D6.3 SYSTEM VALIDATION

2014.12.01

Short Description

This deliverable, due on M36 (October, 3rd 2014), reports procedures and methodologies for verifying and validating the SEAM4US system. So, it mainly concerns the validation of monitoring subsystems, the models calibration and the assessment of energy savings obtained through the control subsystems.

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EXECUTIVE SUMMARY

The validation process of the SEAM4US project posed a number of challenges because of the complexity of the system, developed for efficiently controlling facilities contained in an underground environment. Hence, the present deliverable is fully devoted to the validation of the deployed system in all of its basic hardware and software components: monitoring networks, models and control subsystems.

Three monitoring networks constitute the SEAM4US system, i.e. the energy, the environmental and the occupancy monitoring networks (@ D5.1.2 Final Energy management system deployment handbook for details). The environmental monitoring collected sensor data used for validating the station model. The environmental data also provided further feedback to the algorithms implemented in the control subsystems. The energy consumption monitoring gathered data for energy auditing and for validating the energy savings achieved in the station pilot. The occupancy monitoring, based on the data acquired from the CCTV network cameras, implements a crowd density estimator enabling feedback to control algorithms related to passenger occupancy. The data collected by the monitoring networks were verified using a set of reference measurements carried out during several on-site surveys; proper calibration factors or functions were then defined and applied to the raw measures performed by the networks.

Many models were developed during the SEAM4US project (@ D3.2.2 Final User, Thermal and Control Models for details); these can be grouped into the passenger and the station model. The first concerns the occupancy of the station zones and predicts the number of passengers in each zone at any arbitrary future time on the basis of the data collected by the CCTV system. The station model integrates the facility models (i.e. lighting, ventilation and escalators) and includes the physical details of the whole station in order to study its thermo-fluid dynamical behavior. All the models were calibrated using real data collected by the SEAM4US monitoring networks and through on-site measurements.

Three control subsystems were deployed in the PdG-L3 pilot station; these dynamically drive the lights, the fans and an escalator with the aim of reducing energy consumption (@ D4.2.2 Final System Prototype and User Manual). The final prototype was started-up in the real pilot station in the middle of July according to the project schedule (milestone MS15 at month 33). The data acquired from the monitoring networks, once the final prototype was switched on, was used for verifying the control subsystems. This validation process concerned two aspects; first, checking the proper operation of the real subsystems, whose monitored control variables have to be matched with the values codified by the control policies and second, assessing the saving achieved through energy retrofit measures.

Finally, the following energy savings were calculated for each of the control subsystems: 24.1% ± 1.9% for lighting, 30.6% ± 2.0% for ventilation and 8.5% ± 1.9% for the escalator.

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GLOSSARY AND ABBREVIATIONS

- **ASHRAE:** American Society of Heating, Refrigerating and Air Conditioning Engineers.
- **Backend equipment**: all the hardware that the SEAM4US System requires except sensors and actuators.
- **Baseline**: the status-quo condition of PdG-L3 station, prior to SEAM4US implementation.
- **BEMS**: Building Energy Management Systems.
- **CCIF**: the software interface used by OCC operators to manage and control station and tunnel devices.
- **CCTV**: Closed Circuit TV.
- **Control Subsystem**: refers to all the components needed for controlling the pilot: Controllers, Prediction Models, Device Proxies (software) and Actuators (hardware)
- **Core System**: basic hardware parts of the system (Server and Back-up HDD).
- **DBN:** Dynamic Bayesian Networks.
- **ECM**: Energy Conservation Measure.
- **FMI**: Functional Mockup Interfaces.
- **FMU**: Functional Mock-up Units.
- **GUM**: Guide to the expression of Uncertainty in Measurement.
- **IPMVP:** International Performance Measurement & Verification Protocol.
- **JCGM:** Joint Committee for Guides in Metrology.
- **LinkSmart Middleware**: the platform on which the SEAM4US System is based.
- **MAS**: Mean Absolute Sensitivity index.
- **Monitoring Subsystem**: refers to all the components needed for monitoring the pilot: Monitoring Models, Device Proxies (software) and Sensors (hardware).
- **M&V**: Measurement and Verification.
- **MPC:** Model Predictive Control.
- **NRMSE**: Normalized Root Mean Square Error.
- **OAT**: One-At-a-Time method.
- **OCC**: Operation Control Center.
- **OCR:** Optical Character Recognition.
- **PdG-L3**: Passeig de Gracia - Line 3 (pilot station).
- **PLC**: Programmable Logic Controller.
- **ROI:** Regions Of Interest.
- **RMSE**: Root Mean Square Error.
- **RTSP:** Real Time Streaming Protocol.
- **SEAM4US**: Sustainable Energy mAnageMent for Underground Stations.
- **SEAM4US Simulator**: the overall simulator for predicting the performance of the SEAM4US Control. It has a ‘Model In the Loop’ (MIL) Architecture, and it is composed by a number of components (models and controllers).
- **SEAM4US System**: the whole system, including all the components included in the SEAM4US System Architecture (User Interfaces, Controllers, Models, Device Proxies, System Supervision, LinkSmart Middleware, Sensors, Actuators).
- **VFD**: variable frequency drive.

1. INTRODUCTION

This document reports the procedures and results of the validation phase of the SEAM4US project. It is made up of four sections. Section 2 concerns the protocol adopted for quantifying the impacts of energy efficiency improvements, which was the International Performance Measurement & Verification Protocol (IPMVP). The IPMVP provides four options for the assessment of savings achieved after the implementation of an energy efficient measure; two of these were suitable and hence applied to the project for verifying the lighting, ventilation and escalator retrofits.

Section 3 reports on meter and sensor testing. The monitoring networks deployed in the PdG-L3 station were in effect verified by means of on-site measurements carried out using hand-held instruments. Calibration factors or functions were defined for the sensors when required.

Section 4 illustrates the calibration procedures adopted for the models developed in the project, which can be grouped as passenger and station models. The calibration of a simulation model is required in order to verify that it reasonably predicts the states of a real system/entity by comparing model results to a set of calibration data. The ASHRAE 2002 procedures and methodologies were followed for model calibration. The calibrated models were also used for the assessment of energy savings during the validation phase.

Section 5 analysed each of the control subsystems implemented in PdG-L3. The real pilot for the optimal control concerned the lights in two different areas of the station, the fans and an escalator. The performances of the control subsystems were tested and verified; the energy savings achieved by controlling the facilities were then assessed. These two processes were carried out by means of the monitoring data and/or the calibrated models.

2. SYSTEM VALIDATION GUIDELINES

The procedures and methodologies for verifying and validating the SEAM4US system, from a technical and functional perspective, are based on the International Performance Measurement & Verification Protocol (IPMVP)[1], which defines the standards for quantifying the impacts of energy efficiency improvements.

2.1. The IPMVP protocol

The IPMVP's flexible framework of Measurement and Verification (M&V) options allows practitioners to craft the right M&V plan for their building or industrial facility, inspiring confidence in those who wish to harvest their financial and/or environmental benefits. Clear definition of terms, and heavy emphasis on consistent and transparent methods are the core precepts of the IPMVP. The IPMVP is the de fact standard for measurement and verification of European project retrofit performance in the domain of energy-efficient buildings (e.g. It has been used by the EU project SEEDS - Self learning Energy- Efficient buildings and open Spaces) and, it is based on, and extends, the ASHRAE Guideline 14, 2002. The objective of IPMVP is to determine the savings after one or more Energy Conservation Measure (ECM) have been implemented. In the IPMVP protocol, savings are determined by comparing measured use, or demand, before and after implementation of the ECM program, making suitable adjustments for changes in eventual operating conditions. The key point is to make measured savings in two different periods comparable, which is not often straightforward. Hence, in order to document the impact of the ECM, its energy effect must be separated from the energy effect of any changes or variation of the operational context. The "baseline energy" use pattern before ECM installation should be studied in order to determine the relationship between energy use and the operational context. In other words, a model of the system must be implemented. Following the installation of the ECM, this relationship is used to estimate how much energy the building would have used if there hadn't been any ECM (called the "adjusted-baseline energy"). Then, the saving, or 'avoided energy use' is the difference between the adjusted-baseline energy and the energy that was actually metered during the reporting period, as shown in Figure 1. Without the aforementioned adjustment, the difference between baseline energy and reporting period energy would have been biased by operational context change. Therefore, IPMVP segregates the energy effects of a savings program from the effects of other simultaneous changes affecting the energy using systems.

The comparison of before and after energy use or demand should be made on a consistent basis, using the following general equation:

$$Savings = Baseline\ Period\ Use\ (or\ Demand) - Reporting\ Period\ Use\ (or\ Demand) \pm Adjustments \qquad (1)$$

The "adjustments" term in this general equation is used to re-state the use or demand of the baseline and reporting periods under a common set of conditions. This adjustments term distinguishes proper savings reports from a simple comparison of cost or usage before and after implementation of an ECM. Simple comparisons of utility costs without such adjustments report only cost changes and fail to report the true performance of a project. So, in order to properly

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[1] International Performance Measurement & Verification Protocol Concepts and Options for Determining Energy and Water Savings Volume I – at http://www.ipmvp.org.

report "savings," adjustments must account for the differences in conditions between the baseline and reporting periods. The adjustments term shown in the equation above should be computed from identifiable physical facts about the energy governing characteristics of equipment within the measurement boundary. Two types of adjustments are possible:

- **Routine adjustments**, that are the adjustments for any energy-governing factors, expected to change routinely during the reporting period, such as weather or production volume. A variety of techniques can be used to define the adjustment methodology. Techniques may be as simple as a constant value or as complex as several multiple parameter non-linear equations each correlating energy with one or more independent variables. Valid mathematical techniques must be used to derive the adjustment method for each M&V plan.
- **Non-Routine Adjustments**, applied in case of energy-governing factors which are not usually expected to change, such as the facility size, the design and operation of installed equipment, the number of weekly production shifts, or the type of occupants. These static factors must be monitored for change throughout the reporting period. Examples of static factors needing non-routine adjustments are changes in the:
    - amount of space being heated or air conditioned;
    - building envelope characteristics (new insulation, windows, doors, air tightness);
    - indoor environmental standard (e.g. light levels, temperature, ventilation rate);
    - occupancy type or schedule.

With regards to equation 1, the baseline in an existing facility project is usually the performance of the facility or system prior to modification. This baseline physically exists and it can be measured before changes are implemented.

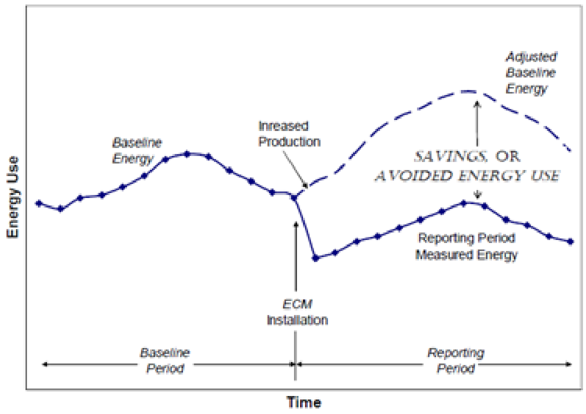

Figure 1. Representation of the definition of saving (or 'avoided energy use') according to IPMVP.

The IPMVP provides four options for determining savings (A, B, C and D). The choice among the options involves many considerations including the location of the measurement boundary. If determining savings at the facility level, option C or D may be favoured. However, if only the performance of the ECM itself is of concern, a retrofit-isolation technique may be more suitable (Option A, B or D). So, the four options provided in the IPMVP are briefly described below:

- **Option A. Retrofit Isolation: Key Parameter Measurement**. Savings are determined by field measurement of the key performance parameter(s) which define the energy use of the ECM's affected system(s) and/or the success of the project. Measurement frequency ranges from short-term to continuous, depending on the expected variations in the measured parameter and the length of the reporting period. Parameters not selected for field measurement are estimated and these estimations can be based on historical data, manufacturer's specifications, or engineering judgment. The plausible savings error arising from estimation rather than measurement has to be evaluated. The engineering calculation of baseline and reporting period energy has to be performed through the short-term (or continuous) measurements of key operating parameter(s) and/or estimated values. Routine and non-routine adjustments can be required. A typical application of this option is a lighting retrofit where power draw is the key performance parameter that is measured periodically. In this case, the estimation concerns the operating hours of the lights based on facility schedules and occupant behaviour.

- **Option B. Retrofit Isolation: All Parameter Measurement**. Savings are determined by field measurement of the energy use of the ECM-affected system. Measurement frequency ranges from short-term to continuous, depending on the expected variations in the savings and the length of the reporting period. In this option, short-term or continuous measurements of baseline and of reporting period energy and/or engineering computations using measurements of proxies of energy use can be used. Routine and non-routine adjustments can be required. A typical application concerns the use of a variable speed drive and controls to a motor to adjust pump flow. Measure electric power with a kW meter installed on the electrical supply to the motor, which reads the power every minute. In the baseline period this meter is in place for a week to verify constant loading. The meter is in place throughout the reporting period to track variations in power use.
- **Option C. Whole Facility**. Savings are determined by measuring energy use at the whole facility or sub-facility level. So, continuous measurements of the entire facility's energy use have to be taken throughout the reporting period. Analysis of whole facility baseline and reporting period (utility) meter data is required. The routine adjustments can be required and performed using techniques such as simple comparison or regression analysis. Non-routine adjustments as required. Typical application of this option regards the multifaceted energy management program affecting many systems in a facility. In this case, energy use must be measured with the gas and electric utility meters for a twelve-month baseline period and throughout the reporting period.
- **Option D. Calibrated Simulation**. Savings are determined through simulation of the energy use of the whole facility, or of a sub-facility. Simulation routines are demonstrated to adequately model actual energy performance measured in the facility. This option usually requires considerable skill in calibrated simulation. The energy use simulation has to be calibrated with hourly or monthly utility billing data. In this case, the energy end-use metering may be used to help refine input data. Typical application of this option regards multifaceted energy management programs affecting many systems in a facility but where no meter existed in the baseline period. Energy use measurements, after installation of gas and electric meters, are used to calibrate a simulation. Baseline energy use, determined using the calibrated simulation, is compared to a simulation of reporting period energy use.

In the IPMVP, the measurement boundary conditions to determine savings are specified. Savings may be determined for an entire facility or simply for a portion of it, depending upon the purposes of the reporting. If the purpose of reporting is to help manage only the equipment affected by the savings program, a measurement boundary should be drawn around that equipment. Then all significant energy requirements of the equipment within the boundary can be determined. This approach is used in the Retrofit Isolation options, i.e options A and B. If the purpose of reporting is to help manage total facility energy performance, the meters measuring the supply of energy to the total facility can be used to assess performance and savings. The measurement boundary in this case encompasses the whole facility (option C). If baseline or reporting period data are unreliable or unavailable, energy data from a calibrated simulation program can take the place of the missing data, for either part or all of the facility. The measurement boundary can be drawn accordingly. This is the case of the option D. Some of the energy requirements of the systems or equipment being assessed may arise outside a practical measurement boundary. Nevertheless, all energy effects of the ECM(s) should be considered. Those energy effects that are significant should be determined from measurements, the rest being estimated or ignored. Any energy effects occurring beyond the notional measurement boundary are called ‘interactive effects’. Therefore, a way to estimate the magnitude of these interactive effects has to be found in order to determine savings. Alternatively, they may be ignored as long as the M&V plan includes discussion of each effect and its likely magnitude.

The IPMVP points out that selecting the period of time to be used as the baseline period and the reporting period has to be done with special care.

The baseline period should be established representing all operating modes of the facility. This period should span a full operating cycle from maximum energy use to minimum. Whole-building energy use can be significantly affected by weather conditions. Typically, a whole year of baseline data is needed to define a full operating cycle. The energy use of a compressed air system may only be governed by plant production levels, which vary on a weekly cycle. So one week’s data may be all that is needed to define baseline performance. In the baseline period, all operating conditions of a normal operating cycle have to be taken into account. So, though a year may be chosen as the baseline period, if data is missing during the selected year for one month, comparable data for the same month in a different year should be used to ensure the baseline record does not under represent the operating conditions of the missing month. The baseline period should include only time periods for which all fixed and variable energy-governing facts are known about the facility. Extension of baseline periods backwards in time to include multiple cycles of operation requires equal knowledge of all energy-governing factors throughout the longer baseline period in order to properly derive adjustments after ECM installation. Finally, the baseline period should coincide with the period immediately before commitment to undertake the retrofit. Periods further back in time would not reflect the conditions existing before retrofit and they might not provide a proper baseline for measuring the effect of just the ECM. ECM planning may require studying a longer time period than that chosen for the baseline period. Longer study periods assist the planner in understanding facility performance and determining what the normal cycle length actually is.

On the other hand, regarding the reporting period, the IPMVP specifies that it should encompass at least one normal operating cycle of the equipment or facility, in order to fully characterize the savings effectiveness in all normal operating modes. Some projects may cease reporting savings after a defined "test" period ranging from an instantaneous reading to a year or two. The length of any reporting period should be determined with due consideration of the life of the ECM and the likelihood of degradation of originally achieved savings over time. Regardless of the length of the reporting period, metering may be left in place to provide feedback of operating data for routine management purposes and specifically to detect subsequent adverse changes in performance.

2.2. Application of the IPMVP protocol to the SEAM4US project

SEAM4US is concerned with the implementation of three CEMs that correspond to as many retrofits. The systems involved in each retrofit (namely fan, escalator and lighting) are powered by electric energy, do not overlap and can be monitored separately. Hence, the more appropriate option can be chosen for each of the retrofit, separately. Escalator and lighting system retrofits share the same main driver, that is the passenger flow rate, and they are quite similar systems in terms of the type of control, so the same option will be used for both of them. Fan control is heavily involved with thermal and airflow dynamics, and its control is model driven. Therefore, it will be treated separately.

2.2.1. Measurement and verification of the escalator and lighting retrofits

IPMVP explicitly recommends option A (Retrofit Isolation: Key Parameter Measurement) for lighting control. Given the similarity between the escalator and lighting regarding the variable driver of the control system, option A can be adopted in principle for the escalator control as well[2]. This is due to several factors, as listed below:

- Interactive effects of the ECM on the energy use of other facility equipment can be reasonably estimated, or assumed to be insignificant.
- Possible changes to the facility, beyond the measurement boundary, would be difficult to identify or assess.
- The independent variables, which affect energy use, are not excessively difficult or expensive to monitor.

The lighting system energy dynamics concern the direct electric energy consumption and, secondly, the heat flow produced by the joule effect. A lighting load reduction often reduces heat gains due to the system energy use. However, the only reasonable measurement boundary would encompass solely the electricity use of the lights, not their heating energy impacts. In fact led lighting energy efficiency is achieved by lowering the energy dissipated by the Joule effect. Hence, heating energy impact can be assumed negligible.

The escalator energy dynamics concern in the first place the direct electric energy consumption and in the second place the heat flow produced by the indirect variation of heat gain due to a different passenger transit dynamics. As in the case of the lighting system, the only reasonable measurement boundary would encompass just the electricity use by the escalator, and not its heating energy impacts, since it is usually considered almost negligible.

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[2] Given the poor performance of the current escalator setup at lower speed and the consequent necessity of an expensive hardware upgrade, a mixed option A – option D has been used (@ Section 5).

Escalator and lighting control and the related energy consumption are mainly affected by the passenger flow rate. Passenger transit monitoring is a regular management task of the metro manager. Reports show typical daily and weekly regularity patterns. Seasonal effects are not visible because of compensations provided arguably by the flow of tourists during the summer season. Daily patterns are shown in the following graphs. Because of these patterns four weeks is a reasonable reporting period. Concerning the calculation of the baseline a distinction must be made between escalators and lighting; lighting control is currently driven on a fixed weekly schedule. Therefore, one week of monitoring captures the full energy consumption pattern necessary to define the baseline of the lighting system. On the contrary, escalator energy consumption is always determined by the instantaneous passenger flow. In this case, the daily pattern must be assumed.

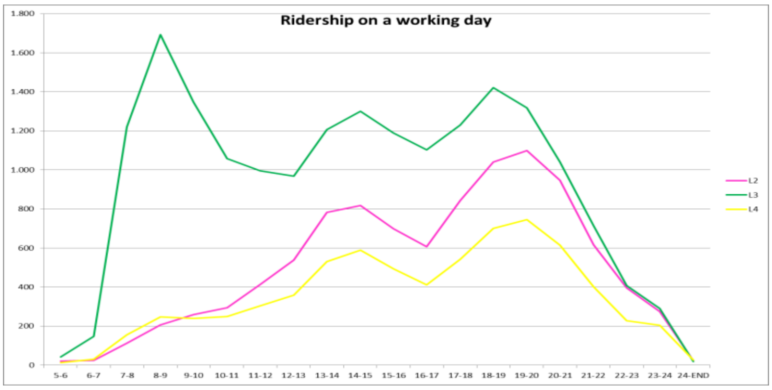

Figure 2. Daily ridership pattern (source TMB).

Given the relatively short assessment period and the absence of any planned maintenance activities no adjustments appear necessary for compensating the reporting period figures in both cases.

2.2.2. Measurement and verification of the ventilation retrofit

The measurement and verification of the ventilation system retrofit raises a number of challenges essentially due to the multiplicity of external influencing factors having daily and seasonal dynamics. Outdoor temperature, wind flow speed and direction and indoor temperature are among them. The external influencing factors cause two major impediments for the application of IPMVP option A and B. The first concerns the SEAM4US operational schedule that foresees, in the DOW, a fully functional system deployed at M33, leaving at most four months for validation. This operational arrangement avoids the measurement of a representative sample of data for calculation of both baseline and savings. The second one is as critical and concerns the representativeness of two subsequent monitoring periods, even belonging to the same season, for the purposes of energy saving calculations. The uncontrolled variability of the external influencing factor influences the energy saving rate that can be achieved by optimal control without compromising comfort level. Therefore, two subsequent periods can allow very different saving rates. For these conditions, IPMVP provides option D, which allows the adoption of standardised, controlled and replicable boundary conditions. Hence, in the end, SEAM4US adopts IPMVP option D (Calibrated Simulation) for the assessment of the forced ventilation (i.e. Fans) retrofit. Option D has a number of benefits for the SEAM4US project, as explained below:

- The SEAM4US control system development has already implemented a whole building calibrated model for the purpose of the model predictive control of the fan. Simulation software predicts metered calibration data with acceptable accuracy. The same model can be used for the baseline and retrofit performance estimation with no additional costs. Additional costs are one of the main drawbacks for option D application.
- Savings with option D can be estimated using a simplified form of equation 1, since the calibration 'error' equally affects both baseline and reporting period models.
- Option D simulations use standardised and representative weather files. This avoids any seasonal effects.
- Option D may be used to assess the performance of all ECMs in a facility, akin to option C. However, the option D simulation tool also allows estimating the savings attributable to each ECM within a multiple-ECM project.

Option D involves the use of computer simulation software to predict facility energy for one or both of the terms in equation 1. Accurate computer modelling and calibration to measured energy data are the major challenges associated with Option D. So, savings determined with Option D are based on one or more complex estimates of energy use. The accuracy of the savings depends on how well the simulation models actual equipment performance, and how well calibrated it is to metered energy performance. Calibration is achieved by verifying that the simulation model reasonably predicts the energy patterns of the facility by comparing model results to a set of calibration data. These calibration data include measured energy data, independent variables and static factor. Calibration of building simulations is done with a representative data set from a period of stable operation. SEAM4US adopts an evidence-based methodology for the calibration process.

Savings with option D were estimated using the following simplified form of equation 1, given that the calibration 'error' equally affects both baseline and reporting period models.

$$\begin{aligned} Savings = {} & Baseline\ energy\ from\ the\ calibrated\ model\ (without\ ECMs) \\ & - Reportingperiod\ energy\ from\ the\ calibrated\ model\ (with\ ECMs) \end{aligned}$$

3. MONITORING SYSTEM VALIDATION

Meter and sensor validation entailed significant challenges for the SEAM4US project, since using large number of sensors and carrying out extensive interventions in the underground environment in non-service (i.e. night) hours, would have risen the implementation and the maintenance costs considerably. On the other side, data quality assurance, which is critical for the system reliability, called for sensor quality and for system redundancy. Accurate measurement, in some sense, was less critical because the control system operates in differential mode. In the SEAM4US system, data failures have three main causes: sensor drifting, sensor malfunctioning and data transmission losses. The SEAM4US system adopts different strategies for each kind of data failure, as explained below.

- **Sensor drifting**. The SEAM4US control works essentially in differential mode. The control is determined by the difference between the actual and the near past values and/or reference values of the monitored parameters that is measured by the same sensor. Hence, the control and the system performance are inherently robust with respect to relatively limited sensor drifts that usually occur during normal system operation. In a few cases, like for example in the case of power consumption, accurate absolute values of the monitored parameter could be required. In these cases, sensors have been calibrated as recommended by the equipment manufacturer. Traceable on-site calibration equipment was utilized to assess the absolute value when possible, given the high impact on the project cost.
- **Sensor malfunctioning**. Sensor malfunctioning usually appears as out of range or static values. The Linksmart middleware system wraps each sensor with a software driver capable of detecting sensor malfunctioning and raises critical events inside the system when this occurs.
- **Data losses**. SEAM4US implements a post-processing layer that performs data filtering, resampling and fusion based on historical series analysis. This module is devoted to checking transmission quality as well. Data losses are dealt with as confidence factors of the measure. These factors are recorded in the system data-base and passed to the control systems that actuate the necessary compensations.

The following sections describe the process used for validating the three monitoring networks that form the SEAM4US system, i.e. energy, environmental and occupancy monitoring networks.

3.1. Energy monitoring network

The energy monitoring network measures the consumption of the main loads in PdG-L3 station and, therefore, it is basically used for validating the savings obtained in the three subsystem pilots deployed in the station, namely ventilation, lighting and escalator pilots. The monitoring network mainly consists in current transformers put around each phase wire of the load being monitored and smart meters which process and forward the signals to the SEAM4US server (details can be found in section 6 of D5.1.2 Final Energy Management System Deployment Handbook).

Therefore, the purpose of the energy monitoring network is the measurement of the power absorbed by the circuits involved in the subsystems pilot before and after the control subsystems deployment. These circuits are listed below:

- circuits 2A-4, 2C-11, 2NC-18 and 2NC-19 for the lighting pilot in the platform PL3:S2; circuits 2A-5, 2C-12, 2NC-20 and 2NC-21 for the lighting pilot in the hall HN2 and corridor CNm (see section 3 of D3.1.2 Final Energy Auditing Report for the nomenclature used for each spatial portion of PdG-L3 station);
- circuits 2NC-2 and 2NC-3 for the ventilation pilot;
- circuit 3NC-3 for the escalator pilot.

The assessment of the power measurements carried out with the monitoring network was performed using a calibrated hand-held instrument which a power quality analyser manufactured by Fluke model 435-II. Figure 3 shows the analyser Fluke 435-II connected to one of the PdG-L3 station circuits during the on-site survey held in July 2014. During this survey, the power absorbed by each of the circuits involved in the pilots was measured using the hand-held analyser that allowed acquiring one power measurement every second. Every circuit devoted to the lighting pilot was measured for 1 hour whereas each circuit involved in the ventilation pilot was measured for 6 hours. The analyser instead was connected to the circuit of the escalator pilot for a whole operating day.

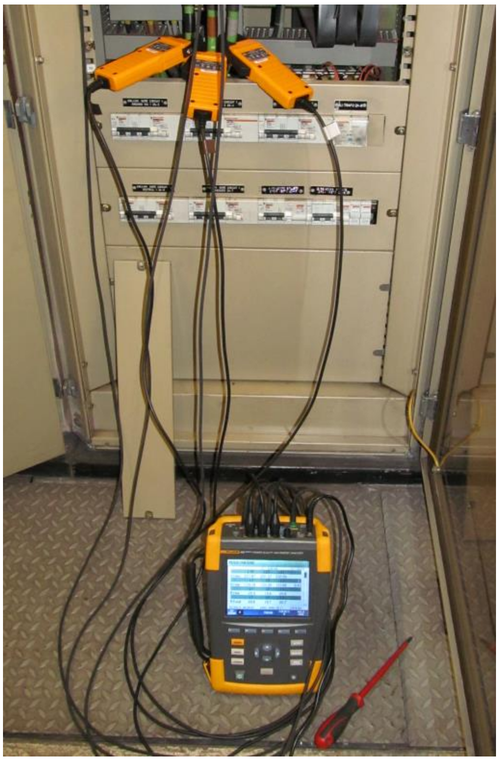

Figure 3. Analyser Fluke 435-II connected to one of the PdG-L3 circuits during the survey of July 2014.

The average power obtained for each circuit using Fluke 435-II was compared with the measurements gathered with the energy monitoring network in order to assess the accuracy of the power data acquired with the network installed in PdG-L3.

Table 1 shows the concurrent average values of power obtained from the Fluke 435-II and the energy monitoring measurements for each of the circuits involved in the pilots. Every value of average power in this table is followed with the expanded uncertainty estimated according to the procedure explained in Appendix C of D3.1.2 Final Energy Auditing Report.

Table 1. Comparison between average powers measured with analyser Fluke 435-II and the monitoring network.

Circuit code	Power measured with monitoring network (VA)	Power measured with Fluke 435 (VA)	Absolute error (VA)	Relative error (%)
2A-4	1,423 ± 9	1,347 ± 3	76	5.6%
2A-5	1,640 ± 10	1,562 ± 4	78	5.0%
2C-11	1,243 ± 8	1,282 ± 3	39	3.0%
2C-12	1,541 ± 10	1,612 ± 4	71	4.4%
2NC-18	984 ± 6	935 ± 2	49	5.2%
2NC-19	1,076 ± 7	1,114 ± 3	38	3.4%
2NC-20	1,260 ± 8	1,186 ± 3	74	6.2%
2NC-21	1,228 ± 8	1,268 ± 3	40	3.2%
2NC-2	11,483 ± 39	10,945 ± 22	538	4.9%
2NC-3	12,273 ± 42	12,854 ± 25	581	4.5%
3NC-3	3,584 ± 45	3,834 ± 25	250	6.5%

The comparison in Table 1 shows a bias between the aforementioned power measurements, which is limited between 3% to 6.5%. These biases are not critical and they are compensated by the system.

3.2. Environmental monitoring network

The environmental monitoring network is devoted to the control of the comfort conditions of the PdG station. It consists of several sensors located in different spaces and aimed at measuring airflow, temperature, CO_2 and PM10 levels. The raw data acquired by the network is post processed by a dedicated middleware module in order to reduce the acquisition noise, to interpolate missing data, to time align the data and to perform the necessary calibration corrections. The calibration was performed according to a set of reference measurements carried out during one on-site survey, in which the environmental measurements were collected by means of hand-held instruments. The measurements involved airflow, temperature and PM10. Our concern on airflow rates, air temperatures and $C0_2$ and PM10 concentrations stem from the role played by these variables in general comfort control[3] and specifically in underground metro stations[4]. All the raw data coming from the aforementioned sensors were interpolated and time aligned. The Cozir ultra Low power sensors installed for carbon dioxide monitoring were supplied and calibrated by the manufacturer. Installation conditions did not affect the validity of that calibration. Post-processing calibration functions were developed and applied to the raw data of the remaining sensors. In addition, the installed PM10 sensors (Shinyei PPD60PV-T2) estimate just the number of particles from a correlation with the optical refraction of a light beam emitted in a dark chamber. So, a post-processing function is used to turn the estimated number of particles into a measure of weight concentration dependent on the type of dust, hence, on the environment to be monitored.

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[3] Bluyssen P., M., (2009). *The Indoor Environment Handbook*, Earthscan, London

[4] A. Pflitsch, M. Bruene, B. Steiling, M. Killing-Heinze, B. Agnew, M. Irving, J. Lockhart, *Air flow measurements in the underground section of a UK light rail system*, Applied Thermal Energy, vol. 32, pp. 22-20, January 2012.

3.2.1. REFERENCE MEASUREMENTS

Table 2 summarizes the measurements recorded during the on-site survey (held on 17-19 September 2013).

Table 2. List of measurements performed during the on-site survey.

Air speed measurements		PM10 measurements		Temperature measurements	
Location (code)	*Date Time*	*Location*	*Date/time**	*Location*	*Date/time**
Cne (6p16CNeDay)	18 Sept. 2013 (from 12:14:50 to 12:39:00)	PL3 (Node 26)	18/09/2013 (12:43)	Cne (Node 6)	18 Sept. 2013 (from 12:15:00 to 12:39:00)
Slb (10p16SlbDay)	18 Sept. 2013 (from 11:32:20 to 11:54:00)	CNl	18/09/2013 (13:07)	CNl (Node 18)	18 Sept. 2013 (from 10:36:13 to 11:08:43)
CNl (18p16CNlDay)	18 Sept. 2013 (from 10:35:30 to 11:08:10)	SLb	18/09/2013 (23:23)	SLb (Node 10)	18 Sept. 2013 (from 11:32:28 to 11:36:18)
CNq (20p16CNqDay)	18 Sept. 2013 (from 13:31:40 to 13:54:20)	SLb	19/09/2013 (01:50)	CNq (Node 20)	18 Sept. 2013 (from 13:32:52 to 13:54:22)
T3.2 (21p16T32)	18 Sept. 2013 (from 14:11:00 to 15:53:00)	PL3 (Node 26)	19/09/2013 (01:59)	PL3 (Node 21)	18 Sept. 2013 (from 14:12:50 to 15:52:00)
T3.1 (30p16T31)	18 Sept. 2013 (from 03:24:30 to 06:49:40)				

*_All the PM10 measurements lasted 2 min and included the collection of three samples, each of them processing 2.832 l of air._

The reference air speed measurements were taken through the vane probe thermo-anemometer with detection of air flow direction “Kimo VT200” instrument shown in Figure 4a (worst accuracy ±1% of reading, range 0.25 to 3.5 m/s), which was installed inside the permanent SEAM4US anemometers. Then, air speed measurements were converted into airflow rate estimations. This instrument allowed acquiring high frequency data (i.e. one sample every 10 s), so solely during the on-site survey the SEAM4US network was also run at the same sampling frequency (i.e. one sample every 10 s), whereas in standard conditions it collects one sample per minute. In addition, the range and sensitivity of the hand-held instrument was very high, so even low speed air flows could be detected.

Reference temperatures were measured by means of the “Testo Model 445” instrument, shown in Figure 4b (worst accuracy ±0.5% of reading, range -200 to 1370°C). in this case also, both the hand-held instrument and the SEAM4US network were operated at a 10 s sampling frequency.

PM10 sensor measurements in the station were converted into dust concentration estimates by means of the comparison and integrative measurement performed by means of the “Fluke 983 particle counter” (6 particle-size channels: 0.3, 0.5, 1.0, 2.0, 5.0, 10.0 µm) depicted in Figure 4c, which is a certified instrument. Thanks to its various channels, this instrument can estimate the weight of all the particles contributing to dust and can split such weights according to the size of dust particles.

Figure 4. The “Kimo” vane anemometer (a); “Testo” instrument for temperature measurements (b) and “Fluke” particle counter (c).

3.2.2. AIR SPEED CALIBRATION AND AIR FLOW RATES ESTIMATION

Airflow control in turbulent flow dynamics raises the problem of the estimation of stable and meaningful flow rates from single point measurements. It is worth noticing that for comfort control, high precision in the absolute value of the measured flow is not required. Instead, stable flow estimations that are cleared from turbulent noise are of fundamental importance.

Airflow rate is correlated to air speed measurement on a flow section. In turbulent flow mode, the calculation of airflow from single point measurement is affected by randomness introduced by local turbulences. In our case, the interference phenomena in corridors are different from the interferences in tunnels. As already shown in D3.2.1, passenger flow causes a random variation of air speed that can be easily smoothed by filtering. While the effect of train transits across the tunnels generates the so called piston effect, which, depending on the geometry of the surrounding spaces, introduces local turbulences and/or a net airflow rate. This contribution cannot be reliably measured by means of single point air speed measurement, so it must be estimated from the overall airflow balance. Hence, the estimation of the calibration coefficients required two phases. In the first phase, the coefficients for calibrating the air speed in corridors were calculated by means of direct comparison between measurements from the SEAM4US network and from hand-held instruments. In the second phase, the overall airflow balance in the station was used to work out the coefficients to be applied to tunnel air speed measurements, in order to estimate the actual airflow rates flowing across them.

First phase – The hand held instruments were installed side by side with the permanent ones belonging to the SEAM4US network. The conversion factors for corridors were then calculated through the following steps:

1. re-sampling of both the datasets with a time step as long as 10 s, which allowed managing data plotted over the same time scale;
2. cross-correlation between the plots from each node of the SEAM4US network and the corresponding reference plot collected by means of hand-held instruments; this analysis gave back information about the synchronization of the two plots and suggested the time offset that has to be operated in the event that they are not synchronized;
3. filtering of the plots on a time window as long as 10 min (i.e. 600 s);
4. splitting every node’s log into its first 75% data (to be used for the estimation of coefficients) and the remaining 25% data (to be used for validation purposes);

5 comparison between the average values of air speed velocity given by those measurements systems and the estimation of the y-offset to be applied in order to calibrate the first 75% measurement logs;
6 estimation of the linear regression coefficients, by means of the OLSM, which gives back the "scale factor" to be applied to the first 75% of the SEAM4US network in order to best approximate the 75% data logged by the hand-held measurement;
7 application of the offset and scale factors mentioned above to the 25% of the SEAM4US logged data and validation of these results by comparison with the 25% of the second portion of the reference dataset, in order to estimate the accuracy of the whole process.

Second phase - Once all the actual airflow rates in corridors were estimated according to the procedure described above, the overall balance of airflow rates in the station was applied to work out the optimum estimation of reduction factors of air flow rates in tunnels. Technically, the balance was written as:

$$Q_{station\,fans} = Q_{CNl} + Q_{CNq} + 2 \cdot Q_{CNop} + \alpha \cdot Q_{T3.1} + \alpha \cdot Q_{T3.2}$$

where: Q_x is the airflow rate in ambient x in m^3/h, and $Q_{CNop} = Q_{CNe} + Q_{SLb} - Q_{CNq}/2$.
The coefficient α was estimated by means of the OLS method and provided the calibration factors to estimate actual air flow rates in tunnels. Technically, that coefficient is a reduction factor which takes into account pressure loss caused by trains and other disturbances inside tunnels, whose experimental estimation is not feasible otherwise.

The corridor conversion factors

Figure 5a depicts a comparison between the first 75% of the data logged by both the SEAM4US sensors and the reference instruments at node 18p16CNlDay. These data were resampled on a 10 s step wide time scale, in order to be plotted on the same x-axis. It can be noticed that the benchmark (black line) presents peaks higher than the SEAM4US sensor (red line) and its average value is slightly higher than the other series. The cross-correlation analysis showed that they are well synchronized; despite the fact that they are logged by different communication systems. In fact, the cross-correlation peak is located at the very middle of the datasets (as shown by the peak at the bottom of Figure 5b, which means that they need no time translation. Once the data was filtered the offset and scaling factors were calculated, respectively to 0.151 m/ and to 1.2719. The 25% of the data set was used for validation as shown in Figure 5c. The two curves describe the airflow speed over 480 s through corridor CNl. It can be noticed that the post-processed SEAM4US (red line) is almost superimposed to the benchmark (black line).

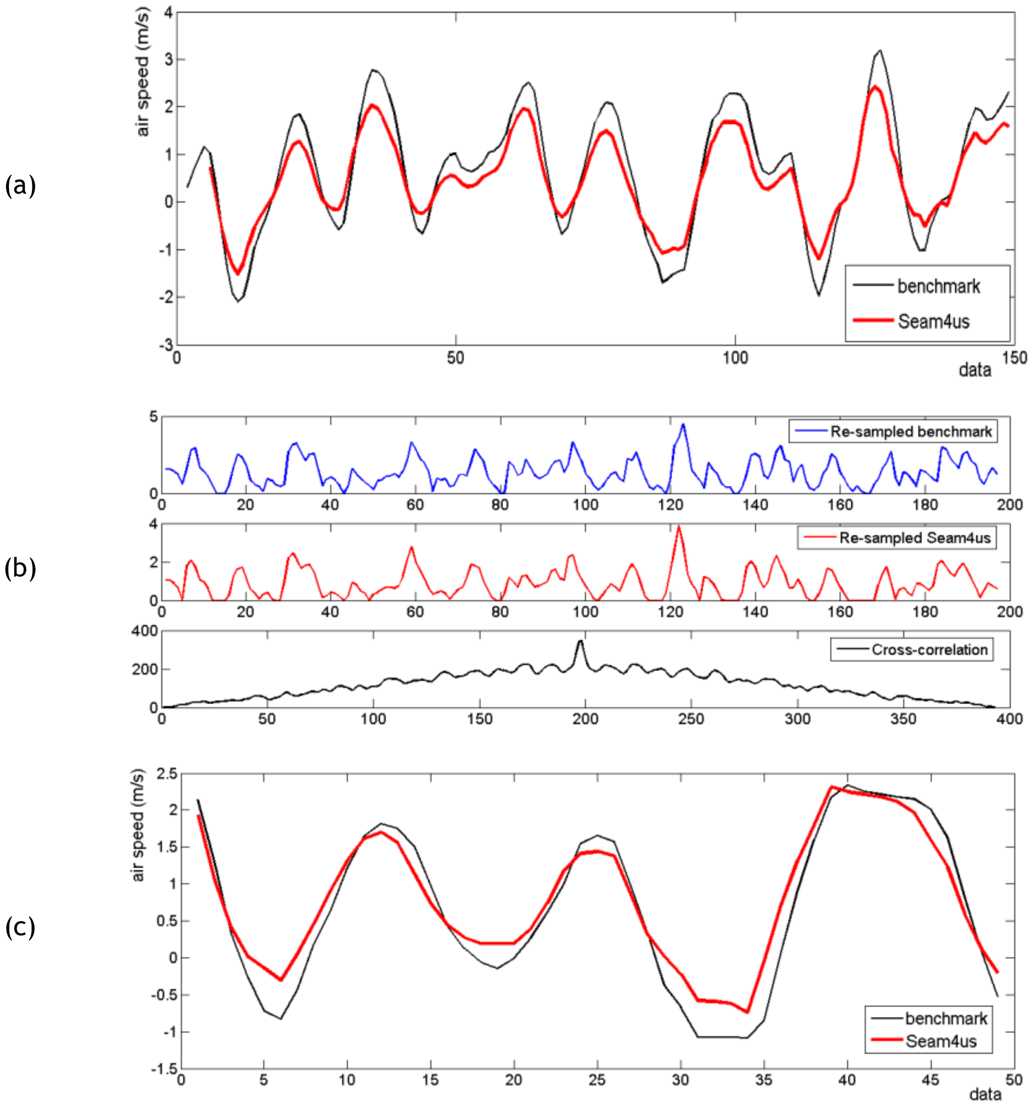


Figure 5. First 75% of the raw data collected by the SEAM4US network and by the benchmark (a) at node no. 18; cross-correlation applied on the datasets (b); transformed curves after application of the conversion factors to the remaining 25% of the data (c).

The application of this procedure to all corridors led to the calibration factors represented in Table 3. In this table, two y-offset values are provided, the first referred to air speed measurements and the second to volume air flow rate. The one to be adopted must be selected according to the nature of the dataset to be converted. Scaling coefficients are unvaried, because of the proportional relationship between air speed values and volume airflow values. Correction factors were used to estimate volume airflow according to the relation: Q = m·Q’+c, where m is the scaling coefficient, c is the y-offset and Q’ is the volume airflow computed directly from air speed measurements. The accuracy of those measurement was verified through percentage errors in terms of air flow rates estimated on the second 25% set of the dataset are given. They are computed as: $(Q_{hh}-Q_{sn})/(Q_{hh})$, where Q_{hh} is the air flow rate estimated from the measurements collected by the hand-held instrument. Q_{sn} is the air flow rate estimated from the measurements collected by the permanent SEAM4US network after the correction factors listed in Table 3 were applied. Whenever this verification was made possible, percentage errors were lower than 10%, after correction.

Table 3. List of calibration factors for corridors.

Station zone	Scaling coefficient	Speed y-offset (m/s)	Volume air flow y-offset (m^3/h)
CNl	1.2719	0.1510	4892
Cne	1.0252	-0.1648	-5340
CNq	1.2364	0.4661	11578
SLb	1.1778	0.1508	6026

Conversion factors for tunnels

According to the procedure set up for the second phase, the coefficient α for tunnels was estimated from the overall balance in the station:

$$Q_{station\ fans} = Q_{CNl} + Q_{CNq} + 2 \cdot Q_{CNop} + \alpha \cdot Q_{T3.1} + \alpha \cdot Q_{T3.2}$$

and

$$Q_{CNop} = Q_{CNe} + Q_{SLb} - Q_{CNq}/2.$$

Where all the contributions, other than the tunnels (object of estimation), were worked out by means of the calibration factors computed above; shown in Table 3.

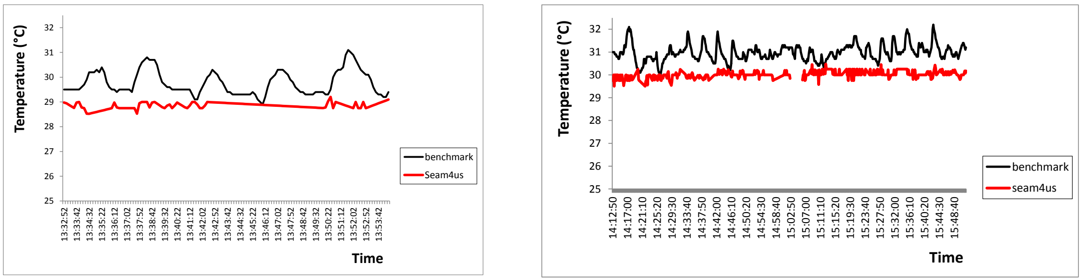
Instead, the air speed measured in the ducts of the station fans (v_{fans}) was converted into air flow rate considering that they have annular cross sections, hence the equivalent diameter was used (D_2 is the outer diameter and D_1 is the inner diameter):

$$Q_{station\ fans} = \mathrm{v_{fans}} \cdot (D_2 - D_1) \cdot \pi^2/4 \cdot 3600$$

As a result from the OLS algorithm, the calibration factor to be assigned to both tunnels is: α = 0.7 (tunnels VT3.1 and VT3.2). In this case no y-offset was assigned to the tunnels, because the mean of the residuals is lower than 10^4 m^3/h, hence it causes very small errors in a complex air exchange where air flows of magnitude as big as 10^5 m^3/h are involved overall.

3.2.3. AIR TEMPERATURE CALIBRATION

The raw temperature data collected during the survey show that the sensors, installed inside plastic boxes for protection from vandalism, are less sensitive to sudden variations than the hand-held instruments (Figure 6), whose probe is in direct contact with the air. In any case, on average their plots are in good agreement. Considering that narrow peaks are determined by the passage of trains, they were considered as non-important in terms of assessing the overall comfort and dynamic behaviour over the time step used for control purposes. Therefore, calibration factors were defined as a y-offset between the average values of the reference sensors on one hand, and SEAM4US sensors on the other. Two slightly different approaches were used for the corridors and the platform given that, in the first case, corridors are equipped with just one sensor; while four temperature sensors were installed in the platform.



(a)

(b)

Figure 6. Raw temperature data in corridors CNq (a) and platform PL3 (b) collected by means of the hand held instruments (Testo) and the SEAM4US network during the on-site survey.

As far as corridors are concerned, temperature data collected using hand-held instruments in the corridors during the on-site survey (carried out September 17-19th 2013) were compared with the data plots provided by the SEAM4US network. The offset between the sensors' average value and the corresponding reference average was calculated for each temperature sensor. The maximum offset calculated was lower than 1°C. The offset factor was estimated in the first 75% of the collected dataset for each time series. the calibration offset was then validated in the remaining 25% of the dataset.

Figure 7 reports a validation case relative to temperature measurement in Node CNq. This node is numbered 20p15 and is located at the middle cross section of corridor CNq. Its y-offset determined by the first 75% of data is equal to 0.8968 °C. The residual difference with the measurement by the hand-held instruments in the remaining 25% is just 0.1611°C.

In Node 6p15 (corridor CNe), the y-offset determined by the first 75% of data is equal to 0.6075 °C (the residual difference after applying the correction factor in the remaining 25% is -0.6243°C, which means this is the uncertainty of that sensor, acceptable for standard comfort estimations). Similarly, in Node 18p15 (i.e. corridor CNl), the y-offset determined by the first 75% of data was -0.1374 °C, and the residual difference after applying the correction factor in the remaining 25% was equal to: -0.21°C. Finally, the measurements in Node 10p15 (i.e. station link SLb) did not work well, so the correction factor was determined as the mean of the previous y-offset values, giving back 0.5745 °C.

(a)

(b)

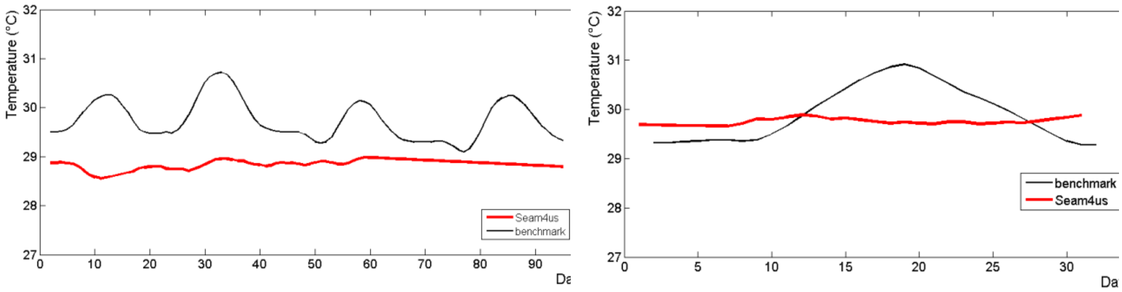


Figure 7. Deviations between temperature plots in CNq (Node 20) before applying the correction factors (a) and after they were applied (b).

A different approach was used for the sensors in the PL3 platform. Here, there are four air temperature sensors currently installed. The measurements provided by each of the PL3 air temperature sensors (i.e. 22p15, 24p15, 27p15, 28p15) were compared with the benchmark, after filtering them through a moving average. a correction factor, in the form of a y-offset, was then worked out for each of these sensors and applied to the raw measurements. Finally, the average value of the corrected temperature plots was compared with the averaged reference measurements. The absolute difference between the two average values is just 0.11°C, which means that on average they are already calibrated. In conclusion, for practical purposes no correction factor is needed for these sensors if we consider the average air temperature values computed by the four sensors installed in platform PL3.

3.2.4. PM10 CONCENTRATION

The SEAM4US network includes one node outdoors and two nodes indoors (in PL3 and SLb) for measuring PM10 concentration. The outdoor node was calibrated by the manufacturer, who supplies the sensor along with a calibration curve to estimate dust. Its output is dust concentration in mg/m^3. Therefore, new conversion factors were worked out just for the two indoor sensors. The conversion procedure was necessary for the following reasons: firstly because the indoor sensors can detect dust concentration whose size is higher than 0.5 µm[5], although PM10 are until at least 0.3 µm; secondly because the indoor sensors can count the number of particles per unit volume, without estimating their size, so we cannot infer the dust weight per unit volume from these data, unless a calibration process is performed in advance, which was the objective of the on-site survey.

Before looking into the details of the procedure, its main steps are summarized below:

1. as a first step, the measurement range was extrapolated from the range measured by the indoor sensors (i.e. 0.5 µm) down to the minimum size relevant for PM10, i.e. 0.3 µm;
2. in the second step, the total number of particles estimated in the range of interest was converted into an estimated weight of dust per unit volume, according to calculation methods provided by literature and parameters/reference values estimated in previous tests. This will be described in more detail in the following passages;
3. finally, the procedure described above was applied to the real-time measurements and the conversion from the indoor sensors' measurements into PM10 estimation was shown.

Concerning the first point relative to the extrapolation of the measurement range, the typical distribution of particle size of the metro station's PM10 was measured by means of the Fluke tool, during the aforementioned on-site survey. In Table 4 the first column lists all the particle diameters of interest, ordered into six intervals. Their central diameter size is shown in the second column. The indoor sensors can detect all the intervals but the first. Hence, the total number of particles detected by those sensors will be relative to the particles belonging to the second, third, fourth, fifth and sixth intervals. As a consequence, the number of particles counted by the second are split into the 5 intervals according to the percentages given by the table, from the second interval to the sixth interval. In addition, the Fluke measurements allowed us to estimate that the number of particles which are not detected by the indoor sensors, included in the first interval, is quantified as 79.3% of the total of detected number of

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[5] The reason for selecting sensors with these limits was essentially due to reducing the cost of the installation, and to consequently improve payback period.

particles. In conclusion, when the indoor sensors sample a certain number of particles, that number is increased by 79.3% to take into account the particles that belong to the lowest range and, that same number is split according to the percentages of the second to sixth intervals to assign the right number to each interval. The numbers of particles are all referred to an air volume as large as 0.283 l, so another conversion is performed to turn that number into the number of particles per air volume unit (m^3).

Table 4. Distribution of particle size in PdG-L3 over the whole PM10 range.

Diameters (μm)		Ratio (%)
Interval	Central value	
0.3-0.5	0.4	79.3
0.5-1.0	0.75	62.2
1.0-2.0	1.5	19.1
2.0-5.0	3.5	17.7
5.0-10.0	7.5	0.88
>10.0	12.5	0.13

A further step must be performed to turn the number of particles per air volume unit into the PM10 concentration, i.e. weight of PM10 per air volume unit. This procedure was performed according to what is suggested by literature.

First, from the number of particles (n^i) in each interval j and the representative diameter d_s, the volume concentration of PM10 can be estimated through the following equation [3,4]:

$$vol^j = \frac{\pi}{6} \cdot \left(d_s^j\right)^3 \cdot n^j$$

In this equation it is assumed that all the particles are spherical, which will be adjusted in one of the next manipulations. Then, for the jth interval, such a number must be converted into mass (m^j) concentration through the equation:

$$m^j = C_F \cdot \rho_{eff}^j \cdot vol^j$$

Where C_F is a correction factor to balance measurement errors, which can be assumed equal to 1 in the case of indoor sensors, ρ_{eff}^j is the equivalent particle matter density, which takes into account both the actual particle matter density and a dynamic shape factor (Υ^j), that adjusts its value because of the deviation of the actual shape from the assumed spherical shape. This parameter must be determined experimentally. Once all the factors m^j are known, the overall concentration of PM10 will be given by [5]:

$$PM_{10\left[\frac{\mu g}{m^3}\right]} = \rho_{eff} \cdot \sum_{j=1}^{6} vol^j \cdot F_{PM10d}^j$$

Where another correction factor is defined as the PM10 fraction per interval[6]:

$$F_{PM10d}^j \triangleq \begin{cases} 1 & d_S \leq 1.5\mu m \\ 0.9585 - 4.08 \cdot 10^9 \cdot (d_S)^2 & 1.5\mu m < d_S \leq 15\mu m \\ 0 & d_S > 15\mu m \end{cases}$$

As a result, all the terms of the last equation are known, but the ρ_{eff} coefficient, which was estimated experimentally as the inverse of the equation above:

$$\rho_{eff} = \frac{PM_{10[\mu g/m^3]}}{\sum_{j=1}^{6} vol^j \cdot F^j_{PM10d}}$$

In fact, PM10 weigh measurements were derived from past laboratory surveys, which gave the value of PM10 concentration at a known time and place. During the on-site survey, a Fluke measurement was performed in the same place at the same time, so as to estimate the total number of particles and compute the unknown variable through the equation given above. As a result $\rho_{eff} = 3.15 \cdot 1012\ \mu g/m3$ was estimated, which was used in the post processing functions relative to PM10 estimation.

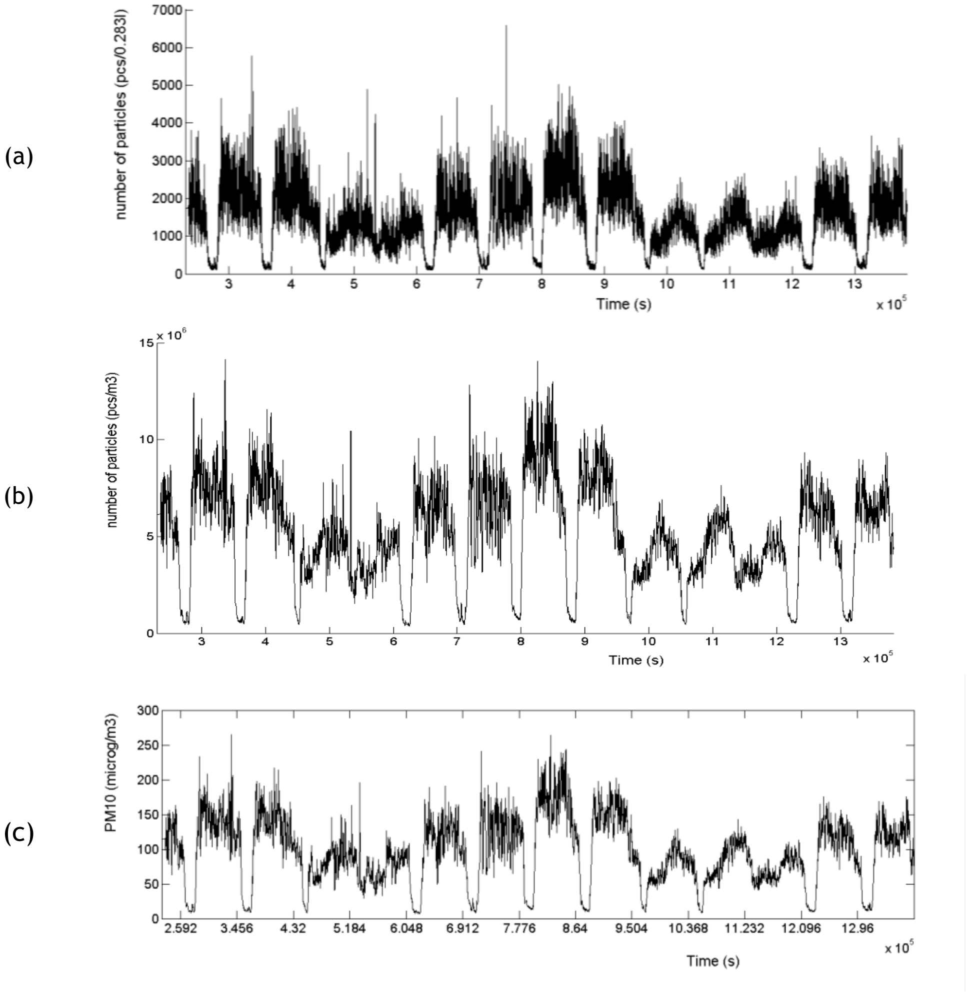

Figure 8. Raw (a) and filtered (b) data about the number of PM10 particles in PL3 during the period from 25th November 2013 to 11th December 2013; estimated dust concentration in the same period (c).

Once the procedure was defined, it was iteratively applied to the measurements collected in real-time by the SEAM4US sensor network. One example is provided in this paragraph, which is relative to the indoor sensor installed in PL3 (i.e. Node 26.0p21), and spans over the measurements collected between 25th November and 11th December 2013. The system stores raw data, Figure 8a, with a 1 min sampling time and are measured as number of particles within 0.283 l of air volume. Then, they are filtered and aligned in time, Figure 8b, based on a time window size as long as 10 min, and represented on a time scale whose step is equal to 1 min. This plot provides the number of particles counted by the sensor in 1 m^3 of air volume. However, such a number is limited to particles whose size is bigger than 0.5 μm; hence, that number was proportionally increased up to the total PM10 particle number, which was estimated according to the first line in Table 4 , i.e. the missing amount represents 79.3% of total PM10 particles. The calculations of the second part of the procedure were then applied and the PM10 concentration shown in Figure 8c was obtained, as a result. The result is expressed following the standard units of measurement.

3.3. Occupancy monitoring network

The occupancy monitoring network provides the crowd density estimator which is the main source of data for modeling passengers' behaviors; it is based on the video streams of the CCTV surveillance system already existing at the pilot station. Thanks to an accurate design of the video processing algorithms, it was possible to achieve a good accuracy in estimating crowds (less that 20% of error, which means that, in general, the density monitored is within a ±2 people range from the actual one).

The main goal of the calibration is to setup (or retrieve, in case the information is already available) all data concerning the regions of interest (ROI) and the perspective correction of each camera. The OCR (Optical Character Recognition) and background detection are also trained during the initialization phase. By definition, the 'regions of interest' include all the parts of the frame relevant to passenger detection thus excluding all the areas (walls, tracks etc.) where human beings are not supposed to be. The setup of the ROI has a two-fold purpose: first, it reduces the amount of data to process and, hence, it speeds the algorithm up; second, it prevents the algorithm to be fed with noise coming from non interesting areas of the frame. Besides the ROI and the perspective correction, the OCR is also trained during the calibration phase. Its main purpose is to recognize from what camera the video carousel starts, even though it is also used throughout the execution of the crowd density estimation algorithms in order to verify what frame is currently being processed. This phase’s last operation is background detection, which is done by observing what pixels remains unchanged for several frames belonging to different temporal sections. Like OCR, this operation is done once during the initialization of the system, but it is also repeated at the beginning of each new video section to retrain the background seeing that changes (including camera malfunctioning) may occur.

The training was done on videos from the CCTV network consisting of one full day recording. Manual calibration was done on 75% of the data and the remaining 25% was used for validation.

4. MODEL CALIBRATION

This section illustrates the calibration procedures adopted for the models developed in the project, here grouped into the passenger and the station models. The model calibration was carried out using data collected by the monitoring networks and on-site measurements.

The calibration of the station model followed the procedures specified in the ASHRAE Guideline 14-2002, Measurement of Energy and Demand Savings, and adopted. This process was conducted according to an evidence-based approach. The passenger model implemented the alignment approach and it was calibrated though the CCTV data. The results of the calibration processes are provided in this section.

4.1. Station model

Station model calibration is required by the adopted IPMVP validation Option D, Calibrated Simulation, which involves the use of computer simulation software to predict facility energy savings in a multiple ECM project. Savings determined with Option D are based on one or more complex estimates of energy use. The accuracy of the savings depends on how well the simulation models actual equipment performance, and on how well calibrated it is to metered energy performance.

The calibration of the simulation model is required in order to verify that it reasonably predicts the energy patterns of the facility by comparing model results to a set of calibration data. The calibration data include measured energy data and the set of the independent variables that most affect energy consumption. ASHRAE 2002 introduces the assessment procedures and methodology for model calibration. Deliverable D3.2.2 – Final Thermal and Control Models, describes the details of the station model used to simulate the station energy dynamics. The following section details the procedures and the result of the calibration process.

The calibration of the station model was conducted according to an evidence-based approach. Evidence based calibration[6] is one of the most recent and robust model calibration technique that overcomes problems concerning noisy and incomplete data sets. To improve the reliability of models calibrated with limited data sets, evidence based calibration constraints the variations of the input parameters to the available evidence, according to a clearly defined set of priorities. For example, sources based on direct observation should be the first priority, followed by data obtained from benchmark studies, then standards, and finally, information from the initial model. Changes should not be made unless the evidence comes from a source higher up in the hierarchy.

SEAM4US monitoring network includes both environmental sensors and energy smart meters. The first data were available as of March 2013, but some data are missing in certain periods as both the hardware system and the software components of the systems were under development and finalization during these months. Table 5 reports the sampling periods of the data used for the calibration process.

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[6] Raftery, P., Keane, M., Costa, A. 2011. Calibrating whole building energy models: Detailed case study using hourly measured data. Energy and Buildings 43 (12): 3666-3679.

Table 5. Measurement Data Set used for Calibration-

Season	**Period**	**Number of days**	**Environmental data**	**Energy data**	**Sampling Rate**
spring	2013.04.12 - 2013.04.19	8 days	YES	YES	10 min
summer	2013.06.28 - 2013.07.04	7 days	YES	YES	10 min
autumn	2013.09.17 - 2013.09.23	7 days	YES	YES	10 min
autumn/winter	2013.11.25 - 2013.12.02	8 days	YES	NO	10 min

Data gathered through the monitoring network have been complemented with survey data, aimed at investigating specific aspects that needed more detailed investigations. Three environmental surveys were held in Barcelona in March 2012, June and September 2013 aimed at gathering data about the environmental behaviour of the station and, at the same time, at assessing and calibrating the monitoring network itself. Higher precision laboratory instruments were used for collecting higher frequency data.

4.1.1. The calibration process

The calibration process was articulated in three main phases:

1. Sensitivity Analysis;
2. A preliminary raw Calibration, that led to an overall revision of the model;
3. An Evidence-based Calibration, supplied with local investigations about critical parameters.

a) Sensitivity Analysis

A preliminary sensitivity analysis was performed, using a One-At-a-Time (OAT) method. A sensitivity index, that is basically the ratio of the change in output to the change in input while all other parameters remain constant, was used for assessing the influence of individual parameters locally. Then, the Mean Absolute Sensitivity index of the (MAS%) over a typical day was computed for each output and each perturbation, to achieve an overall comparison.

$$MAS\% = \sum_i \left| \frac{(O_{p_i} - O_{b_i})/O_{b_i}}{(I_{p_i} - I_{b_i})/I_{b_i}} \right| / n \tag{2}$$

A perturbation of ±10% was considered and applied to a set of 59 parameters, expected to be the most influent. Figure 9 reports the results. Inputs have clustered in 10 groups. The temperature in PL3 and the electrical power consumed by the Tunnel and the Station Fans were selected as the output target parameters. It emerged clearly that the most influent parameter was the Input Frequency to the Station Fans. This denotes that the ventilation regime affects a lot the overall performance of the station building, both in terms of temperature and energy consumption. The Train pressure drop and thermal gain play an important role as well. Finally, tunnel heat gains and pressure drops can be considered quite relevant too.

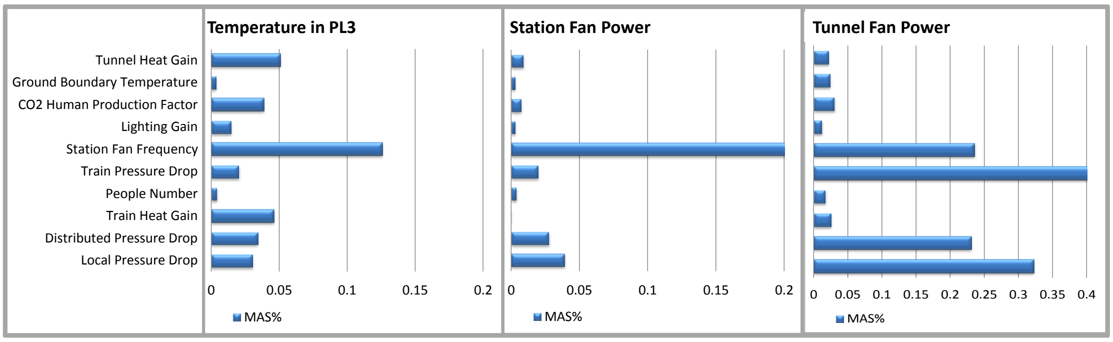

Figure 9. Synthetic results of the preliminary sensitivity analysis in terms of MAS%: inputs (on the left) vs. output target parameters (on top).

b) Raw Calibration

As soon as the first environmental and energetic measurements were available, (April 2013) a first raw calibration phase started. Since a lot of information about actual fan control was not yet available at that time, this preliminary calibration phase was mainly aimed at defining the correct schedule of the main processes. The fan and train schedules were shifted, in order to align the main events in the simulation (fan flow direction inversion, transit of first train, etc.) to the measured data. Since data from only one season were available, this phase was quite limited in scope. Nevertheless, it allowed to identify some discrepancies in the model (mainly coding bugs), and an overall revision was decided, and a number of bugs were fixed.

c) Evidence-Based Calibration

Finally, an evidence-based calibration phase was initiated. As soon as the environmental measures related to different seasons became available, the understanding of the environmental processes occurring in the station improved. The ASHRAE Indexes (Ashrae 14, 2002) that qualify the calibration process are defined as:

$$NMBE = \frac{\sum_n (y_m - y_s)}{n * y_{avg}} \, x \, 100 \qquad (3)$$

$$CV(RMSE) = \frac{\sqrt{\sum_n (y_m - y_s)^2 / n}}{y_{avg}} x100 \qquad (4)$$

Where, y_m is the measured data, y_s is the simulated data and y_{avg} is the mean value of measured data. Figure 10 shows the evolution of evidence based calibration process, in terms of the dynamic pattern of air temperature in the platform, referring to three days from June data. It appears clearly that while the calibration process proceeded, the pattern of the simulated temperature dynamics converged towards the measured one.

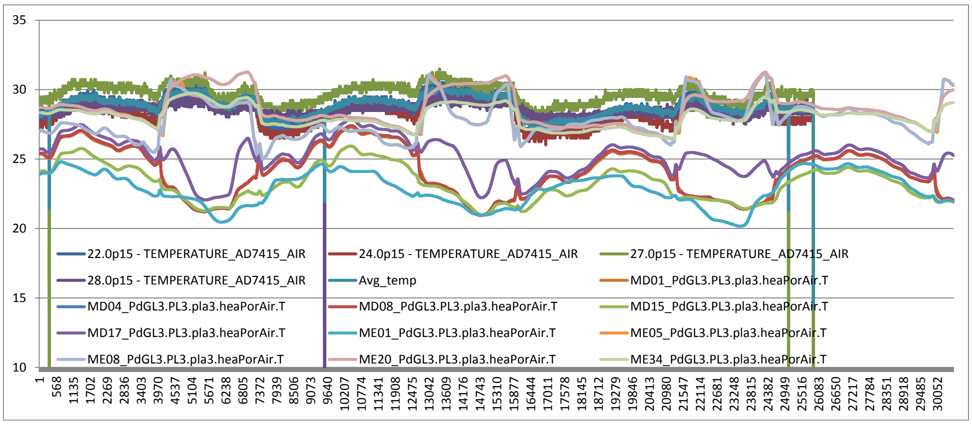

Figure 10. Calibration Evolution: Air temperature in PL3 in three June days.

In Figure 10, each curve represents a different calibration process. The more data were available the more the curves approximate the measured data (the four noisy curves corresponding to the four sensors in the platform). The x-axis represents the number of samples.

Table 3 shows the results of the calibration process, achieved so far, in relation to air temperature in the platform and power consumption of the station fans. With regards to the thresholds defined by the standard, the model can be considered calibrated.

Table 6. Calibration indexes of the Station Model.

Figure	April		June		September		November		Average abs	
	NMBE (%)	CV-RMSE (%)	NMBE (%)	CV-RMSE (%)	NMBE (%)	CV-RMSE (%)	NMBE (%)	CV-RMSE (%)	NMBE (%)	CV-RMSE (%)
Temperature PL3	2.44	4.27	4.24	5.10	4.19	3.23	-0.38	2.96	2.81	3.89
Power	0.08	7.99	1.70	13.17	5.68	15.77	-3.28	4.64	2.69	10.39

4.2. Passenger model

The passenger model is used to predict the number of passengers in each ambient of the metro station. The model uses an alignment algorithm, which is based on history data and is controlled by seven parameters, which influence the prediction accuracy. These are:

- **History length:** length of time used to build the history.
- **Pattern length:** count of timeframes in a row considered to calculate the equality of pattern and observation.
- **Observation length:** count of timeframes in a row considered to calculate the equality of pattern and observation.
- **Penalty observation and pattern value match:** value added to the penalty costs when observation and pattern matches.
- **Penalty gap in observation:** value added to the penalty costs when the observation contains a gap compared to the pattern.

- **Penalty gap in pattern:** value added to the penalty costs when the pattern contains a gap compared to the observation.
- **Penalty observation and pattern value mismatch:** value added to the penalty costs when a symbol in pattern and observation mismatch.

In addition, the CCTV cameras do not work error-free (it is possible that some history data are missing). Hence, a threshold on the percentage limit of missing CCTV data was established. Finally, the camera timeframe influences the prediction accuracy as well. The timeframe is the time interval that is represented by one occupancy value. Since the CCTV carousel provides one occupancy value every 60 seconds the smallest possible timeframe is 60 seconds.

In order to achieve the best prediction, a parameter calibration was carried out. Combinations of two history length (5 days, 7 days), two pattern lengths (50 timeframes, 60 timeframes), and three observation lengths (35 timeframes, 45 timeframes, 60 timeframes) were investigated. In addition, the alignment penalty setting was pre-evaluated. The best performing parameter configuration uses the following parameter settings:

- History length = 7 days,
- Observation length = 45 timeframes,
- Pattern length = 60 timeframes,
- Penalty observation and pattern value match = 0,
- Penalty gap in observation = 1,
- Penalty gap in pattern = 1,
- Penalty observation and pattern value mismatch = 2,
- Threshold history day usable = 85 %.

Other settings do not reduce the prediction-error significantly. The passenger model evaluation considers 1008 predictions. For each prediction, the prediction-error was calculated. The averaged prediction error, i.e. the difference between predicted and actual number of passengers is less than one passenger. The calculated prediction-error for location and weekday is depicted in Figure 11.

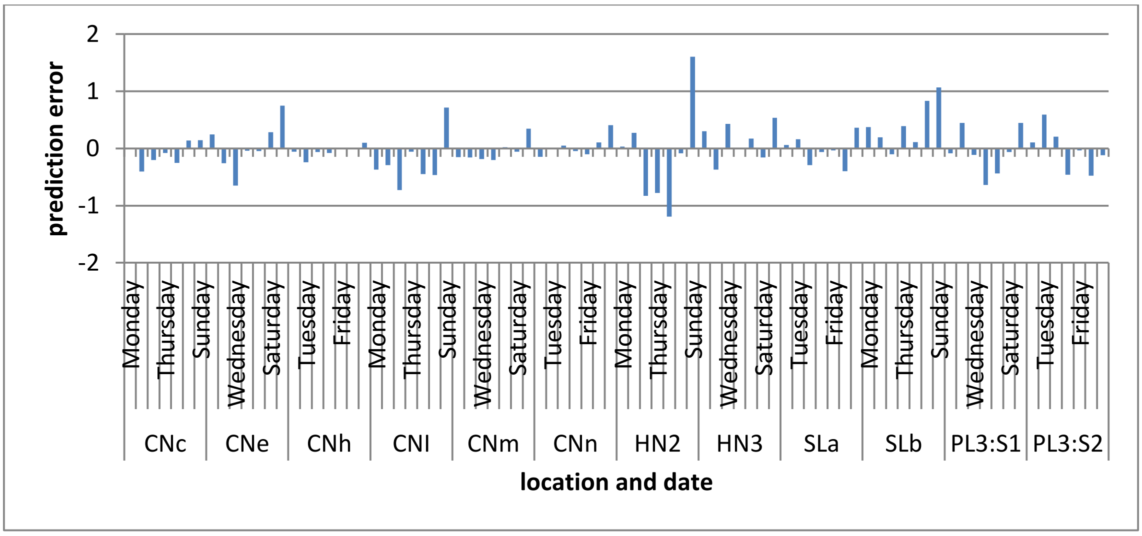

Figure 11. Passenger prediction error per location and weekday.

The prediction-error shows a rather good prediction on locations with lower average number of passenger. On locations with higher average number of passenger and therefore higher passenger fluctuation, the passenger model tends to underestimate. This is indicated by the comparison between actual and predicted number of passenger (Figure 12).

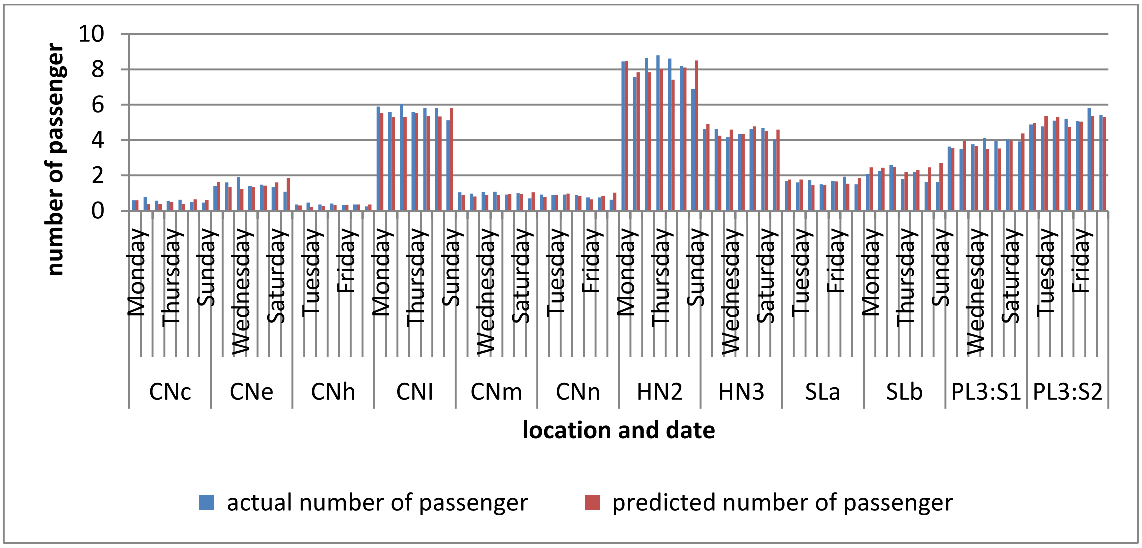

Figure 12. Passenger prediction, actual number of passenger compared to predicted number of passenger.

5. ENERGY SAVING ASSESSMENT

This section is devoted to the analysis of the control systems' performances and the quantification of savings obtained in the real pilot implemented in PdG-L3, which involved the lighting system, the ventilation system and the escalators.

5.1. Lighting system

The operation of the lighting control system and the related energy saving are essentially affected by the occupancy in the places of the station where the pilot is installed, which are the platform PL3:S2 and the hall HN2 (and the closed corridor CNm). The lighting level L (in percent) is set by the controller as a function of the occupancy N (number of people) of the aforementioned spaces through the following linear relation:

$$L = L_{max} - (L_{max} - L_{min})\frac{N}{N_{High}}$$

Where N_{High} is the high occupancy status (defined as 14 for HN2-CNm and 10 for PL3:S2) at which corresponds L_{min} which is the minimum lighting level allowed (53% for HN2-CNm and 77% for PL3:S2) whereas L_{max} is the maximum lighting level, i.e. 100%. Therefore, the assessment of the control system performance is based on the measurement of occupancy and light intensity carried out by the monitoring networks in PdG-L3. Figure 13 shows the typical dynamics of the lighting level and the occupancy as a function of time in a period of an hour; this figure roughly shows the higher the occupancy, the smaller the lighting level.

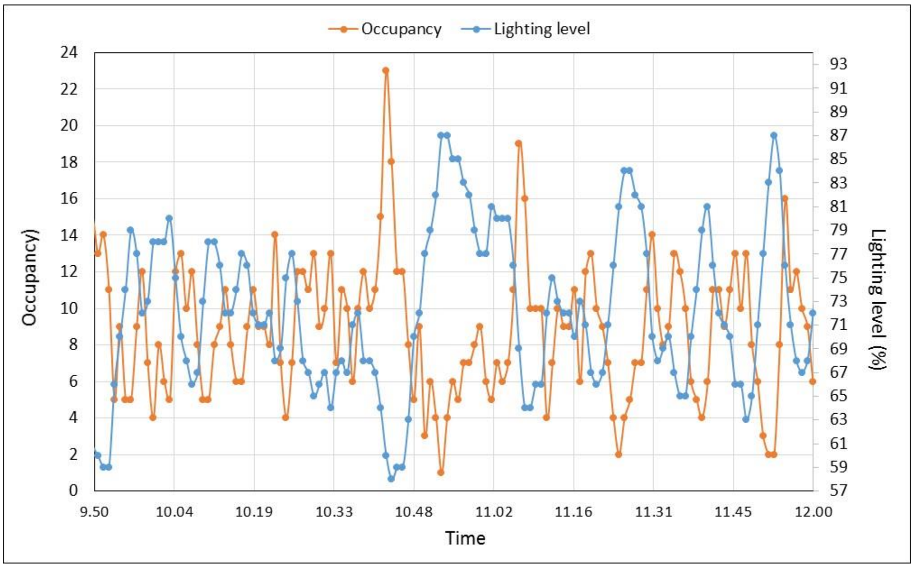

Figure 13. Dynamic trends of occupancy and lighting level as function of time.

In Figure 14a and Figure 14b, the measurements of lighting level are represented as a function of the measured occupancy in PL3:S2 and HN2-CNm, respectively. These figures also show the linear interpolation of the measured lighting levels and the theoretical lighting level, i.e. the linear relation imposed by the controller, pointing out the consistency of the measured data with the theoretical ones. Indeed, the two lines match closely and, hence, it proves the effectiveness of the controller's performance. The small difference in the inclination of the measured and theoretical lines are essentially due to the saturation on dimming as the occupancy becomes high which limits the decrease of the lighting level avoiding over reduction.

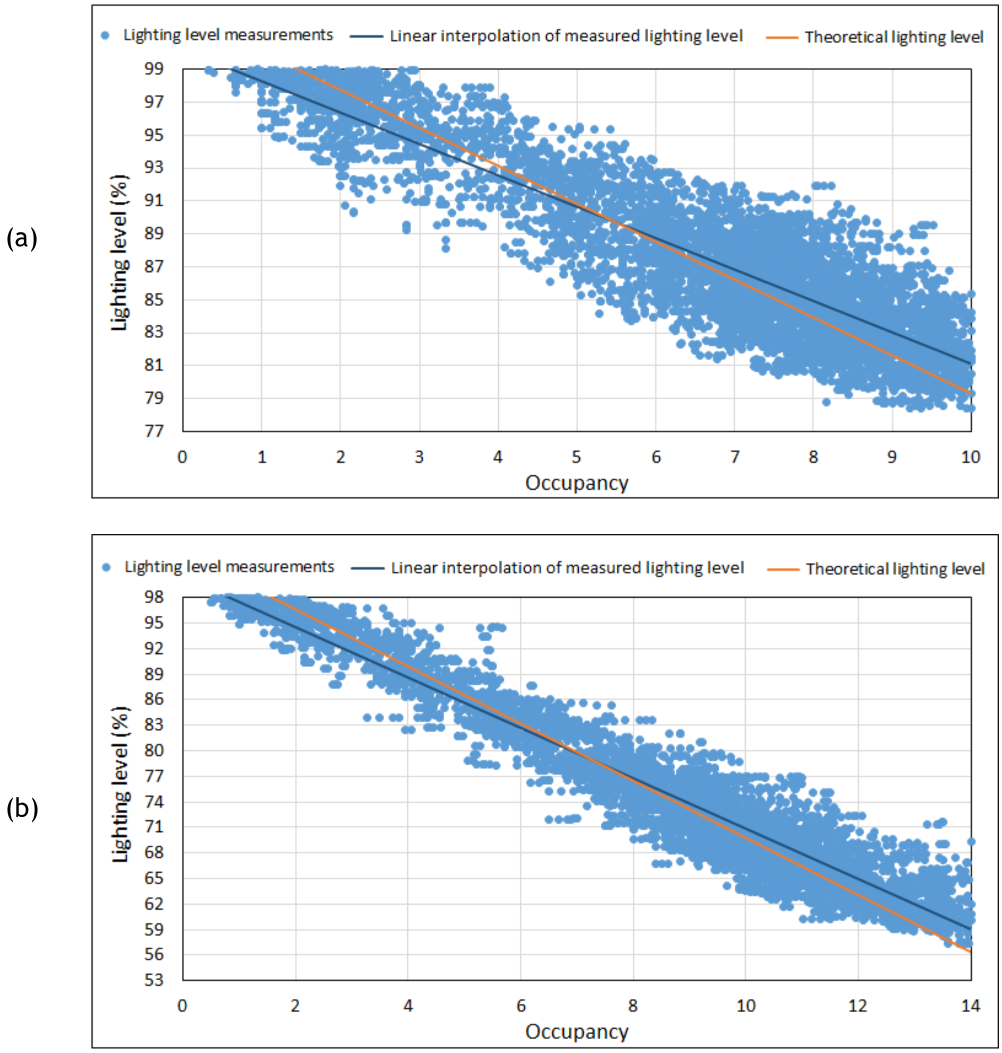

Figure 14. Dynamic trend of occupancy (a) and lighting level (b) as a function of time.

The effectiveness of the lighting control system is then illustrated in terms of consumption's reduction as lighting levels decrease. Indeed, the power absorbed by the lamps controlled should be theoretically reduced in a linear relation with the increase of dimming, as shown in Figure 15a and Figure 15b. In addition, the power measurements performed by the smart meters between September and October 2014 were related to the measured lighting levels, as shown in the blue curves in Figure 15a and Figure 15b. These figures illustrate the average value for a given lighting level of the power absorbed by pilots in PL3:S2 and HN2-CNm, respectively[7].

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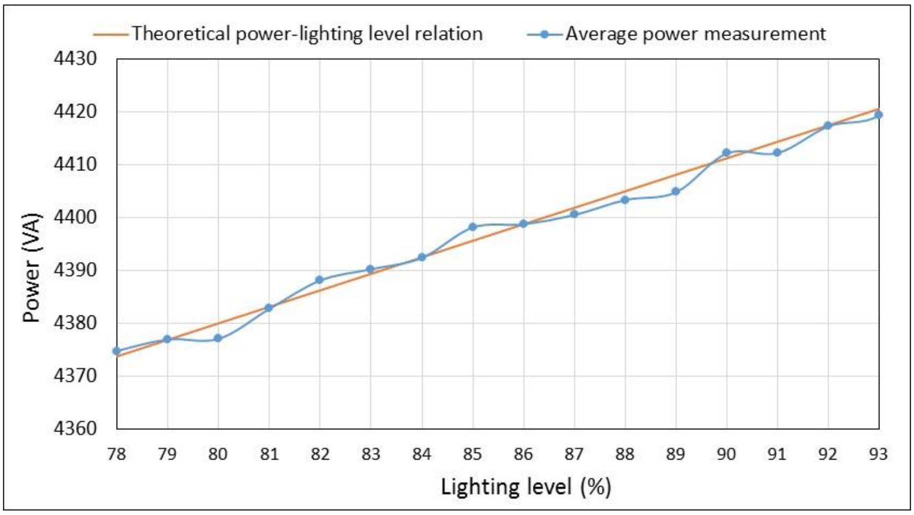
[7] The relation power vs. lighting levels is defined considering the nominal power of the LED lamps installed in the pilot PL3:S2 and HN2-CNm, that is the fraction of power controlled by the SEAM4US system, which is 300 W and 560 W, respectively (the power factor was estimated to be about 0.96).

(a)



(b)

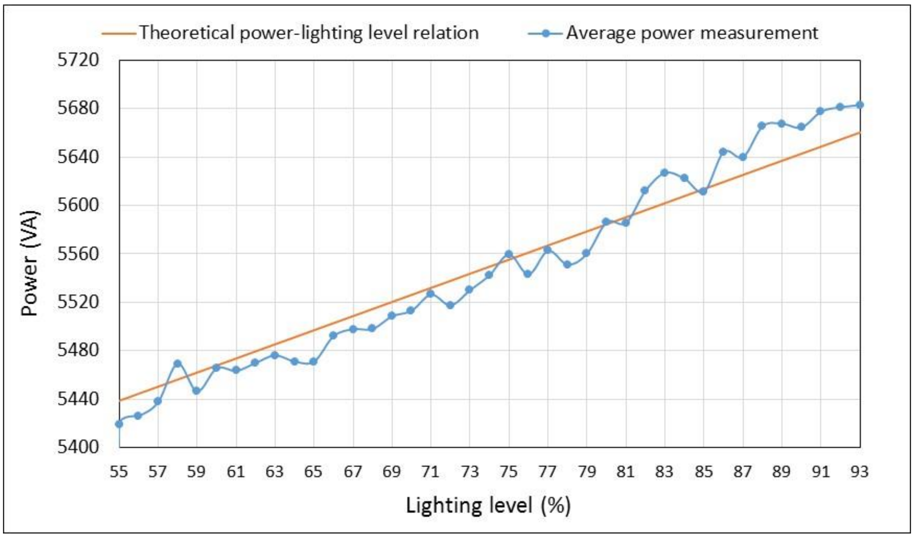


Figure 15. Power as a function of the lighting level for PL3:S2 (a) HN2-CNm (b).

The figures show that the average power measurements for each lighting level are very close to the theoretical ones and this definitely confirms the effectiveness of the control system's performances.

The verification of the lighting system retrofit is carried out using the consumption data measured by the energy monitoring system. Indeed, as recommended by the IPMVP, the SEAM4US validation procedure for the ECM developed for the lighting system follows the Option A – Retrofit Isolation: Key Parameter Measurement. Therefore, absolute saving is determined through field measurements of consumption and is calculated by means of the following relation:

$$Savings = Baseline\ energy\ (without\ ECM) - \ Reporting\ period\ energy\ (with\ ECM)$$

The selected length of the reporting period is two months, i.e. September and October 2014. This period is enough to assess the saving obtained by controlling because of the daily regularity patterns shown by the passenger flows.

The baseline consumption was defined for both the pilot deployed in PL3:S2 and in HN2-CNm as the average power consumed in April 2014 (before the pilots deployment) by the circuits involved in the pilots during the working hours 7:00 – 22:00, as described in section 5.2 of D3.1.2. So the baseline consumption for the pilot in PL3:S2 is 4442 ± 5 VA whereas for HN2-CNm it is 5701 ± 16 VA. These values were compared with the average powers consumed in the reporting-period, i.e. with the pilot deployed, and measured by the installed smart meters during the same working hours - that is from 7:00 to 22:00. Table 7 shows the average power baseline and the measured ones in the reporting-period for both the pilot in PL3:S2 and in HN2-CNm (the expanded uncertainties were calculated accordingly to Appendix C of the D3.1.2). Energy savings are also provided in this table. Of course, the savings are calculated considering the fraction of the controlled lamps. The savings errors were calculated accordingly to the errors' propagation rules reported in Appendix C of the IPMVP volume I.

Table 7. Measured consumption and savings obtained in the lighting pilot.

Areas of lighting pilot	Average power baseline (VA)	Average power in reporting-period (VA)	Fraction of lamps controlled (%)	Saving (%)
PL3:S2	4,442 ± 5	4,393 ± 1	7.0	**15.8 ± 1.7**
HN2-CNm	5,701 ± 16	5,536 ± 3	10.2	**28.3 ± 2.8**

The difference in energy savings for the two areas of the pilot is explained in Figure 16 which shows the cumulative distribution of the operating time at a given lighting level. This figure shows that the controlled lamps in HN2-CNm operate between the lighting 53% and 70% levels for about 50% of the time whereas the lamps in PL3:S2 work for 50% of time at a level between 77% and 84% and, hence, the saving obtained for the pilot in HN2-CNm is higher than the one achieved in PL3:S2.

Given that the platform has 34% of the installed power and halls and corridors have the remaining 66%, we can extrapolate the saving values for the whole station as an average saving of **24.1% ± 1.9%**.

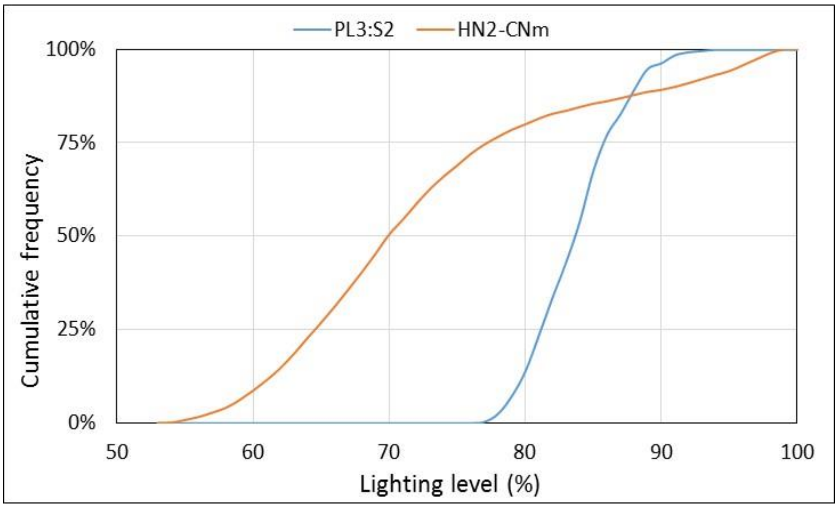


Figure 16. Cumulative distribution of the operating time at a specific lighting level.

5.2. Ventilation system

The measurement and verification of the forced ventilation system retrofit raises a number of challenges due essentially to the multiplicity of external influencing factors having seasonal dynamics. Outdoor temperature, wind flow speed and direction and indoor temperature are among them. Seasonal dynamics of influencing factors cause two major impediments for the application of IPMVP Option A and B - Key parameters Measurements. The first concerns the operational schedule of SEAM4US that foresees, in the DOW, a fully functional system deployed at M33, leaving at most four months for validation. This operational arrangement avoids the measurement of a representative sample of data (one year typically) for the calculation of both baseline and savings. The second is as just as critical. It concerns the representativeness of the monitoring periods, even if extended to a whole year, for the purpose of energy saving calculations. In fact, relevant variations of weather conditions are nowadays much more frequent than in the past, and may occur even within two subsequent weeks. In this case, the effects of complex weather variations cannot be compensated but with a thorough modelling of the weather dynamics and of the building response, which, in fact, corresponds to the implementation of the option D[8]. Therefore, the SEAM4US validation procedure for the ventilation system retrofit essentially follows IPMVP Option D – Calibrated Simulation. Nevertheless, in order to provide further evidence to a purely simulation based performance assessment a second set of analysis was carried out based on measured performance data. The objective of this second analysis was to demonstrate that the estimations provided by the Option D, which are purely simulation based, are in the range of what can be effectively measured by the monitoring system. Of course, the results of the two analyses differ because the weather conditions stated in the weather file are different from what effectively occurred during the two months. Hence, since the SEAM4US control heavily depends on the weather and indoor conditions, results differ. Therefore the purpose of the second analysis was to produce evidence that the measured dynamics fell within the estimation provided by the Option D. The two sections below give the details of both assessment procedures.

5.2.1. Performance assessment through calibrated model

Option D, Model Calibrated Simulation, involves the use of computer simulation software to predict facility energy for both terms of the following equations, as recommended by the IPMVP protocol. Savings calculation using this simplified equation is made possible because the calibration error equally affects the baseline (without ECM) and controlled reporting period (with ECM) figures.

$$\begin{aligned} Savings = {} & Baseline\ from\ the\ calibrated\ model\ (without\ ECM) \\ & - Reporting\ period\ energy\ from\ the\ calibrated\ model\ (with\ ECM) \end{aligned}$$

Accurate computer modelling and calibration to measured energy data are the major challenges associated with Option D. The model calibration procedure was accurately conducted according to the standards, as described in section 4.1 of this deliverable.

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[8] This is very much the same issue that faced in the modelling community and that led to the definition of standardized weather files.

Option D – calibrated simulation has a number of benefits in the context of the SEAM4US project:

- The SEAM4US control system development already implemented a building calibrated model for the purpose of the model predictive control of the fan. Simulation software predicts metered calibration data with acceptable accuracy. The same model can be used for the baseline and retrofit performance estimation with no additional costs. In fact, additional costs are considered one of the main drawbacks for the application of Option D.
- Savings with Option D is marginally affected by the model calibration error, since the calibration 'error' equally affects both baseline and reporting period models.
- Option D simulations use standardized and representative weather files. This avoids any seasonal effect.

In order to let the saving percentage assume any practical and operational significance, a comparison of the main physical factors (namely platform temperature, CO_2 level and PM10 level[9]) that affect the comfort were conducted between the baseline (without ECM) and the controlled (with ECM) situations. The performance assessment was carried out using a standardized Barcelona weather file[10]. The simulation was performed by means of the SEAM4US simulator described in section 8.1 of D3.2.2-Final User Thermal and Control Models. The control policy adopted in the SEAM4US controlled simulations is the same one implemented in the deployed system. It is summarized in the following Table 8. Seasons determines different operation modes for controller and are not defined as meteorological seasons rather as the TMB operation modes: Winter={Jan, Feb, Mar}, Spring={Apr, May, Jun}, Summer={Jul, Aug, Sep, Oct}, Autumn={Nov, Dec}.

Table 8. Control policy parameters.

Symbol	Description	Value			
		Winter	Spring	Summer	Autumn
$\boldsymbol{FreSF_{Min}}$	Minimum frequency of station fan	-25	-50	-50	-25
$\boldsymbol{FreSF_{Max}}$	Maximum frequency of station fan	25	50	50	25
$\boldsymbol{\widetilde{T}}$	Typical temperature value	25	27	30	28
$\boldsymbol{\overline{TemPl3}}$	Setpoint temperature for PL3	22	24	27	25
$\boldsymbol{\widetilde{DT}}$	Typical temperature in-out value	20	10	5	10
$\boldsymbol{TemPl3_{Max}}$	Maximum temperature for PL3	31 °C			
$\boldsymbol{\widetilde{PElSF}}$	Typical electric power for station fan	13600			
$\boldsymbol{\widetilde{PElTF}1}$	Typical electric power for tunnel fan1	20000			
$\boldsymbol{\widetilde{PElTF}2}$	Typical electric power for tunnel fan2	70000			
$\boldsymbol{ACOPl3_{Min}}$	Minimum Air Change for PL3	3.93 kg/s			
$\boldsymbol{\overline{ACOPl3}}$	Setpoint Air Change for PL3	50 kg/s			
$\boldsymbol{\widetilde{CO2}}$	Typical CO_2 value	1000 ppm			
$\boldsymbol{\widetilde{DCO2}}$	Typical CO_2 in-out value	400 ppm			
$\boldsymbol{DCO2Pl3_{Max}}$	Maximum CO_2 in-out for PL3	700 ppm			
$\boldsymbol{\widetilde{PM10}}$	Typical temperature value	400 ug/m^3			
$\boldsymbol{PM10Pl3_{Max}}$	Maximum PM10 value for PL3	700 ug/m^3			

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[9] Relative humidity has been neglected because its level in the underground environment is almost constant and rather low in both situations.

[10] IWEC- WMO#081810 - Europe - Original Source Data (c) 2001 American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), Inc., Atlanta, GA, USA. www.ashrae.org

α_{DF}	Weigth of frequency variation term	0.000
α_{DT}	Weigth of in-out temperature term	0.067
α_{T}	Weigth of temperature term	0.266
α_{PT}	Weigth of tunnel fan power term	0.046
α_{PS}	Weigth of station fan power term	0.005
α_{AC}	Weigth of air change term	0.002
α_{CO2}	Weigth of CO_2 term	0.018
α_{PM10}	Weigth of PM10 term	0.004

The following Table 9 reports the estimated savings for each season.

Table 9. Estimated Energy consumptions and Savings for each season.

Season	Months	Baseline (KWh/week)	SEAM4US control (KWh/week)	Saving %
Spring	3	1595.84	1072.27	32.81 ± 1.98
Summer	4	1541.03	1030.01	33.16 ± 1.10
Autumn	2	370.57	310.28	16.27 ± 5.17
Winter	3	370.33	309.93	16.31 ± 4.94
Weighted Average		**1066.98**	**740.60**	**30.59 ± 2.00**

The following Table 10 summarizes the variation of the comfort factors. For each factor the mean difference and its standard deviation. The mean difference is calculated as:

Mean difference = mean (Baseline Value - SEAM4US controlled value)

Table 10. Mean difference and standard deviation of the main comfort parameters.

Season	Platform Temperature (°C)		CO_2 (ppm)		PM10 (µg/m^3)	
	Mean difference	Standard Deviation	Mean difference	Standard Deviation	Mean difference	Standard Deviation
Spring	-0.46	0.25	-25.02	46.94	-5.70	58.22
Summer	-0.17	0.13	-61.15	57.80	-17.96	56.39
Autumn	0.36	0.18	34.86	60.58	7.94	14.20
Winter	0.10	0.10	13.61	42.78	4.16	10.81

Table 10 shows that the SEAM4US optimal control achieves significant energy savings without penalizing the environmental comfort. For example, in the spring worst case 75% of the differences between baseline and controlled temperatures lays within an interval of ± 0.5°C.

5.2.2. Performance assessment through measured data

A second set of analysis were carried out based on measured performance data recorded during the months of September and October 2014. The objective of this second analysis was to demonstrate that the estimations provided by the previous model calibrated analysis, which are purely simulation based, resemble what can be effectively measured by the monitoring system. The SEAM4US system adopted the same control policy used in the calibrated simulation.

Table 11 reports the calculated savings for the reporting-period represented by the two aforementioned months. The consumption baseline was defined as the average power consumed between the middle of May and the first week of July 2014, as described in section 5.1 of D3.1.2. The consumption baseline and the average power absorbed in the reporting-period were both calculated through the measurements recorded by means of the smart meters deployed in the PdG-L3 station. The expanded uncertainties in Table 11 were calculated accordingly to Appendix C of the D3.1.2 whereas the savings error were calculated accordingly to the errors' propagation rules reported in Appendix C of the IPMVP volume I.

Table 11. Measured consumption and savings obtained in the ventilation pilot.

Months	Average power baseline (VA)	Average power in reporting-period (VA)	Saving (%)
September (Summer mode)	23247 ± 121	15894 ± 915	31.6 ± 4.0
October (Summer mode)	23247 ± 121	13368 ± 860	42.5 ± 3.7
Average	23247 ± 121	15031 ± 701	**35.3 ± 3.1**

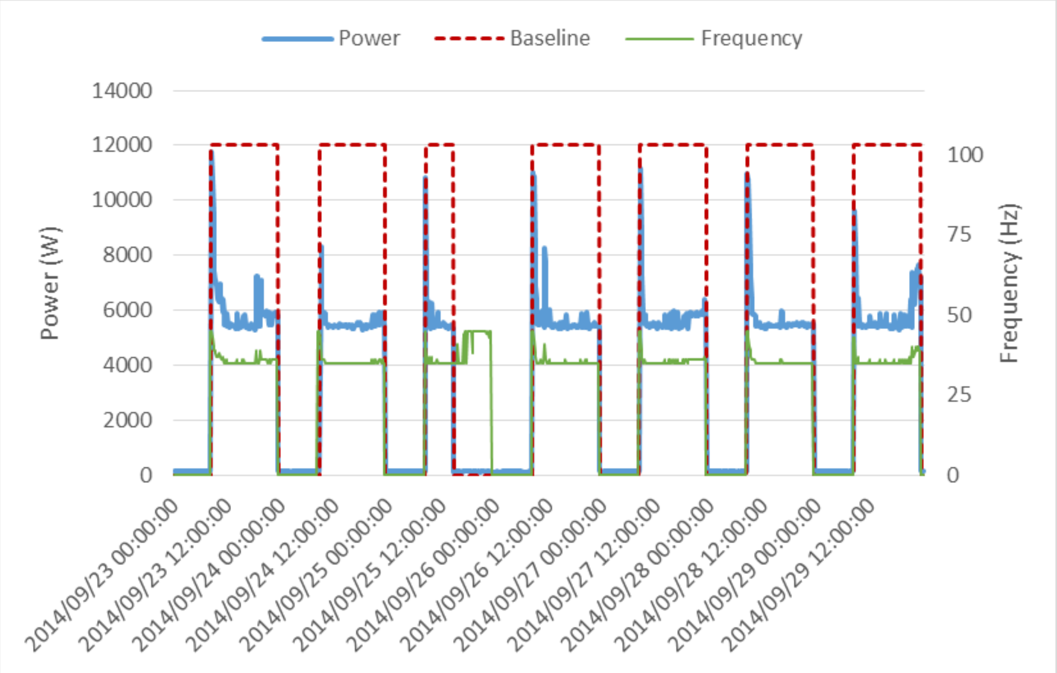

Figure 17. Measurements of frequency and power consumed by fans during a week in September 2014.

The following Figure 18, Figure 19 and Figure 20 detail the comfort factors; that is, temperature and concentrations of CO_2 and PM10 measured in platforms PL3 by the environmental sensors under SEAM4US control, during a week in September.

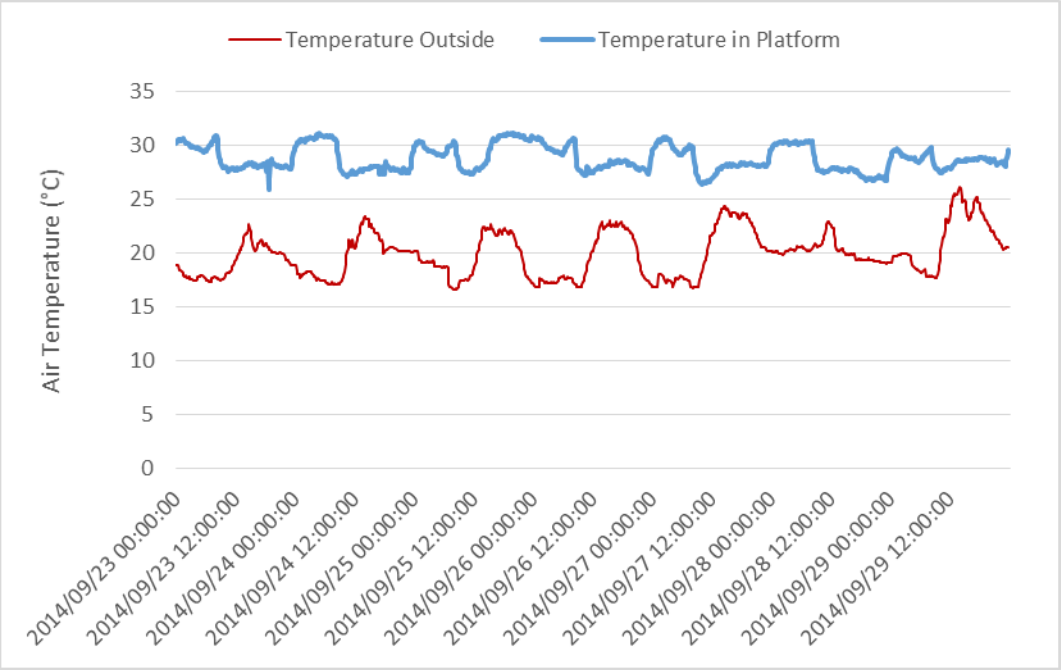

Figure 18. Measurements of the air temperature in platforms PL3 during a week in September 2014.

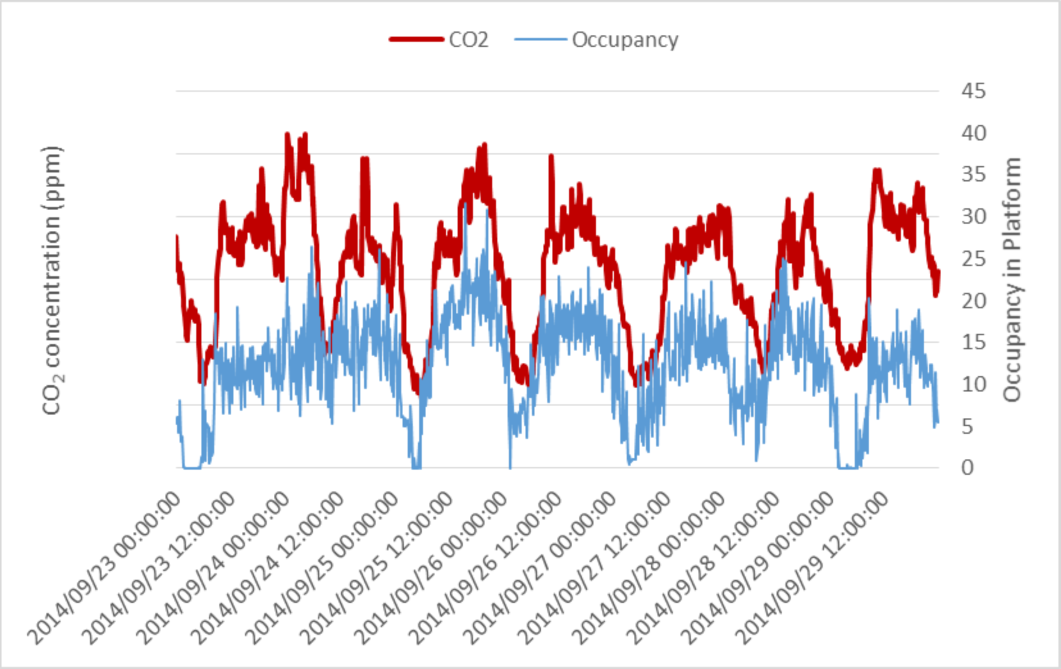

Figure 19. Measurements of CO$_2$ concentration in platforms PL3 during a week in September 2014[11].

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[11] In this figure, the y-axis was not reported because of privacy issues concerning sensible data in public environments.

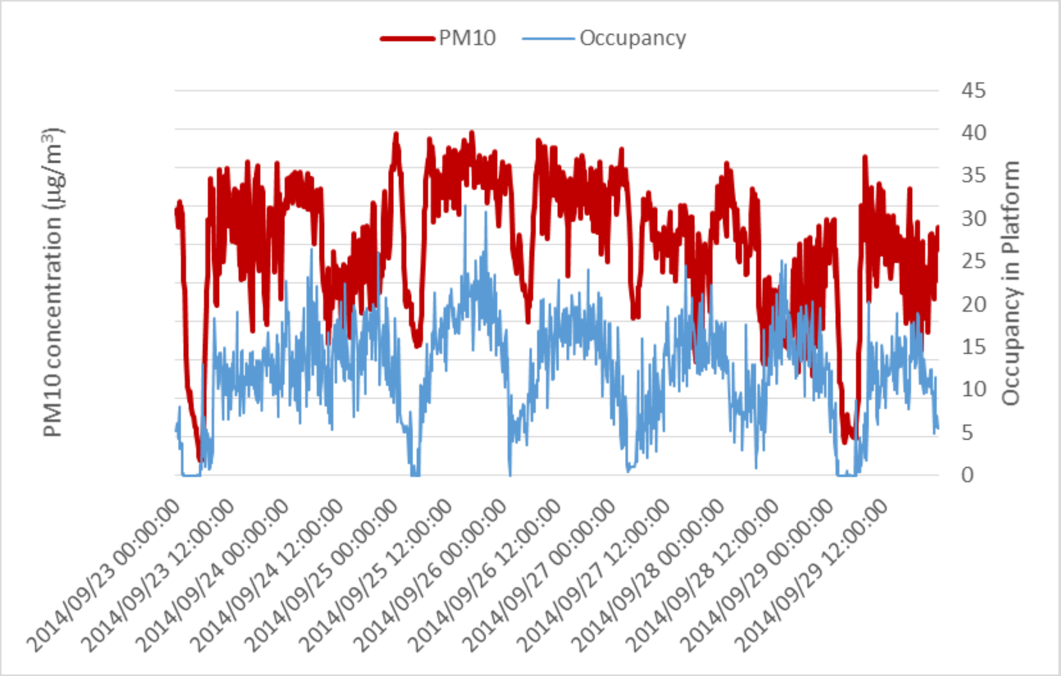

Figure 20. Measurements of PM10 concentration in platforms PL3 during a week in September 2014[12].

5.3. Escalators

The operating conditions of an escalator are determined by two main factors: occupancy and speed. Therefore, the proper behaviour of an escalator's control system depends on the two following events: first, the congruity between predictive occupancy and the signal sent to it for controlling its speed and, second, the consistency between the hint sent from the control system for regulating the escalator's speed and the actual speed assumed by the escalator. In this perspective, Figure 21 shows the occupancy and the speed hint sent by the control system as a function in a one hour time period. The rule that correlates speed hint and occupancy is based on a threshold set to the value of fifteen people. If occupancy is under this threshold, the speed hint is 0.4 m/s whereas, when the occupancy exceeds the above threshold, the hint is 0.5 m/s. So, Figure 21 qualitatively shows that the monitoring data of occupancy and speed hint comply with the aforementioned rule. In fact, the monitoring data collected in September and October 2014 pointed out that the speed hint was consistent with the threshold of occupancy specified in the controller 76% of the time.

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[12] In this figure, the y-axis was not reported because of privacy issues concerning sensible data in public environments.

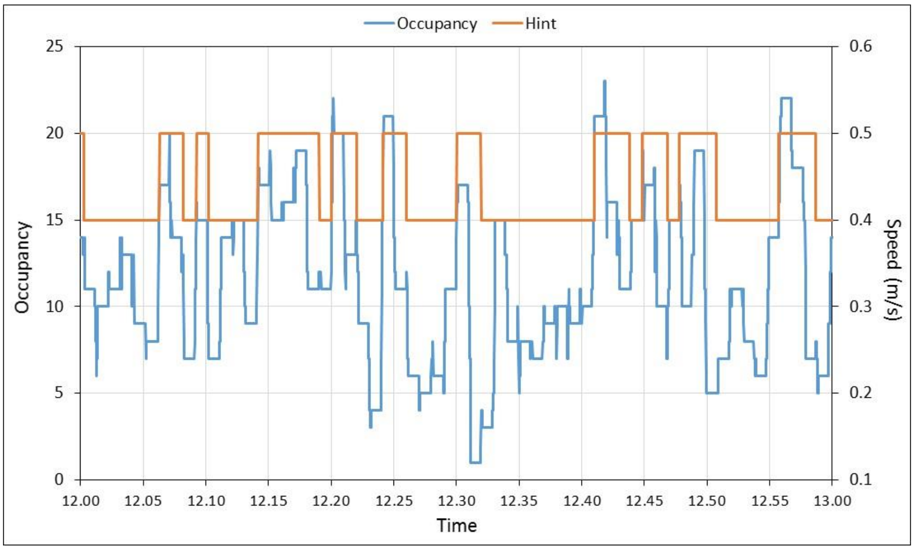

Figure 21. Dynamic trends of occupancy and speed hint as a function of time.

The second aspect to be assessed in order to evaluate the escalator's control system concerns the correlation between hint and actual escalator speed. In this perspective, Figure 22 shows the speed hint and the actual escalator speed as functions of time in a period of one hour. The monitoring data collected in September and October 2014 pointed out that escalator speed is actually set to the value suggested by the controller 75% of the time.

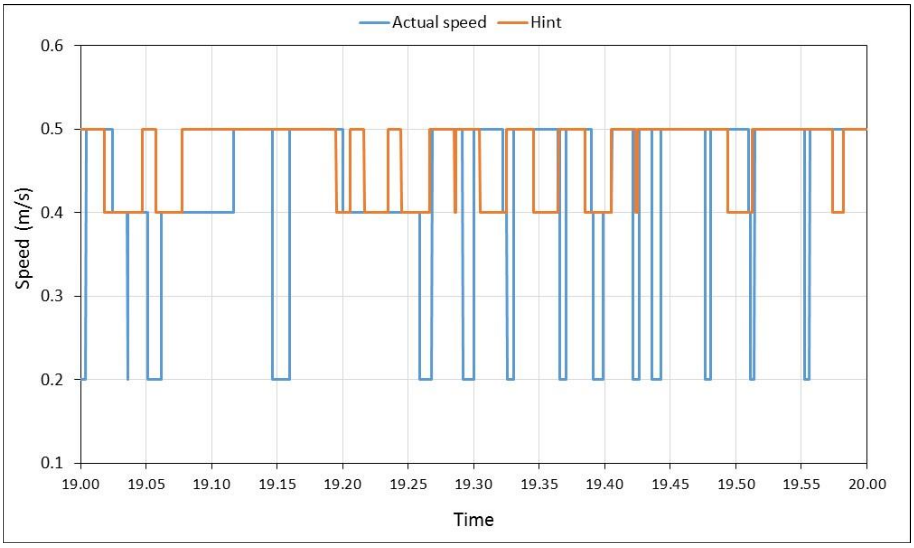

Figure 22. Dynamic trends of speed hint and actual speed as a function of time.

In summary, the data collected in the reporting-period, i.e. September and October 2014, by the monitoring network indicates that the escalator's control system operates correctly, that is, in accordance with the policy implemented by the controller.

Concerning the assessment of savings, the IPMVP recommends Option A – Retrofit Isolation: Key Parameter Measurement for the verification of the escalator retrofit. Unfortunately, the monitoring data collected in September and October 2014 revealed an increase of consumption when the escalator ran at 0.4 m/s rather than at the rated speed, i.e. 0.5 m/s. This occurrence is pointed out in Figure 23, which shows the average measured power absorbed in the reporting-period by the escalator running without load.

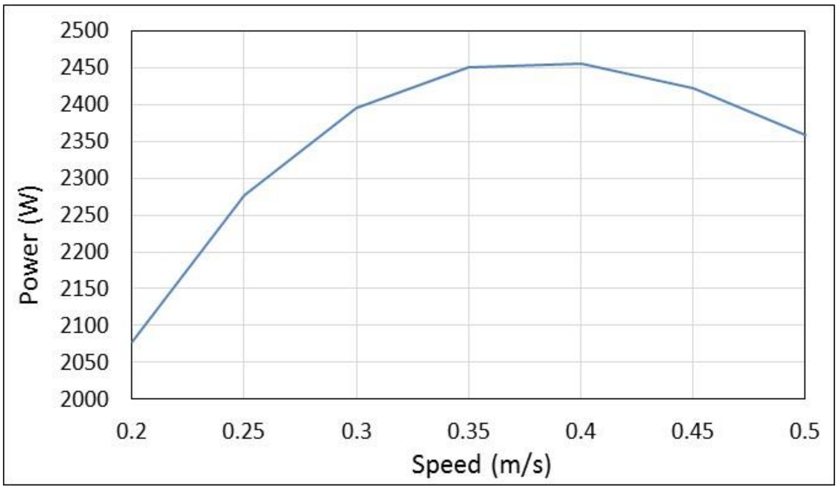

Figure 23. Average power absorbed by the escalator as function of the speed for September and October 2014.

The overconsumption at 0.4 m/s compared to the power absorbed at 0.5 m/s is due to a strong loss of efficiency of the escalator's system when its speed decreases, as shown in Figure 24. This figure shows the efficiency of the unloaded system calculated in per unit (p.u.) of the efficiency of the escalator operating at 0.5 m/s. The efficiency in p.u. was calculated using the power data collected by the smart meter in the reporting-period.

The escalator's loss of efficiency at lower speed was not foreseen at design time because of a lack of technical documentation from the escalator manufacturer[13].In any case, this loss of efficiency is a specific feature of the escalator installed in PdG-L3[14]. In order to obtain an energy saving through the escalator's control policy, the escalator's hardware would have had to be adjusted to the requirements of the dynamic control for compensating the strong loss of efficiency occurred at reduced speeds. This was not feasible for several reasons explained in D1.2.3 Annual reports – Year 3. Therefore, the assessment of the escalator pilot in terms of savings was carried out using Option D of the IPMVP, based on calibrated model simulations.

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[13] The escalator manufacturer certified the escalator's PLC reprogramming without raising any issues concerning its loss of efficiency.

[14] The feasibility of energy saving through speed modulation is well documented (Intelligent Energy Europe, E4 Project - Energy Efficient Elevators and Escalators, March 2010) in literature and it is rapidly hitting the market (http://www.hitachi.com/environment/showcase/solution/industrial/escalator.html).

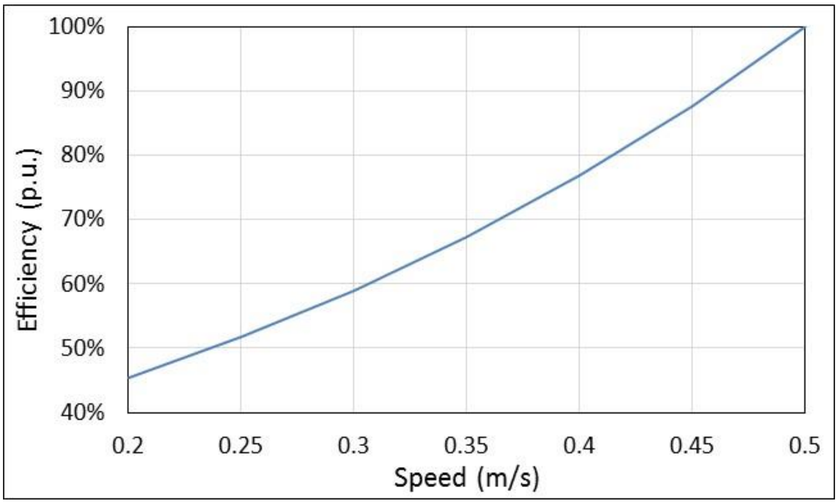

Figure 24. Efficiency in per unit of the escalator as a function of the speed in September and October 2014.

The escalator's loss of efficiency was not figured out in the modelling calculations reported in deliverables D3.1.2 and D3.2.2 because, at that time, the available data was limited to 0.2 m/s and 0.5 m/s and no data was available at intermediate speeds. Once these data were gathered, the escalator model was re-calibrated in order to obtain the same system efficiency conditions measured using the monitoring data. In the model, this was achieved mainly by setting the efficiency of the inverter to 58.3% at 0.4 m/s. Figure 25 shows the power measurements and the power calculated by the re-calibrated model as a function of the speed considering an unloaded escalator. Figure 26 instead shows the measured and the model-based calculations of the efficiency as a function of the escalator's speed.

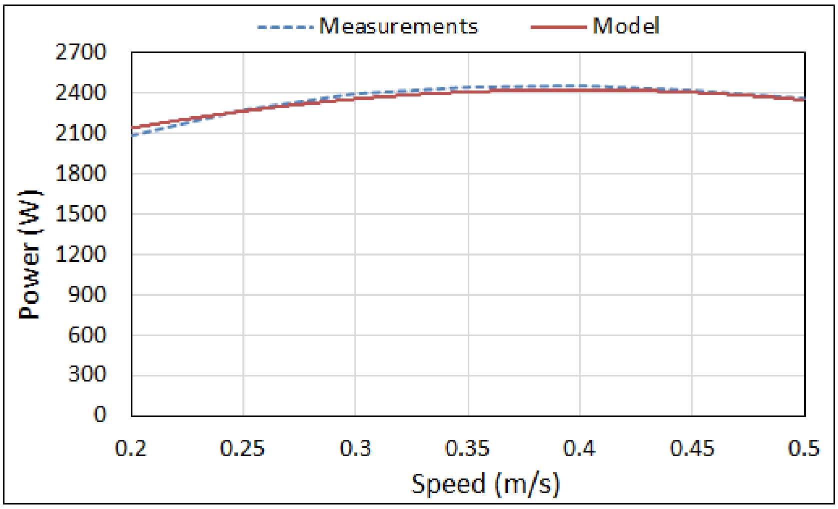

Figure 25. Measured and calculated power absorbed by the escalator as a function of the speed.

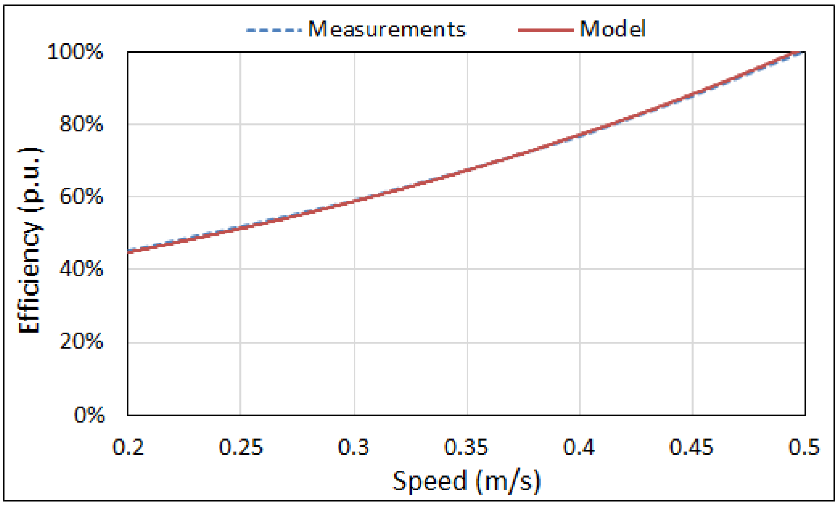

Figure 26. Measured and calculated efficiency of the escalator as a function of the speed.

The overconsumption calculated through the monitoring data collected in three full days at 0.5 m/s and other three full days at 0.4 m/s was 8.0%; the overconsumption obtained by using the re-calibrated model was 8.5% (the negligible difference is due to the different load profiles).

Therefore, the re-calibrated model was used to simulate this hardware's adaptation oriented to improving efficiency at low speeds and calculating achievable saving. The aforementioned model reconfiguration consisted essentially in increasing the inverter's efficiency at 0.4 m/s, from the actual value 58.3% to the same value at 0.5 m/s (i.e. 93.5%), which is actually an achievable value through an inverter upgrade. Figure 27 shows the calculations of power absorbed by the escalator at different speeds carried out using the re-calibrated model and taking into account adjustment in terms of system efficiency.

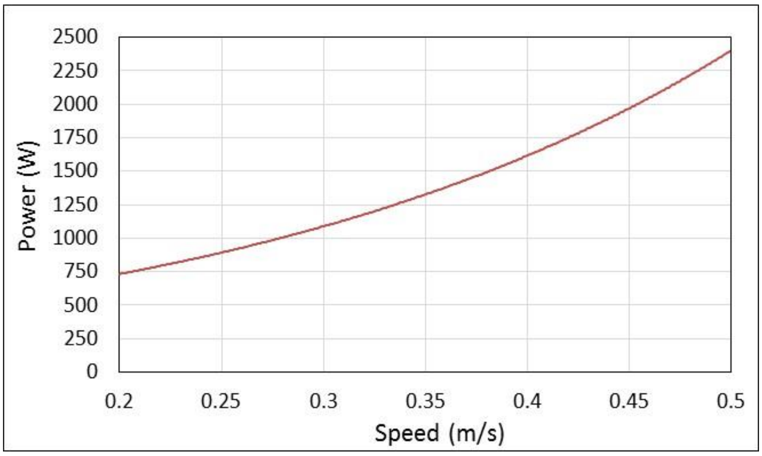

Figure 27. Power absorbed by the escalator as a function of speed calculated considering hardware adaptation.

The power profile as a function of the speed is hence changed thanks to the simulated hardware's adaptation and no peak is found at speeds lower than the rated value of 0.5 m/s (as in Figure 23).

The energy saving achievable by implementing the escalator's control policy, which does not include the hardware's efficiency adjustment, can be estimated in this way as **8.5% ± 1.9%.**

6. END-USERS EVALUATION

At the end of evaluating the general impact of the deployed ICT (hardware/software) system and its effectiveness from the energy savings point of view, five executive TMB officers were surveyed and requested to provide feed-back on several aspects of the SEAM4US pilot project implemented in the Passeig de Gracia station in Barcelona.

The executives polled occupy key positions within TMB's organization chart, namely they are the Responsible for the Station Systems and Equipment Projects Unit, the Telecommunications Project Manager, the Project Manager engineering in low voltage and electromechanical systems in the metro network, the Director of Business Development and International Relations and the Director of Research & Development. The positions mentioned deal with technical, research and business development functions. Moreover, 4 out of 5 of the professionals covering the above roles are experts in ICT or possess advanced ICT knowledge The fifth is a daily user.

All the officers polled know – in different degrees and with regard to diverse aspects – the SEAM4US project, as they have had the opportunity to deal with it directly as in the case of the Director of the Research & Development unit. In other cases, they have dealt with the project in term of its compliance with transportation rules, standards and regulation. Speaking on a more general level, they have had some role in the harmonization of the existing system with the pilot one.

With regards to the hardware, and more specifically about the sensors aimed at collecting data to monitor several aspects of the underground environment and of its relationship with the external one, the main constraint reported concerns their maintenance. The critical aspects mentioned in this field are i) the use of batteries for the sensors' power supply which entails frequent changing, ii) the high quantity of the sensors needed to correctly monitor the environment at the purpose of addressing the parameters, iii) the sensors' experimental feature which makes them frail and vulnerable to easy breakage due to environmental accidents or vandalistic acts.

No criticalities are reported concerning the aesthetic impact of the deployed system for the underground users. The old facilities of Passeig de Gracia – line 3 station and the fact that the sensors are mainly placed in key points where passengers cannot see them easily, contribute to reducing any possible visual disturbance caused the deployed hardware to zero, as a whole. Nevertheless, the officers polled deem the devices placed out of the technical rooms to be too exposed to damaging factors and in need of being somehow protected and made more robust through their upgrade to industrial standards of production.

Concerning the interaction between the SEAM4US system and TMB's staff, all the polled executives would consider specific training necessary i) to enhance the competences of the operational staff in charge of managing and maintaining the equipment of the SEAM4US system and ii) to put in place specific intervention protocols for restoring possible damaged devices in the briefest delay possible. From the point of view of the energy savings, the results of this survey indicate that the hardware investment needed to equip the station with an adequate number of devices would be effective if the system was extended to the whole metro system. We were already aware of this from the remarks proposed in the submitted marketing plan.

7. CONCLUSIONS

The system developed in the SEAM4US project is a complex software and hardware architecture for the optimal control of metro stations devoted to energy savings in non-traction consumption. The system, built up in the real station pilot of PdG-L3 in Barcelona, can be grouped into three main interrelated parts: the models, the monitoring networks and the control subsystems. The technical validation involved each of these parts of the system, definitely including the assessment of the savings obtained by controlling the energy intensive systems of the metro station, i.e. lighting, ventilation and escalators (@ D3.1.2 Final Energy Auditing Report). For this last aspect, the International Performance Measurement & Verification Protocol (IPMVP) was used as the guideline for the procedures for quantifying the impacts of the retrofit measures deployed in PdG-L3 (@ Section 2).

The meters and sensors installed in the metro station were used for monitoring energy and environmental parameters like airflow, temperature, CO_2 and PM10 levels in order to calibrate the models, control comfort conditions and validate the savings. The measures performed by the monitoring networks were verified in several on-site surveys by means of certified hand-held instruments; then, proper calibration factors were defined and applied to the raw data from the sensors (@ Section 3). The models developed during the project were then served to the control subsystems to foster optimal control decision making to be applied at any given time. An overall station model was developed to simulate the controlled devices (ventilators, escalators, lights) and to study the station’s thermo-fluid dynamical behaviour. A passenger model was created to predict the number of passengers in each zone at any arbitrary future time, based on data collected by a CCTV system. These models, which were widely described in D3.2.2 Final User, Thermal and Control Models, were calibrated using the data collected by the monitoring networks and during on-site surveys (@ Section 4). The validation of the control subsystems developed in PdG-L3 concerned two aspects; firstly, the verification of the proper operation of the real subsystems, whose monitored control variables have to be matched with the values codified by the control policies and secondly, the assessment of the saving achieved through the energy retrofit measures. Both these aspects of the control subsystems’ validation were analysed in this deliverable (Section 5).

The control subsystem for the lights was deployed in two different areas of the station: one side of the platform and a hall including a closed corridor. For both these parts of the lighting pilot, the correct performance of the controller was successfully accomplished, as detailed in this deliverable. The saving was assessed through the data gathered by the energy monitoring network during the reporting-period, September and October, 2014. So, the energy saving obtained controlling the lights of the lighting pilot was calculated to be **24.1% ± 1.9%**.

The validation of the forced ventilation system retrofit was very intricate because of the influence of the thermo-fluid dynamics in the metro station. Therefore, savings assessment was performed by following the calibrated simulation procedure established in the IPMV protocol. In addition, an analysis based on data collected by the monitoring network was also carried out. The results of this second analysis corroborated the consistency of the calculations provided by using the calibrated model. The saving obtained through the model calibrated simulations for a whole operating year is **30.6% ± 2.0%**.

For what concerns the escalator pilot, an analysis based on the monitoring data was carried out in order to demonstrate the proper performance of the control subsystem. This analysis pointed out that the escalator's controller operates properly, which means in accordance with the policy developed. Nevertheless, the energy measures collected by the monitoring network revealed an overconsumption of the escalator running at reduced speed (0.4 m/s) instead of the original rated speed, i.e. 0.5 m/s. This overconsumption was due to a strong loss of efficiency of the escalator's system when its speed decreases and it was not pointed out by the modelling calculations reported in previous deliverables, namely D3.1.2 and D3.2.2. So, the escalator's model was re-calibrated using a more completed set of data collected once the pilot was started-up. The re-calibrated model was used for simulating the hardware adaptation required for applying the escalator's control policy and, hence, for assessing achievable saving. Therefore, the saving obtainable by controlling the escalator's speed as function of the occupancy was evaluated to be **8.5% ± 1.9%**.