applied at the building;
- An optimization process based on genetic algorithms is initiated to test different candidate control strategies on the neural network models in order to determine the best control strategy to be applied in the building;
- The resulting control strategy is applied to the building and the whole process is repeated every hour in a receding-horizon manner.

In the reinforcement learning approach, the following steps have been followed:

- The cost function (negative reward) is defined as a combination of (i) discomfort costs and (ii) energy costs. Figure 11 left shows the complex cost function design for the SE pilot building;
- The basic approach is strongly data-driven, being a variant of the widely-used the Fitted-Q Iteration. The main difference with the classical definition of the FQI algorithm was enhancing the algorithm in order to allow application in a receding-horizon manner, that is being applied every e.g. one hour and designing a control strategy until the end of each day. A sketch of the modified concept is shown in Figure 11 right.

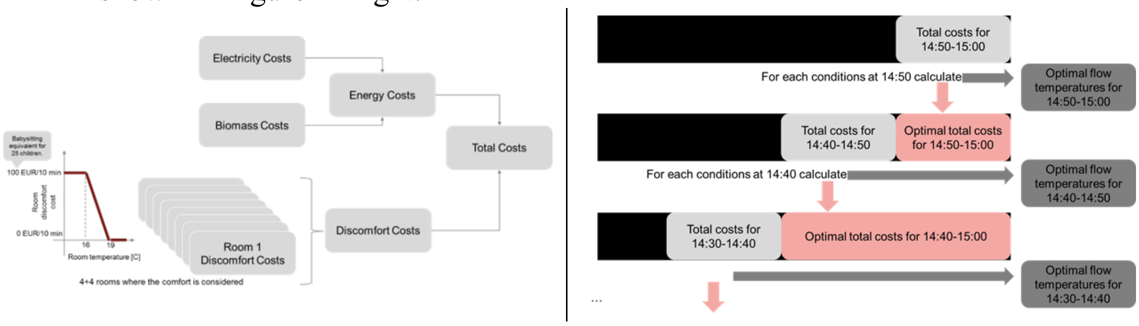


Figure 11: Left: Cost function for the reinforcement learning approach. Right: FQI with variable length of the states vector.

➢ Assessment Services

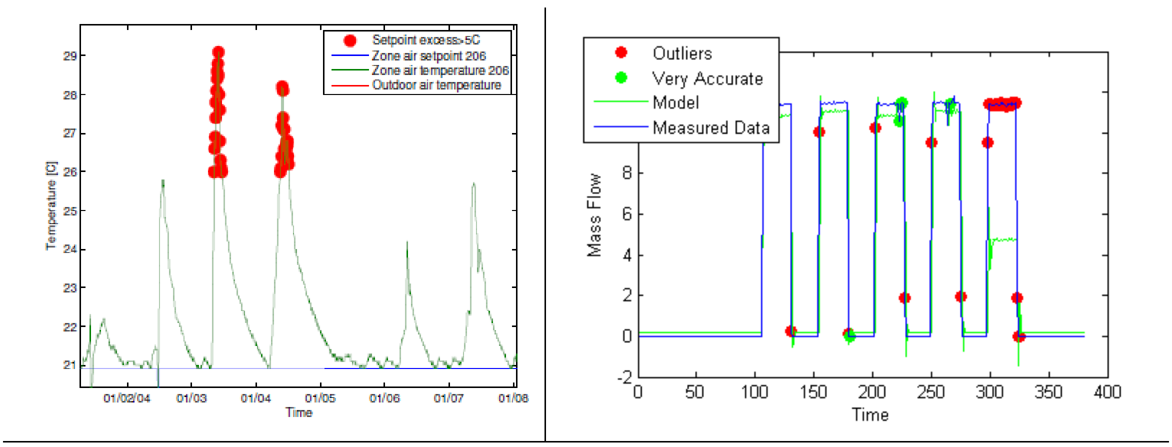
Assessment services have an indirect but equally important role in achieving operational efficiencies – or, more precisely, in mitigating operational inefficiencies. In a perfect world, systems would be tuned and working perfectly all the time; situations like simultaneous heating and cooling, or continuous operation of fans and chillers, should not happen as they contradict all notions of reasonable operation. Still these situations occur all too often, and if left undetected can have undesired effects in performance and/or comfort. In complex systems all possible modes of interactions are hard to predict and all possible errors and error conditions might be hard to enumerate. Moreover, performance of equipment will degrade over time and, if undetected, can have pernicious effects to performance. It is for this reason that assessment functionalities (or assessment analytics) should be a part of a Technical Building Management toolset.

This is already understood and documented in the BACS standards. As indicated in EN 15232 and ISO 16484-7, a special category is allocated for TBM functions; mostly highlighting the importance of fault detection and diagnosis as well as the need for reporting information on energy consumption, indoor conditions (comfort), and a broad (but unspecified) set of recommendations for improvement. The act of reporting is inextricably linked to calculation of KPIs.

Within BaaS we have defined three types of Fault Detection and Diagnosis analytics:

i. Rule-based diagnostics: The rule-based diagnostics comprise of analytics that are implemented as a set of fixed rules, which are specific for each sub-system of the building and are compiled by an expert;
ii. Context-free diagnostics: The most important drawback of the rule-based diagnostics is the need of rich context information which might be costly to be provided. The context-free diagnostics relaxes from the assumption on the context information and works only with the observed data directly;
iii. Model-based diagnostics: Finally, the model-based diagnostics are able not only to detect abnormal behaviour, but also to quantify the related inefficiency, which is important, since the awareness of the discrepancy between real and reference power consumption is one of the most interesting functionalities that inform the end-user about the operational costs. Even though that in literature model-based diagnostics rely on defining first-principles models for each monitored system – which requires a complex configuration effort – within BaaS we have followed data-driven modelling approaches, such as Gaussian Mixtures models and Particle Filter tracking algorithms.

An example of a detected fault using an algorithm from each category is shown in Figure 12. Apart from the FDD analytics that are deployed in the Application Layer, diagnostics based on Key Performance Indicators (KPIs) are performed within the BaaS data warehouse (DWH). The DWH functionalities allow online calculation of key performance indices that can serve to more intuitive formulation of diagnostic rules.



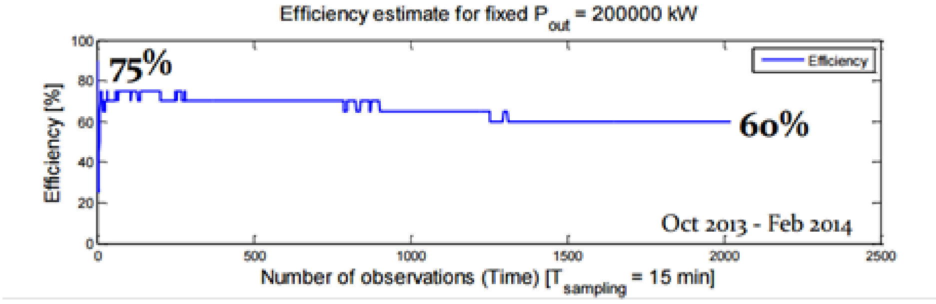


Figure 12: Top left (rule-based diagnostics): Temperature set-point differs more than 5°C compared to the zone temperature. Top right (context-free diagnostics): Detection of anomaly in mass-flow signal that did not correspond to the values. Bottom (model-based diagnostics): Boiler degradation in time - the efficiency decreases.

- Integration

Within the BaaS ICT architecture, the Application Layer (AL) is designed to host the necessary algorithms to analyse the building data, interactions of processes and generate respective mechanisms to control the building. Specifically, the services provide core intelligence, building/facility assessment and monitoring, prediction and optimization services, utilizing information made available by the data layer service.

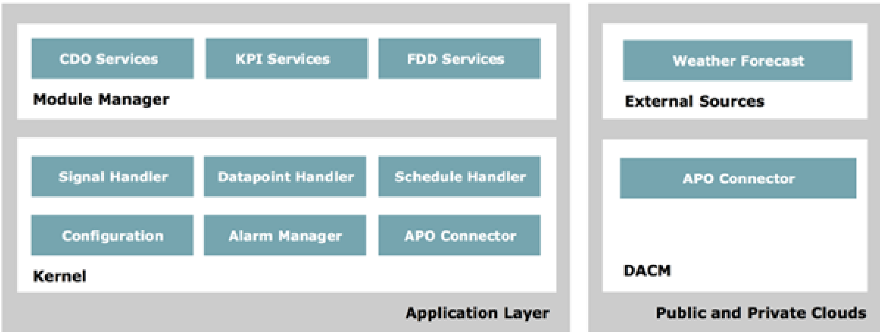


Figure 13: Application Layer architecture

The Kernel, which is a crucial interoperable component of the AL comprises a set of software modules, responsible for support of the execution of installed services and supporting their data access requirements. All services requiring access to real or historical data as part of their execution process, utilize interfaces that create requests to the Kernel and, if needed, queries are relayed to the Middleware (MW). The responses to such queries are events containing raw data that might require pre-processing, which then are forwarded to the requesting services through the AL. The pre-processing functionality is achieved on a set of software abstractions which provide methods for accessing signals and stored data through a unified interface.

The Kernel is taking care of the proper installation and life-cycle management of registered services. All the components presented in the Kernel need to interact and exchange information in order to perform an operation. For that purpose, the design of the components follows a modular approach that fits naturally with the objectives of OSGi. The modularity reduces the complexity of the development, therefore the OSGi has been chosen as the framework for developing and deploying software components within Kernel. The internal low-level communication between the components is done with the service references declared in every single component as dependency.

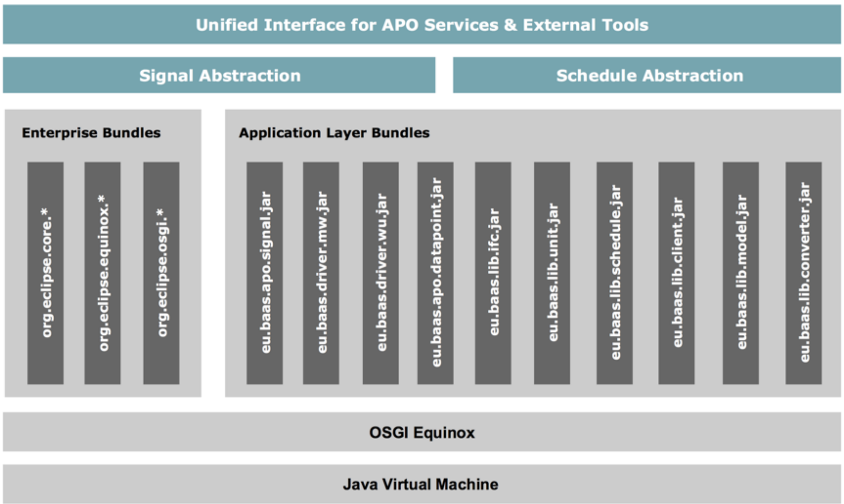
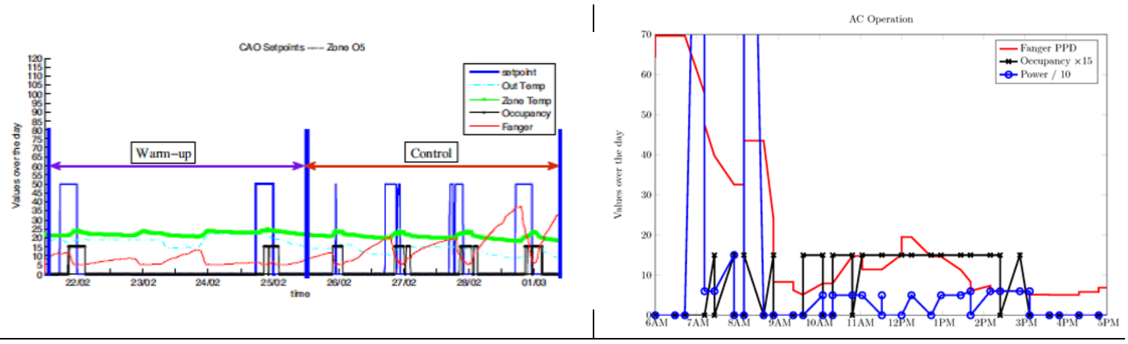


Figure 14: Deployment Layer architecture

All the BAC functionalities of the TUC test-bed, as well as the ZUB and CARTIF pilot buildings, along with the TBM analytics for these buildings, have been configured and deployed in the Application Layer. The schedules (time-series) of the control actions applied to the buildings, as well as the schedules for the historical sensor data, are retrieved externally using the Client Library.

Figure 15 shows some typical results from the deployment of BAC functionalities in the three buildings. The top row shows the control of the radiators (left) and of the AC unit (right) in one office of TUC building, for a winter and a summer experiment respectively. The middle row shows the hot water temperature control of the distribution circuit (left) and the heating setpoint for one office (right) for the CARTIF winter experiment. The bottom row shows the control of the blinds in one office (left) and the hot water temperature control of the distribution circuit along with the building heating setpoint (right) for ZUB building.



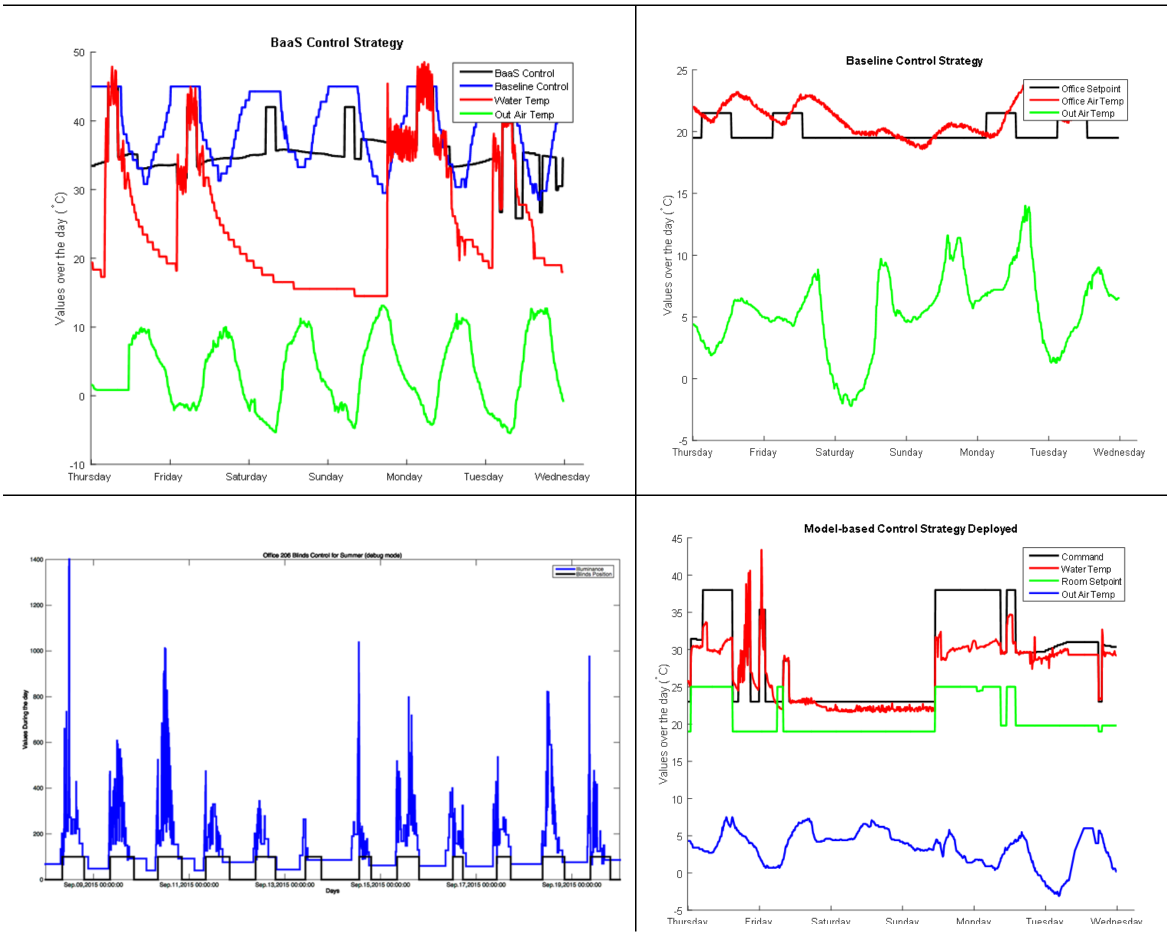


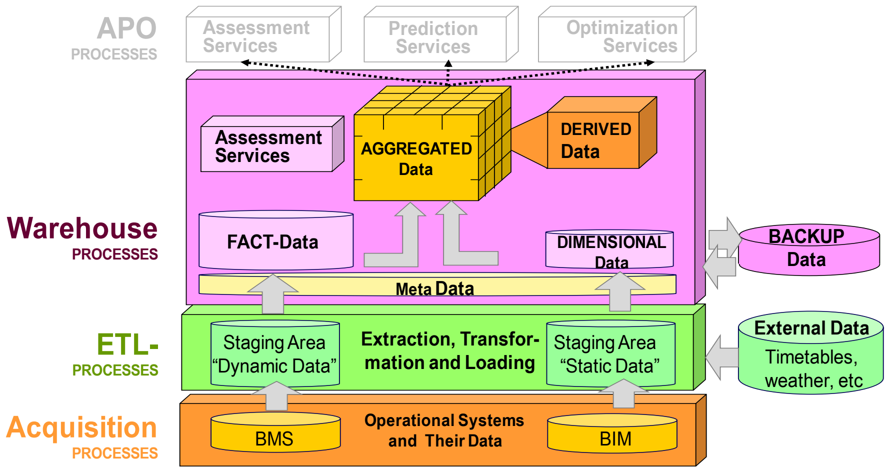
Figure 15: Top: Winter and summer validation experiments in TUC test-bed. Middle: Winter Experiments in CARTIF pilot building. Bottom: Winter Experiments in ZUB pilot building

3.3 Technological Objective TO1: Data Management: Working on existing initiatives and ongoing projects results, integrating State of the Art of extended BIM, EEB Ontologies and Standards

TO1 is primarily focused on the WP2, WP3 and WP7. The data warehouse is one of the core elements within BaaS due to the requirement for data storage and subsequent data analysis.

➢ Interdisciplinary Model Integration for Monitoring and benchmarking

The data warehouse platform developed under WP2 supports the integration of data generated by two distinct IT-platforms, (1) building monitoring data. This is so called dynamic data generated by monitoring systems and usually managed by BMS (see lower left) and (2) the building documentation.



This is so called static data generated by the AEC-sector and usually managed in BIM-systems (see lower right). Since this data can be compiled in an automated way substantial efficiency gains can be achieved through this (standardised) data integration.

Figure 16: Datawarehouse schema

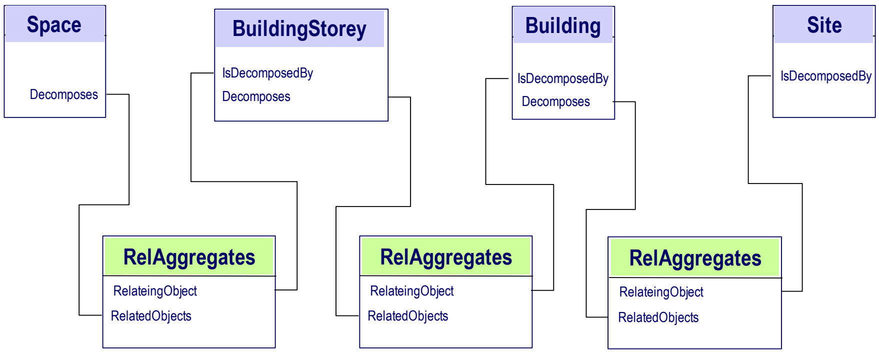
➢ Fact data

IFC provides numerous property sets, amongst them so called Performance History Property Sets. These property sets provide a value and a time stamp. The advantage of using IFC4 property sets is that fact data is already structured according to its source system. The table below provides just a few examples of property sets. IFC4 provides 33 distinct performance history property sets.

	BuildingAutomation		
1	Pset_ActuatorPHistory		Pset_SpaceThermalLoadPHistory
2	Pset_AlarmPHistory		Pset_SpaceThermalPHistory
3	Pset_FlowInstrumentPHistory		Pset_BoilerPHistory
4	Pset_SensorPHistory		Pset_ChillerPHistory
5	Pset_UnitaryControlElementPHistory		Pset_CoilPHistory
6	Pset_UtilityConsumptionPHistory		PSet_CondenserPHistory

Table 1: Building Automation IFC objects

➢ Dimensional Data

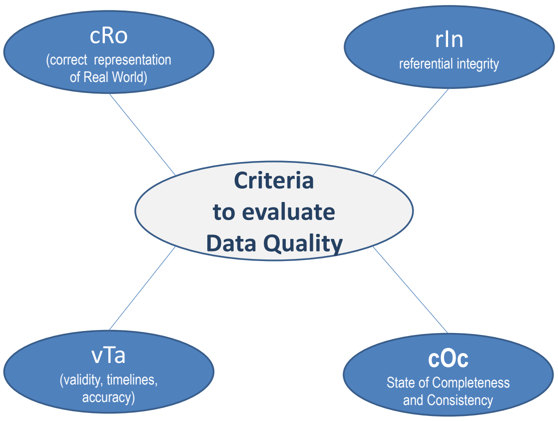


Especially the availability of hierarchical relation-ships in the BIM model allows the fast and efficient generation of "analytical hierarchies in the Data Warehouse Platform, e.g. see the location hierarchy modelled in IFC4 on the left.

Figure 17: Dimensional data approach

➢ Data Quality Considerations

BaaS developed a methodological approach for data quality checking and data cleansing.



(1) The cOc check ensures that data is complete.
(2) The cRo checks ensure that data is in the expected range, i.e. data makes sense from a contextual (engineering) point of view.
(3) The rIn checks ensure that data is properly linked, e.g. the location and type of measurement devices are known.
(4) The vTa checker ensures that data is valid (e.g. generated by the appropriate source) and complete over time (e.g. taken at a comparable time stamp)

Figure 18: Data quality

➢ Integration with Energy Simulation and Control Tools

Whole BIM models are necessary for providing input to high-level services at time of generating the simulation models. Additionally, extra data sources are important for the proper implementation of the control strategies, as for instance, the information coming from the buildings. Typically, these data sources are heterogeneous and they do not work in the building context. Then, harmonization mechanisms are required for allowing interoperability among all the elements.

Thus, every data related to the buildings topology and the components installed in them are capable of being described in an ifcXML model. ifcXML information allows the creation of 3D building models, such as Figure 19. From the definition of the building layers, walls and windows the different building topologies and the zones to be simulated can be defined, as well as sensor networks. Then, according to SO1, when reading the information contained into the BIM models, thermal simulation of each of the building components and its control associated can be lately replicated into thermal simulation software. To achieve this result, the information classified in BIM and the information demanded by the simulation models must be univocally connected, making compatible the IFC classes with physical models. It is defined in this way component parametrization, inputs, outputs and as well how different models are combined.

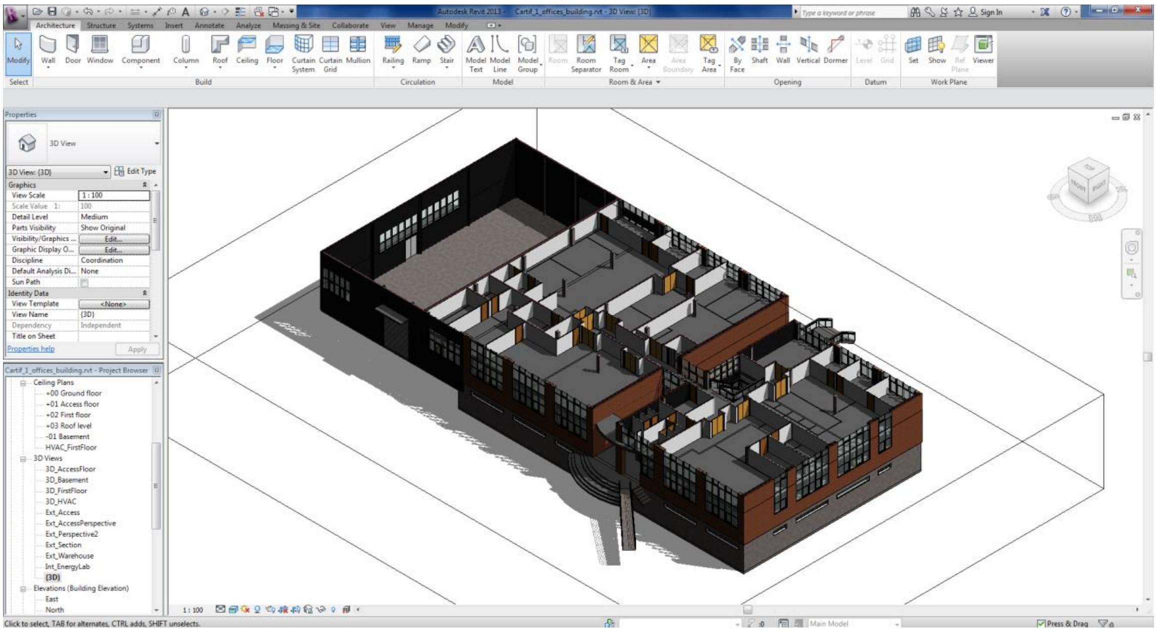


Figure 19: CARTIF 3D model in Autodesk Revit

For this reason, a BIM repository in form of BIM Server has been utilized under IFC4 in order to share the building models in this harmonized way. Two instances, as remarked in Figure 20, have been utilised with the goal of balancing the load of the requests and do not concentrate all the queries into a single entity. The models, whose level of detail depends on the control strategies, are made available through the middleware platform (Communication Logic Layer) that also harmonizes the data samples (see TO2).

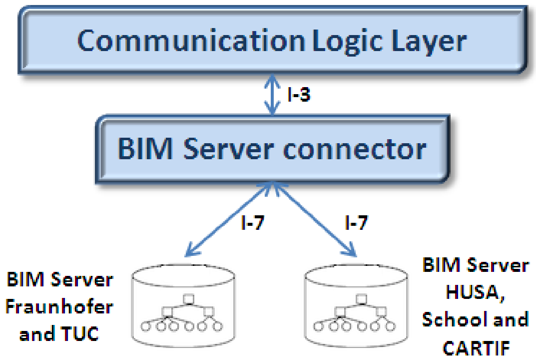


Figure 20: Deployment of BIM Servers

The above efforts to improve the modelling, accessibility, and standardised management of building documentation is a pre-requisite for the intelligent, advanced analysis of building monitoring data, leading to the capability for advanced performance analysis and subsequently high-level, aggregated benchmarking. Only the availability of descriptive data (also called dimensional data) usually compiled from BIM allows the introduction of a multi-dimensional performance analysis approach. The achievement of this BaaS Technical Objective comes timely, since commencing in January 2016 new legislation has been introduced in the UK (BS 1192-3) which emphasises on compulsory usage of BIM for building operation support. Standardisation efforts undertaken in other major EU-countries (e.g. Germany, Spain, France) indicate that BS 1192 is used to assist in the development of a common EU-standard.

The integrated usage of monitoring data (fact data) and BIM-data (dimensional data) is supposed to be a "unique selling point" for BaaS (and previously was for CAMPUS21) since these two projects aim to intensively bridge the gap between BIM (Construction Sector) and BMS (Automation and Control Sector). Bridging this gap is a pre-requisite that envisage efficiency gains in the construction and facilities management sectors can be achieved, since only through automated, integrated usage of the two major 'information sources' (i) the data quality can be improved, (ii) gaps or inconsistencies in data can be detected and compensated in a model-driven approach, and (iii) the understanding of building performance is further developed and not "simplified" like in data driven approaches.

Finally, the use of these standards is complemented within the WP7 where several discussions have been carried out with standardization bodies. In this particular case, buildingSmart has developed IFC standard and BaaS consortium has actively collaborated in order to provide feedback and advance in the next versions of the standards. Additionally, as BaaS has made use of the BIM Server platform, feedback has been also provided in terms of performance under the different forums and wikis that buildingSmart has available.

3.4 Technological Objective TO2: Middleware Platform: System Integration, Interoperability and Standards

The last objective, TO2 has as core the middleware platform which is completely developed under WP3. However, it is important to highlight that the middleware also contributes to the TO1 in terms of data harmonization, among others. This middleware platform is the core for the communication and interoperability among the pieces of BaaS system.

Thus, the developed platform was built relying on existing open standards, frameworks and technologies. Its design follows SOA and EDA principles and the CLL effectively utilizes the selected technologies, providing secured and encrypted communication via the Internet to assure security and privacy of transmitted and stored data. The CLL interconnected application layer instances, the data warehouse (TO1), and the building sites in 4 different cities across 3 countries unifying 3 different automation protocol standards. The designed architecture is drawn Figure 21, where the different pieces are interconnected by the Domain Controller (DC) at building level and the Data Acquisition and Communication Manager (DACM) responsible for the communication and other issues, such as alarms and user management, among others.

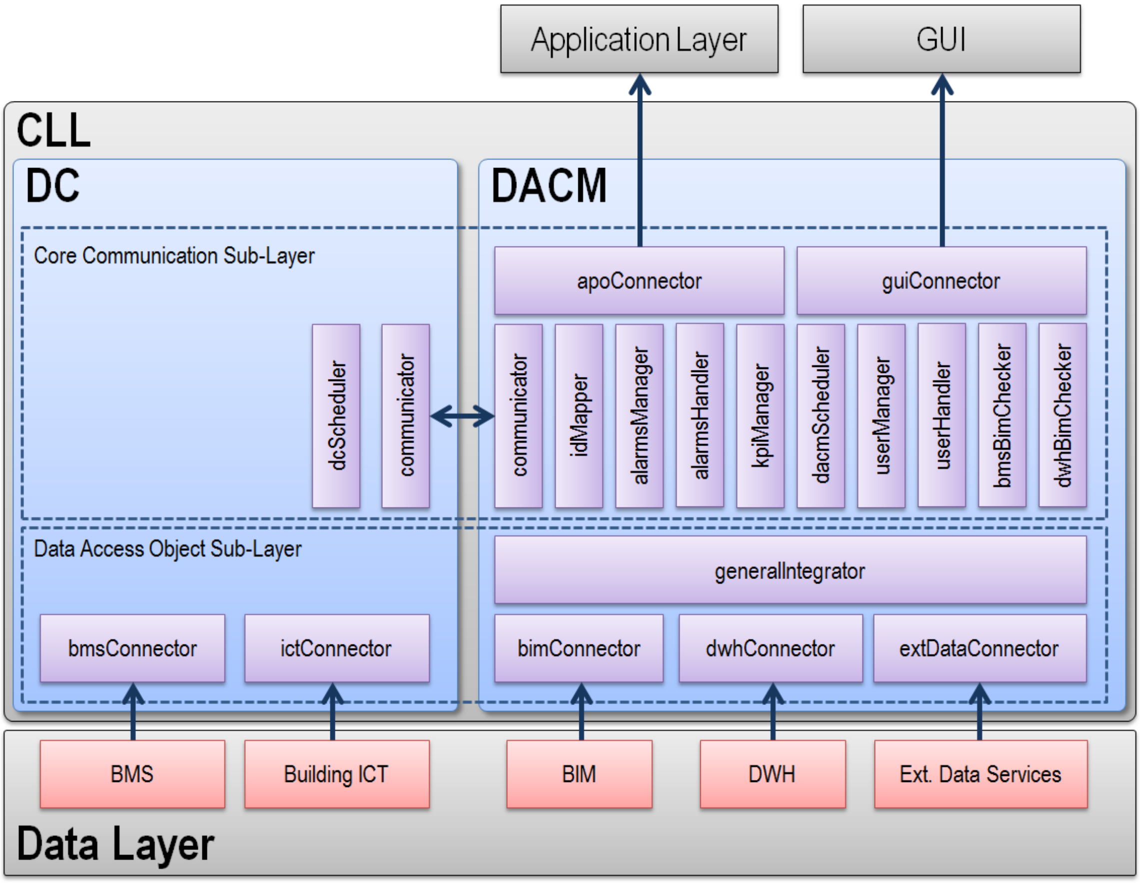


Figure 21: Middleware platform architecture

The CLL provides a unified communication model integrating distributed components of BaaS system: remote buildings with installed Buildings Management Systems, their Building Information Models, external services (e.g. weather forecasts), the data repositories, the BAC and TBM services on the application layer, and the GUI. As remarked in TO1, IFC4 data model has been used for the harmonization and data representation. Thus, IFC classes are mapped into the middleware operational phase where the aforementioned information is translated. The advantage is the capability of homogeneously integrating services, whenever the language is IFC4. Moreover, related to harmonization, related to low-layer multi-protocol connectivity to integrate a variety of building automation systems, auxiliary ICT-systems, and data storages, the CLL provides high-layer application interfaces. These abstract the complexity of communication to facilitate the integration of BAC and TBM services, as it was mentioned in the SO2 in the integration of the high-level services and its data exchange via middleware.

Regarding SOA and EDA principles, the developed platform under the CLL designed components according OSGi approach whose main advantages lie in the loosely-coupled services and “service-oriented” programming where each component is treated as a service that interacts with any other to overcome a task. This is even enhanced by the interface design according to OSGi, which provides an event-based mechanism to exchange information among different entities without the need of coupling them. This process uses the publisher-subscriber methodology where the sender only publishes the event into the framework and those components that listen to this event are the subscribers without caring who the sender is.

With these considerations and the development of the components depicted before, the BaaS CLL was deployed in all the buildings following the scheme in Figure 22. Since its deployment, interruptions were kept to minimum and the produced ones are related to maintenance aspects. Moreover, this deployment scheme is based on distributed architectures and explicit considerations related to cloud computing. This approach is not a fully cloud, although it provides the Building as a Service in terms the CLL abstracts the complex facilities of the building in a homogeneous manner. High-level services do not need to worry about the physics because the CLL is able to provide this information. Besides, the deployment has followed and efficient, flexible, and scalable design, where additional DCs could be integrated (i.e. more buildings), as well as high-level services. To sum up, the compatibility with different Cloud deployment options makes the CLL suitable for different business models.

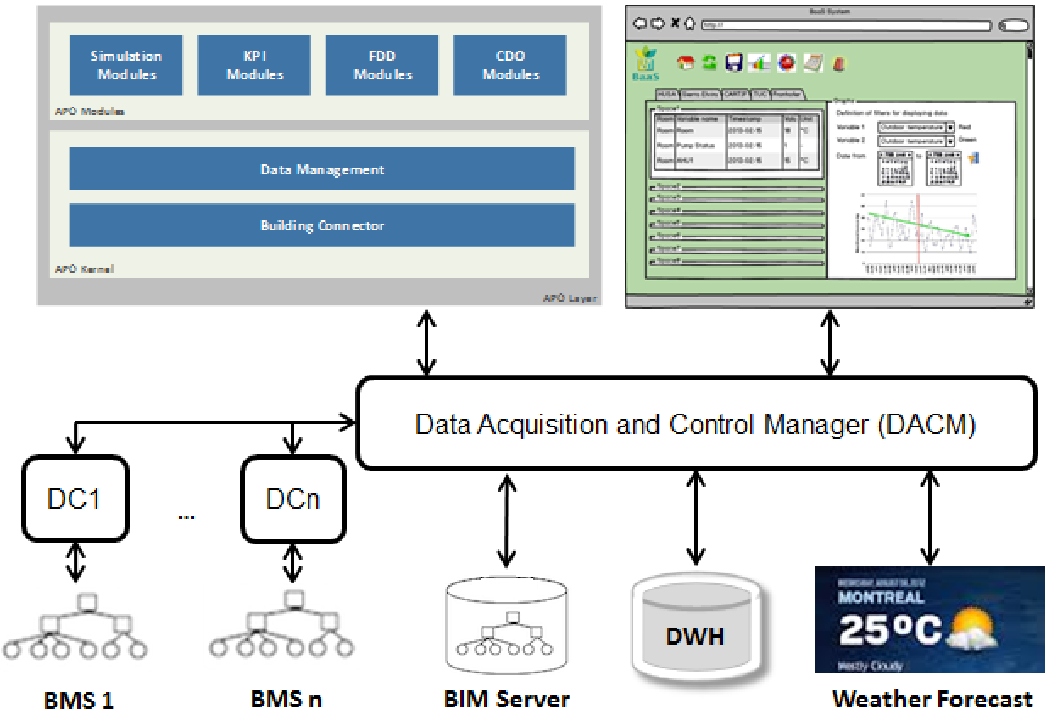


Figure 22: Deployment scheme

After an initial and stable deployment, continuous assessment of functionality and performance led to extensions of the CLL compared to the original design: for ease of application layer (e.g. complex data points of the Lon protocol), increased reliability (XMPP online status, data buffering), and additional security aspects beyond the VPN based access (authentication and authorization, GUI, enabling encrypted outsourcing of data to cloud storages).

Last but not least, privacy and security aspects have been taken into account (also received from technical comments), which have been iteratively addressed:

- The different links of the deployment are protected by a certificate-based OpenVPN infrastructure.
- The CLL User management and GUI implement standard means of security:

- User management accounts for user roles with differing access rights and permissions. User authentication is realized via standard mechanisms of username/password credentials. Standard means of ensuring password strength are a possible extension.
- User interactions with the GUI are protected by unique session tokens generated after successful user authentication.
- Different GUI Views are implemented in separated Web-Application contexts, encapsulating the risk of being compromised.

- Additional means of encryption for securely outsourcing "data at rest" to cloud storage providers were developed in collaboration with experts of the EU project SMARTIE. The concept was presented to the IoT community and implemented prototypically in the BaaS project without interfering with experiments.
- European regulatory aspects related to handling personal data have been discussed to guide practitioners in transnational deployments. The regulatory framework allows handling and sharing of energy data in the BaaS way, however exporting the data across countries depends on the involved countries' specifics.

Finally, standardization issues have been accounted in the middleware and contributions, together the CAMPUS21 sister project, have been provided into M2M standardization bodies. Furthermore, the publication of the fourth version of the IFC-standard in May 2013 greatly improved the work in BaaS, since a standardised meta-model for building services systems became first time available on an international scale. Thus, work in BaaS could focus on the further development of performance indicators and benchmarking criteria on component, sub-system and systems level in two well defined areas, (i) user comfort – primarily defined on "space" level and (ii) systems performance – primarily defined on the level of technical systems. This integrated approach is unique, since many other projects focus on a "non-integrated" approach, i.e. the emphasis is exclusively on the reduction of energy consumption, CO2-emmisions or operational cost. However, only an integrated approach ensures that the user comfort is not degraded through energy efficiency measures.

4 Lessons learnt

4.1 Lessons learnt from the application layer point of view

Through the final evaluation of the deployment of BaaS system, as well as the performance of the deployed control strategies, we can distil significant knowledge regarding the energy-efficient control of buildings.

The most basic conclusion is that there has to be a clear separation between low-level and supervisory-level control. The experience from BaaS deployment showed that when optimisation of energetic performance is concerned, supervisory-level controllers should be selected/tuned to affect performance improvement; low-level control has a more openration role, where targeted adjustments should be performed to support the higher-level logic.

Regarding supervisory-level control, a close study on the baseline control strategy of BaaS buildings reveals that open-loop controllers (e.g. controllers that generate actions based on the time of day) fail to capture the effect of very important features (like the solar radiation in a specific day or the actual in-building thermal conditions) and thus can lead to energy- or comfort-related problems, such as overheating. As such classical model-predictive control (MPC) approaches, fail to account for a number of important features and deviate, in real world, quite significantly from the theoretical performance bound. Closed-loop control schemes on the other hand, that utilize sensor feedback, can account for most of the influencing factors/disturbances affecting the building (like weather conditions) and adjust the operation of the controllable elements of the building in order to compensate for their effect.

A counter-intuitive conclusion from the deployment of the model-based control design process is that frequent dynamic updating of the control strategies may not be a critical aspect of an efficient BMS. Especially for buildings with slow dynamics, what is important for the control algorithm is to identify a set of dominant features (such as the storage of heat gains, e.g. from incident solar radiation, for heavy-weight buildings with large glazing areas) and adjust the parameters of all building controllers properly. This can lead to a scheme where a specific controller selected from a set of pre-defined control parameters is loaded to the BMS every day. The selection can be based on measured and predicted exogenous (e.g. weather-related) parameters as well as in-building (e.g. occupancy, internal gains) features.

The fact that frequent dynamic controller updates are not critical for intelligent building control is also supported by the resulting control strategy generated by the model-based control design process in ZUB (and can also be generalized for most buildings with good construction and equipped with HVAC systems with high time-constant). This strategy, in essence, attempts to discover an optimal pre-heating schedule for the entire building. This makes sense, since any change in the control actions (e.g. changing the heating setpoint of an office) has no effect in the indoor climate conditions of the offices in real time, due to the very high thermal mass (inertia) of the building and the time-delay of the actuating system (TABS). Thus, the best strategy is to pre-heat the building to ensure comfortable interiors early in the morning, but stop heating in time to avoid over-heating in the afternoon – out alogirthms were able to discover these strategies and properly adjust pre-heating parameters, according to the current daily forecast.

The analysis on the control properties of the previous paragraph is also a valid argument on why we did not utilize weather predictions as inputs to the controllers within BaaS, but used historical data instead. First of all, the use of accurate weather predictions is critical only in the control of slow-reacting buildings (like ZUB), where accurate predictions on e.g. solar radiation can help to determine the optimal pre-heating schedule of the building. In addition, we have verified during the deployment that the quality of the weather predictions can be very low, thus the estimation of the micro-climate in the area of each study building is a strong pre-requisite towards utilizing weather predictions in the control strategy. Finally, another reason for not including weather predictions as inputs to the controllers is the desire to have future collaboration with building automation solutions providers and encapsulate the designed control parameters in embedded hardware controllers. In this case, there are only few product lines by specific companies with the ability to provide access to external weather forecast services.

Another important aspect of the deployment analysis, is that within BaaS we have verified the suggestions provided in ISO 16484 regarding BAC functionalities. Here, indeed controlling all layers of the building systems (generation/distribution/emission) in a coordinated manner can lead to improved building performance compared to control solutions restricted to specific building sub-systems. In addition, higher flexibility and richer collection of controllable elements can lead to more efficient control strategies.

The entire deployment and assessment phases of the BAC functionalities have highlighted the significance of TBM functionalities. BaaS project execution confirmed observations expected by industrial partners: any building optimization tool faces 3 major challenges:

- Limited building instrumentation. Apart of few standard temperature sensors, a standard building is typically not equipped by any advanced sensor and total number of connected sensors is pretty low. Some sensors are hard-wired to nearest control loop and data is not collected and archived.
- Building instrumentation and building management system are often not properly commisioned or their installation degraded since commissioning. As feedback control can compensate for such arrangement, it may remain unnoticed for a quite some time.
- Equipment ages and even with relatively good maintenance reaches its time-between-failures which results in not optimal operation. This again may remain unnoticed for a quite some time.

Suprisingly many such faults and issues can be easily detected manually, but this required a skilled technician's intervention. This is often problematic, as every technician is typically under pressure being responsible for a number of sites or even worse – he or she knows about the issue, but he/she is not fully aware of financial consequences. With pernament pressure on cutting costs and increasing labor cost, it is more likely that building automation will be more automated with less manual interventions in a near future.

As any system optimization depend on reliable and accurate data collection it is essential to regularly run at least simple fault detection tools in order to make sure collected data are solid input to any optimization algorithm; there is just a little benefit in controlling in an intelligent manner a malfunctioning system.

The following comment is also in place: there is a potential for energy savings through improving the building control strategies. But depending on the building there might be more or less energy saving potential. This directly relates to the quality of the fabric and the associated sensitivity that can be exploited from better control. So, improved control is a viable ECM but only for buildings with good design and construction. The TUC building is an illustrative counter-example: because of the poor airtightness and light-weight characteristics there was very small energy saving potential through control; TBM though remained relevant, mostly for counteracting irrational user behaviour. In that sense a fabric-first approach is recommended: first ensure that the fabric and building services have no obvious problems (e.g. poor airightness). Once these are resolved then ICT-based solutions (e.g. better control) can have a positive impact on consumed energy and occupant comfort. In that sense our work leads to the mantra: “There is no sense in optimising a faulty building.” This has been well understood in BaaS for all buildings available in the context of our experimental investigations.

Also the level of sensing equipment is important: the TUC, CARTIF and ZUB buildings had an immense number of sensors that provided useful information but they are not required in normal building operation. The amount of sensing to be installed gives additional opportunities for more intelligent control, but also increases the integration complexity. This is also reflected in EN15232, but the standard is misguiding in that the expected savings may not always realised in practice as they depend on other parameters like the building fabric and the control sensitivity. Moreover, the existence of that large number of sensors installed, allowed the researchers to find which of the sensors represents better the building state, or in other words, how accurate is the thermal representation of a building when, only the typical thermostats existing in a building are used to identify and validate the simulations models, that will be lately used for control. As it has been seen, those simulation modules are useful for buildings which capacity or the speed with which they react against changes of occupancy or expected weather conditions is so slow. In those cases, accurate models are giving the best to BaaS.

Nevertheless, prior to any optimization is essential to do at least basic level of FDD (fault detection and diagnostics). Many HVAC systems are faulty, that means stuck or broken dampers, leaking valves are ever present in real systems. Optimization of such system is still possible, but it does not lead to optimal system behaviour, many faults are compensated by HVAC control. This preserves thermal comfort for tenants, but leads to energy wasting, and consequently to worse Return of Investment (RoI). Despite possible rich data collection, it is still difficult to fully automate fault detection and diagnostics; real HVAC systems are very heterogeneous and rich building information models are rare. Therefore it is difficult automatically interpret all data points meaning and in reality it may be necessary to add man in the loop to properly assess HVAC state.

More detailed technical comments are also in place: within BaaS we developed and tested a number of algorithmic approaches to supervisory-level building control design. These fall under two broad categories: model-based in which a physics-based model of the building is used as a surrogate of the real building; and, data-driven in which data from past building operation are used to train regression models in a supervised ML fashion. The attractive features of data-driven approaches are that there are very little requirements except from past data. As such it requires relatively little effort for the problem setup. In the case of model-based approaches the need for the setup and calibration of a simulation model poses significant requirements that – if a model does not already exist – can make it prohibitively expensive to setup.

This has been realised early on within BaaS and we chose to use standard models rather than purpose built state space models. In addition the work within WP4 (building simulation) where the extraction of information from structured data sources (e.g. IFC files) towards automating the setup of simulation models can have positive effects to the time (and amount of expertise) required for the setup of the simulation model. On the other hand for data-driven approaches, relatively good quality data are required. The predictive capabilities of regression models are as good as the data provided. It is impossible to explore controller setups that deviate significantly from the data available to identify new innovative strategies: as such data-driven methods are quite appropriate for controller parameter tuning. This is reflected on the experimental evidence collected: the performance of the model-based controllers was superior to data-driven ones but at the expense of much more complexity. It has been shown that both approaches are valid (and some concrete numbers are provided as project outputs) but the lesson learnt suggests that: model-based approaches are best suited to *offline* understand and select good supervisory controllers (as well as relevant configuration parameters); data-driven approaches can then be used for *online* tuning and day to day operation. This hybrid approach seems to be ideal from a cost-effectiveness perspective. Fault detection is probably more important than control optimisation. In all buildings investigated, problems surfaced that were detectable with the data we had available. Exploiting the data and detecting anomalies (including controller misconfigurations) is likely to have the biggest impact in the real world – actively contributing to the discussion regarding the gap between predicted and actual performance.

4.2 Lessons learnt from the DWH point of view

In general, the main prerequisites for failures and mistakes during the BaaS research project can be named as:

- unplanned violations of accurate data input for constant readiness of this data for analysis, with consecutive excess of deadlines and norms for admissible data cleansing/replacement exercises;
- failure to follow the agreed schedule for compulsory actions of maintenance on demo-sites and equipment involved; this include an irregular (or even absence) intervals between related staff (e.g. facility managers and technicians working on-site) training events dedicated to support those new techniques, methods and approaches developed for the project' progress;

In case when these prerequisites have no concrete reasons and sequential actions have not been taken by the research coordinator - then faults and mistakes won't be slow to appear, and accumulation of them into unsolvable brainteaser is more real, as more rough the initial prerequisites are.

4.2.1 Lessons learned for "Data Compilation and Cleansing"

The task of data gathering in BaaS include the extraction of the performance-related data from number of demo-sites, processing and compilation of this data into the DWH as well as the critical evaluation of data sources' stability and the assessment of data quality with following cleansing.

Data compilation procedures in BaaS were performed with making sure that errors are minimized and that ancillary and benchmark information is used where possible. Specific adjustments to the MW and DWH also being employed to make source data consistent (e.g. regular updates to mapping tables).

The following issues discussed under this topic:

Insufficient harmonization between standards

Observations:

BACnet introduces eight different device profiles, such as Smart sensors, smart actuators, application specific controllers, advanced application controllers building controllers operator displays, operator workstations and advanced operator workstations. In consequence the standard focuses exclusively on the specification of control systems. There is no requirement for a standardised description of the relationship between the above mentioned control elements and the related buildings elements, e.g. the sensor is installed in room "X" or the actuator controls supply system "Y".

In the absence of such definitions programmers of control systems add this information as comments into the documentation of the BAC-system. It is obvious that the "non-standardised" documentation will lead to inconsistent, incomplete documentations and does not allow the automatic generation of documentations. Labour intensive "interpretations" complemented by field inspections are required, in case of maintenance, replacement, or extension of BAC-systems and components.

In comparison to the above situation the Building Information Modelling Standard ifc (ISO 16739) provides holistic modelling capabilities for buildings, building services systems and building automation and control systems.

BaaS solution: In order to address the above deficit, we developed so called "Mapping Tables" which allowed the middleware to map the BACnet-semantics and identifiers against the ifc semantics and identifiers. However, the development and maintenance of those mapping tables is labour intensive and may lead to errors in case BAC-components are added or modified.

Recommendations:

For the development of "future proof" BIM and BAC-documentations it is recommended to select a standardised, open, comprehensive meta-data model. One example and an already introduced "Best Practice" in countries like South Korea, Finland, Norway, Singapore is the Industry Foundation Classes (ifc). Furthermore, commencing in January 2016 the U.K. Government has made the preparation of BIM-documentation a mandatory part in all public procurement processes for new buildings, extensions and renovations. A part of this documentation are (1) the EIR-document (employers' information requirements) and (2) the BEP (BIM execution plan).

Owner, operators of buildings shall request that the following elements of the ifc4-standard are completed:

ifcRelContainedInSpatialStructure: This objectified relationships documents the relationship between any spatialStructureElement (site, building, storrey, space) and any DistributionElement. Since ifc breaks down DistributionElements in two major groups, such as DistributionFlowElements and DistributionControlElements the "Spatial Relationship" between building elements, buildings services systems and their components and building automation systems and their components can be defined in a standardized way, using commonly agreed semantics.

Secondly, the ifcRelFlowControlElement clearly supports the modelling and documentation of the relationship between any DistributionFlowElement and DistributionControlElement, i.e. the relationship between components of building services systems and building automation and control systems.

Future design methodologies and tools are intended to integrate building automation network and therewith to enable a comprehensive building model including the automation facilities. The existing model structures in building automation networks have to be reused and integrated in IFC.

Inconsistent usage of data types for API-programming

Observations:

Usually, data compiled from sensors and meters is persistently stored in databases, either installed as standalone systems or being part of so called “advanced operator workstations”. Multiple so called “active network components” are involved in the transfer of data from source to sink.

During our work in BaaS and numerous other projects we observed that the consistent configuration of the incoming and outgoing interfaces of such devices can be improved. Observed reasons for wrong configurations are usually an insufficient systems’ documentation (see above) and a limited understanding of the consequences when installing API with wrong configuration.

In our projects we observed a tendency that “for ease of installation” field engineers prefer the usage of non-numerical data types. However, as a consequence of such “quick-fix”, “efficient” solutions measurement values are no longer interpreted as numerical values but by the value of their “character code (e.g. ASCII oder Unicode). Such values may even pass quality checks of DBMS since their values are in ranges equivalent to contextually meaningful values (e.g. ASCII code number 0 to 9 is in the range between 48 and 57, Unicode numbers 0 to 9 is between 30 and 39).

Recommendations:

We recommend to define, introduce and request the documentation of holistic quality checks as part of the commissioning during installation and upgrade of active network components in building automation and control networks (e.g. for gateways, routers, sensors, meters).

These quality checks shall include the identification of the value supposed to be measured (the physical phenomena) and the value being received by the “terminal device” in the information management chain (e.g. the database). In case of deviations, an immediate diagnosis shall be required, including a comparison of “input” and “output” values for each component.

In order to reduce the cost for those diagnosis tasks either the legislator or professional bodies can consider the definition of a minimum standard for diagnosis and quality checking interfaces for active network components.

4.2.2 Lessons learned from Performance Analysis

Fact data (in case of BaaS it is sensed and metered data) was recorded in incremental time steps. It was predicted (based on R&D experience) need for this information, which was compiled by determined time periods (e.g. for the last hour, the last 24h, the last calendar day/month) for further detailed building/system/component performance analysis. Therefore, the “raw data” stored in the fact table of the data warehouse needs to be aggregated in order to produce valuable information. The aggregation can be executed within different boundary conditions, such as “for one zone”, “for one building storey”, “for one system”, etc., which means multiple dimensions can be considered for the aggregation of sensed and metered data.

Derived information is calculated from multiple fact data sets based on the analysis of dimensional data and defined algorithms. Examples for derived information include the calculation of Coefficient of Performance (CoP) for dedicated devices. In order to allow the calculation of derived data, dimensional data must be comprehensive enough that the dependencies amongst system elements can be clearly determined.

The following issues discussed under this topic:

A misinterpretation what BIM is

Observations:

Many actors in the area of energy and facilities management, including owners and operators of buildings, still interpret BIM as a 3D-repository of building information. This leads to the following wrong perceptions: (1) A graphical representation is required. (2) Data about spatial relationships needs to be acquired through field inspections and is not a mandatory part of BIM. Both assumptions are wrong.

Furthermore, when requesting “relevant BIM data about the placement of sensors, actuators and other automation components in rooms” we received in the first instance floor plans in pdf-format. Since pdf is only a file-format for “graphical representation” and not a semantically rich format for building documentations this type of information provision requires a substantial additional workload for the population of “objectified relationships”. Usually, partners being responsible for data management and data analysis do not have easy access to the buildings in question. Therefore, filed inspections are costly, or even not a possible alternative for data acquisition.

Recommendations:

When starting new projects all project partners shall be provided with training to create an awareness what BIM is (and what is NOT BIM). Secondly, it is recommended that owners, operators and facility managers are briefed about mechanisms how to “export relevant data” from a holistic BIM-repository. A basic understanding of the meta-model definitions would enable BIM-users to formulate the appropriate “selection patterns”, including the knowledge what keywords and parameters shall be used for the formulation of such retrieval patterns. Furthermore, IT-service providers shall be encouraged to develop (parametrised) libraries for frequently used retrieval patterns. In case those libraries are developed with open standards they can be easily shared and used by “non-IT personnel”.

In the sections above we recommended to request the completion of the ifc relationships ifcRelContainedInSpatialStructure and ifcRelFlowControlElement. For the formulation of “intelligent, frequently used” retrieval patterns the availability of the following additional relationships might be of advantage:

- ifcRelAggregates (to define hierarchical relationships between spaces);
- ifcRelAssignsToGroup (to benefit from knowledge how elements are grouped in sets);
- ifcRelConnectsPort (defining how elements are sequentially connected, e.g. in directed graphs)

How to avoid repetitive efforts to program “simplistic” analysis tools.

Observations:

The Access, Predict and Optimize (APO) services delivered by BaaS were aimed to provide building stakeholders with appropriate decisions and services that are formulated based on available data taken from sources (such as a DW, BMS, BIM and external data sources such as weather data) available. It is appropriate for stakeholders to know how to access data across multiple sources while also knowing where to retrieve relevant data. However, the approaches and tools selected by different stakeholders to work with data may vary due to subjective reasons, e.g. because of personal skills and preferences. Furthermore, even in the case when data treated within selected SW environment (e.g. Oracle DWH for BaaS WP2), there are specific needs appearing to interpret, convert and represent this data differently. The tools used for that diverse range of applications include the MATLAB and MS Excel as the most common SW. Moreover, each separate stakeholder could develop his own unique Java code or Macro doing specific exercise, for example accessing DWH and extracting data from it in form of *.csv file, then converting data into some necessary format, cleansing it, analysing or adding other data. Finally, this data processed and used by stakeholder successfully, but the “root data” stored in DWH remains unchanged because stakeholders less likely willing to spend their time and update the DWH with improved data.

Recommendations:

Distributed responsibilities within one project/organisation/building management activity leading to repetitive efforts in data processing and limited or no feedback results of such a data use, and thus weak quality of central data repositories. This can be significantly improved by implementing a standardized approach to the way how stakeholders collecting and processing data, at list within a single project or organisation. Limited number of tolls and methods should be collaboratively nominated to be used during the project, so responsible person(s) will not only maintain the library of those codes and apps developed for specific purpose, but also make sure the data is updated (if possible) to its best quality possible.

One of the examples for IFC-compatible data is recommendation that IFC model checkers/viewers are selected to be able firstly see if building geometry is IFC compliant and second, to have the instant capability to view a virtual building without the need for memory hunger software.

4.3 Lesson learnt from the middleware point of view

In terms of middleware development, this piece of software has been properly implemented. although some complications have been faced, all of them are common in any software development, the middleware is successfully deployed and it is running 24/7. Nevertheless, the main conclusion from the middleware is that BaaS confirmed the findings of sister project CAMPUS21: OSGi is a stable and mature technology. It enabled the modular and scalable software design. Continuous operation in 24/7 was possible with minimal interruptions that were caused by external events.