ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-MODPL02

VIRTUAL CONTROL COMMISSIONING FOR A LARGE CRITICAL VENTILATION SYSTEM: THE CMS CAVERN USE CASE

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Abstract

The current cavern ventilation control system of the CMS experiment at CERN is based on components which are already obsolete: the SCADA system, or close to the end of life: the PLCs. The control system is going to be upgraded during the LHC Long Shutdown 2 (2019-2020) and will be based on the CERN industrial control standard: UNICOS employing WinCC OA as SCADA and Schneider PLCs. Due to the critical nature of the CMS ventilation installation and the short allowed downtime, the approach was to design an environment based on the virtual commissioning of the new control. This solution uses a first principles model of the ventilation system to simulate the real process. The model was developed with the modelling and simulation software EcosimPro. In addition, the current control application of the cavern ventilation will also be re-engineered as it is not completely satisfactory in some transients where many sequences are performed manually and some pressure fluctuations observed could potentially cause issues to the CMS detector. The plant model will also be used to validate new regulation schemes and transient sequences offline in order to ensure a smooth operation in production.

INTRODUCTION

During the past 6 years, the CERN Cooling and Ventilation (CV) group has been gradually migrating their existing control systems and deploying all the new ones using the CERN industrial control standard: UNICOS employing WinCC OA as SCADA and either Siemens or Schneider PLCs. This work already covers nearly 200 PLCs, and is deployed on 10 production WinCC OA servers, running around 35 WinCC OA projects, being monitored 24hr/day by the technical infrastructure operators in the CERN Control Centre.

The two remaining major HVAC (Heating, Ventilation and Air-Conditioning) systems using a legacy and now virtually obsolete SCADA system (Wizcon) are the ATLAS and CMS caverns plants. These systems are large, complex ventilation units, covering multiple buildings, across multiple PLCs, which are scheduled to be upgraded during the first half of the LHC Long Shutdown 2 (LS2), beginning in 2019. This will bring these control systems into the CERN standard, and will guarantee their functioning through the next 15 years of operation, during the future upgrade phases of the LHC.

Since these ventilation systems are critical to the operation of the two largest detectors of the LHC, CMS and ATLAS, they are critical to the operation of the LHC accelerator itself, since any failures can impact the beam availability. In order to ensure a smooth and quick upgrade of the control system, as well as allowing engineers and operators to achieve improved control system performance, a virtual commissioning of the CMS ventilation cavern will be performed, using a dynamic model that has been developed.

Current Ventilation System

The current ventilation system for the CMS experimental cavern was designed and installed during the period of the LHC installation between 2000 and 2005. It has been in operation for nearly 10 years, since the start-up of the LHC in 2008, and the SCADA system is obsolete, and the PLCs are close to the end of their operational lifetime. Furthermore there has been no major improvement made since the LHC began operation considering that the application is critical, and cannot be stopped for long. During the upgrade any potential performance or maintenance issues will be addressed as well, based on experiment and HVAC plant operator input.

CERN Industrial Control Standard

The CERN industrial control standard for continuous processes, the UNICOS CPC framework [1], has been discussed in detail in previous publications. This standard provides many advantages for the development, operation and maintenance of the control applications. Therefore, given the aforementioned need to upgrade the ventilation system, the CERN UNICOS CPC standard will be used to migrate during the next possible upgrade window: the Long Shutdown 2 of the LHC, scheduled to begin in 2019. Since the CMS ventilation system is critical, it is preferable to be able to do a virtual commissioning of the system, with a first principles model, prior to the deployment in-situ.

PROCESS MODELLING

In order to apply a model-based approach for the virtual commissioning of an existing plant, the process must be analysed, from a global level down to each individual component. During this phase two complementary data sources were used: CV group internal documentation and the Electronic Documents Management System (EDMS), which is a global CERN documentation storage location. The CV data provided "As-Built" HVAC sub-contractor project

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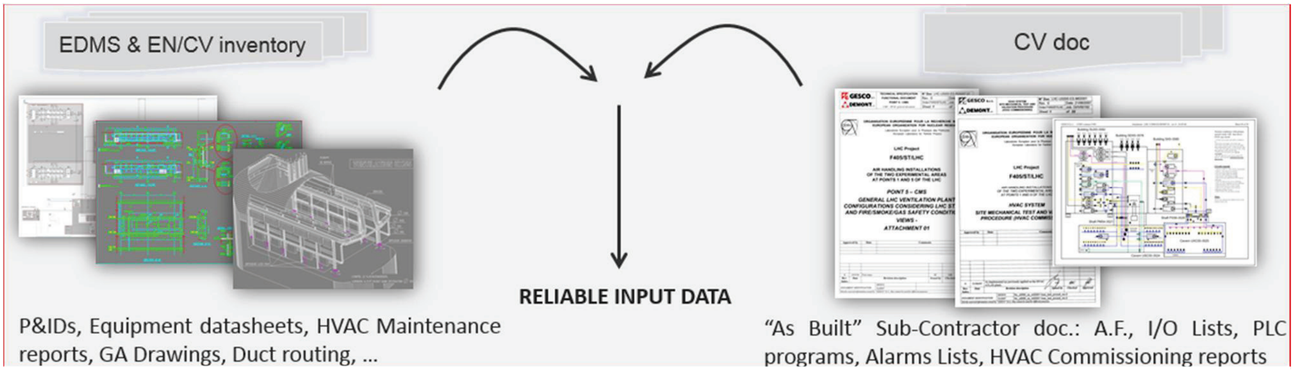

Figure 1: Process and Equipment Analysis.

data (e.g. Functional Analyses, Input/Output lists and PLC programs), and EDMS contained not only HVAC-related information such as P&IDs, equipment/devices datasheets and maintenance reports, but also miscellaneous characteristics (e.g. civil work, electrical wiring diagrams, etc.) required to build and set the model parameters. Considering the quantity of information and the fact that all the data could not be digitized at that time, this data mining phase ended with a consistency checking task, during which efforts have been made to deduce missing information from retrieved data (Fig. 1).

Modelling Software

Since 2008 CERN has been developing industrial control dynamic simulation models [2] with EcosimPro [3] software. EcosimPro is an object-oriented, differential and algebraic equation solver, based on a non-causal modelling language, with a user-friendly interface to build complex system models. It includes an efficient solver for large-scale systems, and can be coupled to the real PLC in order to check control software before deployment. Given the benefit of a dynamic simulation approach for the design and the maintenance of cryogenic control systems, initially the water cooling plants were modelled. In view of the success of this work [4] the approach was extended to other domains such as HVAC.

HVAC Library Development

A first HVAC library version for EcosimPro was developed at CERN during 2014 that included major HVAC plant components. One of the interesting development guidelines at that time was to consider the process fluid (i.e. the air) as a gas mixture whose concentration rates are likely to change. Indeed, as far as HVAC processes are concerned it is common practice to consider a standard atmosphere gas composition, which results in simplified equations, constant characteristics (e.g. air molar weight) and standard psychrometric diagrams: this can be justified because a small variation of one gas concentration value does not have a significant effect on HVAC systems. However, since CERN HVAC plants are used for the ventilation of rooms which house processes that handle gases (Nitrogen and Helium for cryogenics, Carbon Dioxide, etc.), some existing and future regulation loops may include the management of such gas concentration (ventilation regulation to maintain CO2 concentration below a defined level, discrete events in case of gas detection, etc.). For this reason, each HVAC library air source component allows the user to define a customizable gas concentration vector, and all the corresponding humid air properties are dynamically calculated inside all the elements according to the gas concentration vector that passes through them.

With this version of the HVAC library, it was possible to build simple models of HVAC plants with a minimum of required inputs. However, due to the limited amount of available settings the accuracy of the model behaviour might not be sufficient to reflect the behaviour of a real component. Therefore it was necessary, prior to starting the CMS HVAC plant modelling phase, to continue the HVAC library development. Various formulas were improved and validated to increase the modelling accuracy, and additional components have been developed (such as enthalpy wheels, ductings, pressure relief dampers, caverns, 3-way valves, a few examples of which are shown in Fig. 2). Also all the existing elements have been improved to increase their accuracy. For instance, although the updated damper model requires more information (shape, blades type, characteristics of the ducting on which the damper is installed), various simulation cases (in comparison with measurements from real plants) demonstrate a good ratio between accuracy and quantity of input data.

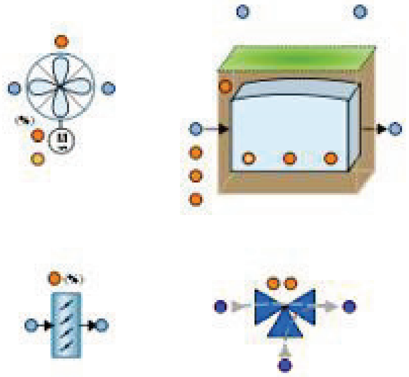

Figure 2: Example components from the HVAC Component Library in EcosimPro.

As an example of HVAC component development, Fig. 3 summarizes the modelling process that has been applied for ventilation fans. First, an ideal fan is defined by the curve of its wheel (provided by the manufacturer), which establishes the relationship between the wheel rotation speed, the differential pressure across the fan and its airflow.

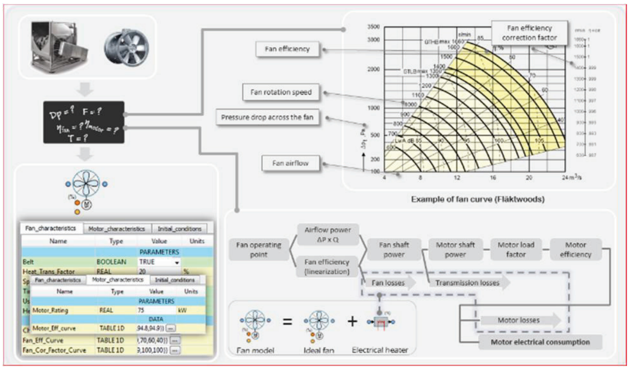

Figure 3: Development of Fan Model.

Considering that a significant amount of CERN energy consumption is attributable to HVAC systems, CV control engineers are more and more concerned by this issue. The modelling and simulation approach is a good candidate to test optimized energy-consumption control scenarios over long periods (from a month to a year) therefore the fan model has been built in order to dynamically compute the fan motor electrical power (thus the consumption within a period through the integration of this value) depending on the fan rotation speed, its differential pressure, the transmission type (direct or with a belt), the motor rating, the fan wheel and motor efficiency curves.

Moreover, considering the fact that the heat produced by the motor itself is partially absorbed by the air passing through the fan, the EcosimPro object-oriented language enables to associate the ideal fan with an electrical heater component (whose role is to add sensible heat to an air stream): using connection equations between the heater input signal and the ideal fan losses variables, the exact amount of heat transferred to the air stream (which depends on considerations such as the motor position in the air stream and the air flow type around it) can be easily set based on two fan operating points associating the fan airflow to the difference of temperature across it.

HVAC Library Validation

Once the EcosimPro HVAC library was developed, a multi-level validation step was necessary before considering the CMS experiment cavern HVAC plant modelling.

Static stand-alone tests

Firstly, each component has been tested stand-alone with reference steady states: given a set of defined and non-ambiguous input parameters (component settings, inlet(s) air properties, input signals values), the aim was to check the consistency and the accuracy of all the humid air characteristics calculated (directly or not) inside the component. Psychrometric diagrams and properties tables (NIST: National Institute of Standards and Technology, ASHRAE: American Society of Heating, Refrigerating and Air-conditioning Engineers) have been used as references. For example the specific enthalpy calculation (done in the humid air Port) has been checked and absolute and relative differences tables have been generated within the acceptable variation range of humid air properties considered for this development (e.g. [-20°C: 50°C] for the dry bulb temperature).

Dynamic (transient) stand-alone tests

Secondly, components have been tested dynamically: by varying all the possible component air inlet(s) properties, this step allows to observe the component behaviour considering smooth and fast transient variations. This phase also permits to detect and solve typical modelling issues such as simulation time problems and non-physical states (division by 0 when no air flow, setting boundaries for infinite values, using differential expression for convergence, etc.). Besides, the component robustness is verified when faced with multiple and potentially non-physical simultaneous parameter variations. Figure 4 shows how the robustness of the HVAC port equations related with the air mixture properties has been checked considering the simultaneous variation of several gases concentration rates of the considered atmosphere.

Components assembly tests

Together with stand-alone tests, an important aspect of the component modelling consists in verifying that all the equation formulations inside each component are compatible with the ones of the other components. These checks typically led to modifications in order to solve algebraic loops, simulation slowness and convergence issues.

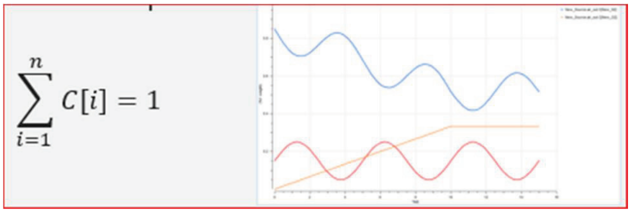

Figure 4: Test of the gas mass concentration law for a source component.

SIMPLE HVAC PLANT MODELLING

For all the UNICOS-based control systems at CERN the history of each single accessible value (from a transmitter measurement to actuator position and feedback signals) can easily be extracted from a year-period database.

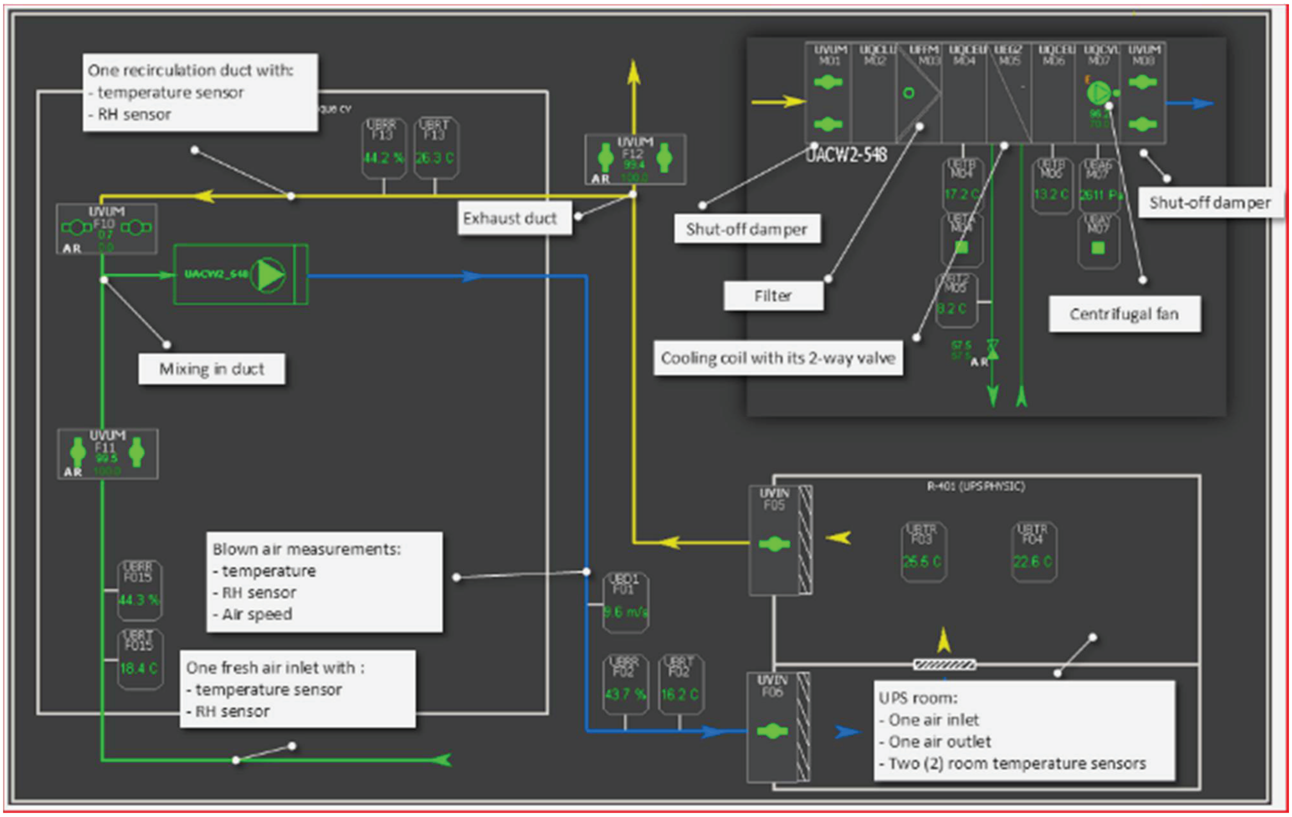

Figure 5: A simple 1 AHU ventilation system in CERN computing centre.

Through simple HVAC plants modelling (process and associated control), the goal was to confirm the pertinence of the approach used during the HVAC library development by comparing the behaviour of a plant model with all the real data gathered during a defined period. Three different CERN plants with a representative range of HVAC equipment have been chosen for these tests: one room ventilation system in the CERN computer centre, one ventilation system in a building for SPS power converters and one ventilation system in a building used for the LHC cryogenics.

As an example, Fig. 5 shows the supervision top-view of the first plant which has been considered. The associated top-level view model of the HVAC process in EcosimPro is detailed in Fig. 6, which shows the macroscopic view of the ducting, the Air Handling Unit (AHU), and the room to be supplied. The AHU process view is shown in Fig. 7 which shows the level of modelling detail, down to the individual actuators and the installed sensors. In addition to the process modelling, a plant control model (based on the CERN EcosimPro UNICOS control library) has been connected to the process model within EcosimPro. Based on retrieved equipment datasheets and real operating points, all the model components parameters have been set. Although model boundaries such as the outdoor temperature and humidity were accessible, the evolution over the time of the heat loads (sensible and latent) inside the room had to be estimated by trial and error.

The case-by-case (i.e. component per component) studies of several period simulations enabled to compare not only the behaviour of each component model in comparison with the corresponding HVAC equipment measurements (e.g. modulating damper position and control signal over the time), but also the global behaviour of the model composed by the process and its control: thus, the graph in Fig. 8 shows, over a 5 day period of time, the simulated fresh air damper position compared with measurements. Without considering the global assumptions (heat loads, etc.), we were able to find consistent damper parameters that reproduced the real damper behaviour. In addition, and more unexpectedly, this simple HVAC plants modelling phase has also enabled us to identify some regulation issues on the real plants, such as a 3-way valve malfunction and some transmitters' calibration problems.

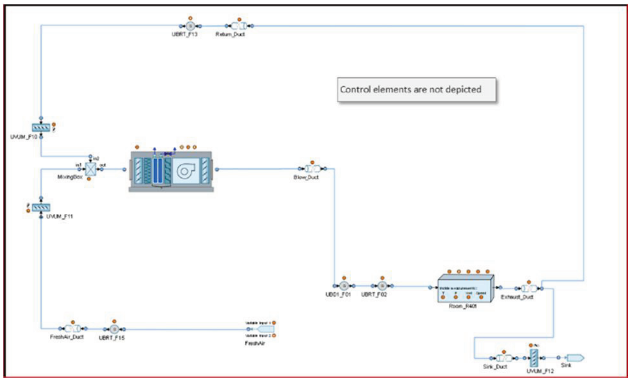

Figure 6: The single AHU ventilation system shown in Fig. 5, modelled in EcosimPro.

ISBN: 978-3-95450-193-9 doi:10.18429/JACoW-ICALEPCS2017-MODPL02

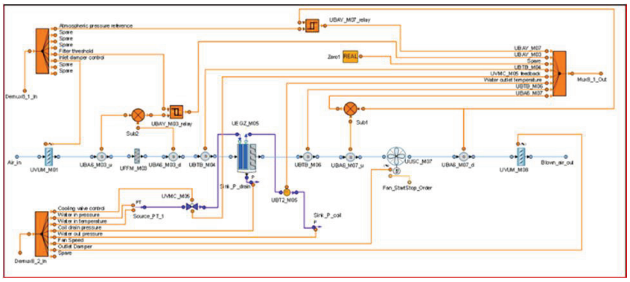

Figure 7: The component level model of the AHU in EcosimPro.

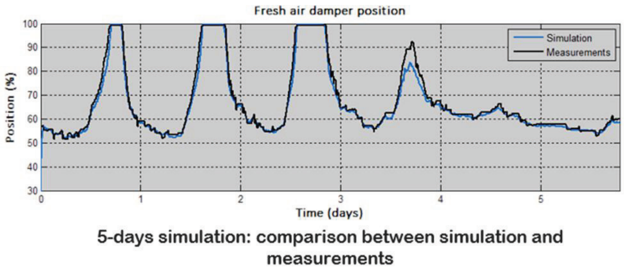

Figure 8: Comparison of simulated and measured fresh air damper position.

DEVELOPMENT OF CMS HVAC PLANT MODEL

Now with this validated HVAC library it is possible to build physical models of the CMS HVAC plant. Note, the model building is more difficult because there is no recorded data to tune the models, therefore there is a strong dependency on the documentation work outlined at the beginning of this paper (see Fig. 1).

Plant Short Description

The CMS HVAC Plant is composed of several sub-systems dedicated to specific areas of the CMS buildings complex, as shown in Fig. 10. The CMS HVAC Plant architecture is made of 5 separate functions distributed over 11 PLCs, with a complex arrangement of power and control cubicles, as well as emergency equipment for firemen.

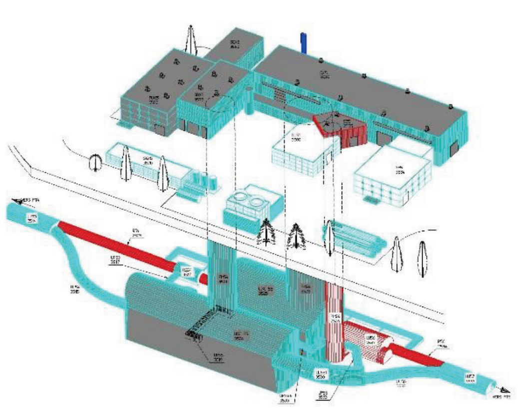

Figure 10: CMS plant overview of buildings surface and underground.

All the CMS HVAC plant buildings have the same obsolescence issues, but those which can be updated without impacting the operation of the LHC (most of the surface buildings) will not be modelled. Although both CMS caverns (the experiment and the service ones) could be subject to detailed modelling and simulation studies, the scope of the modelling is limited to the CMS experiment cavern (UXC55) HVAC plant, see Fig. 9, due to its criticality, its complexity and the potential of improvements (from an operating and performance point of view). For example the HVAC operators are expecting some specific control improvements (automatization of starting/stopping procedures, etc.), and the CMS experiment members have specific requirements regarding the cavern pressure stability.

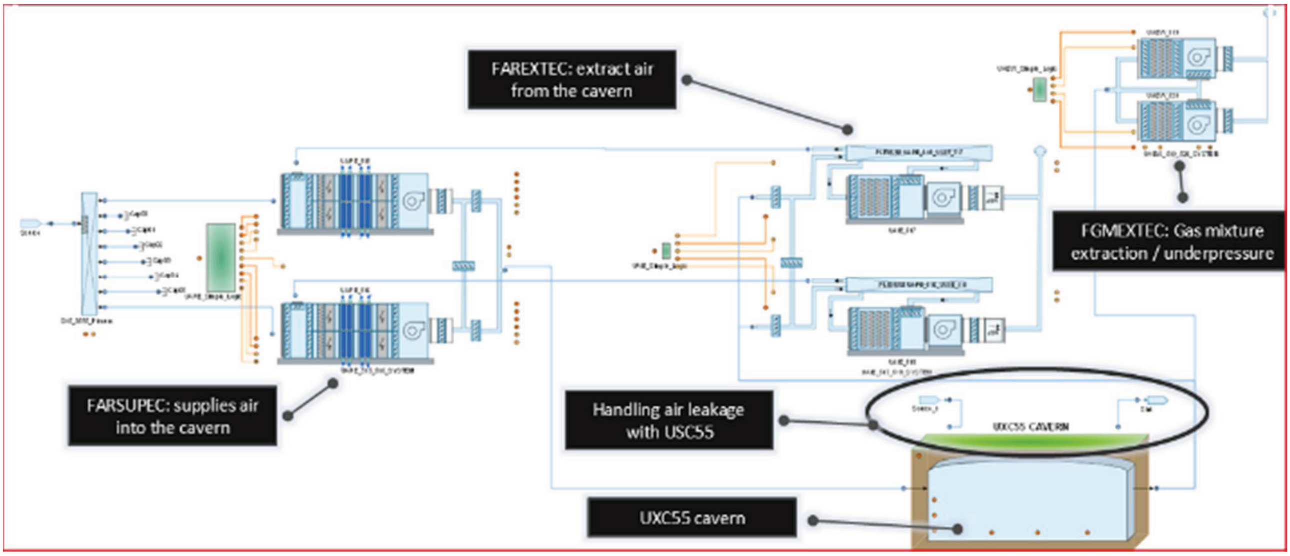

Figure 9: EcosimPro model of the CMS UXC55 Experimental Cavern.

Plant and Control Modelling

The physical model shown in Fig. 9 contains 3 pairs of AHUs (supply, exhaust and gas extraction), one cavern and access shaft volume component and two sets of 3 dampers. The damper set model is shown in detail in Fig. 11 and is quite different from the real system. This modelling is in fact a solution to a typical modelling issue related with backflow inside a component. Indeed, during normal operation of the HVAC system, the shut-off damper is susceptible to airflow from both inlet and outlet: it is not a unidirectional air flow component. However, considering the use of differential equations inside the damper component model, the plenum and the ducting ones, they are not able to face significant back flow during more than short transient states. That is why the equivalent-behaviour model has been set and has been checked from a control and an aeraulic aspect.

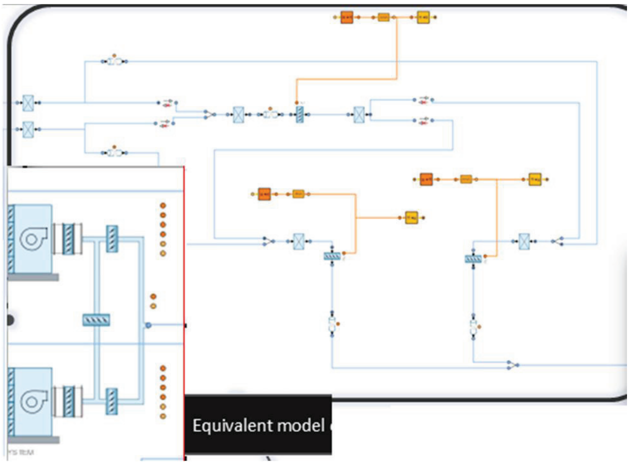

Figure 11: Model of set of 3 dampers.

Model Settings and Testing

As previously mentioned, one of the main roles of the UXC55 HVAC system is to maintain a stable pressure inside the cavern: firstly, for safety reasons a negative differential pressure with surrounding volumes (service cavern and tunnels) shall always be maintained to ensure any radiation risk is contained, whatever the HVAC System running state (normal operating, but also during start/stop/changeover sequences). Furthermore, fast air pressure variation can be potentially harmful for the CMS detector and shall thus be avoided. That is why particular attention has been paid to this aspect during the modelling and parameter tuning. Also the thermal and humidity loads can only be estimated roughly. The control logic is included in the model, in such a way that it is possible to simulate the plants with or without a PLC connected.

Some initial simulation results are shown in Figs. 12 and 13, demonstrating the successful convergence of the large dynamic model, under transients. The wall cavern temperature is set to 18 °C because at 100 m below ground it is reasonable to consider the ground temperature at this value, and the steady state cavern temperature depends on the assumptions made about the cavern wall properties, the cavern equipment thermal inertia and heat transfer surface, etc.

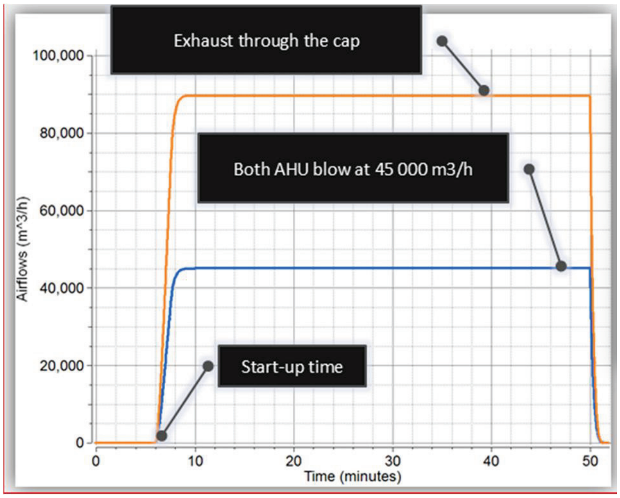

Figure 12: EcosimPro simulation results for the UXC55 simulation of a start-up in gas detection mode, with the cap open.

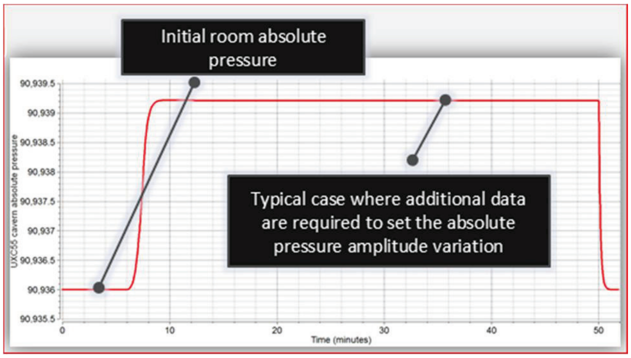

Figure 13: EcosimPro simulation results of the cavern absolute pressure.

VIRTUAL COMMISSIONING

Now that the model of the CMS HVAC plant has been developed it is possible to integrate control algorithms. These are based on an initial functional analysis developed in anticipation of the requirements, not yet available from the process engineers. The logic was based on grafcets (finite state machines) which were implemented within the EcosimPro code, in a time-continuous form, such that different transients could be executed, to further evaluate and test the model. For example, various operating scenarios were performed over a period of several hours, including different discrete events: a step-by-step start-up, gas detection, cap opening/closing, equipment failure and acknowledgement. These demonstrate the possibility to adapt the control automatically while keeping the regulation loops active.

Integration with PLC Controls

In addition to validating the preliminary control algorithms in pure simulation, the model was also integrated with 3 PLCs in the lab with the architecture shown in Fig. 14, using the PROCOS tools [2], and a WinCC OA SCADA was connected, see Fig. 15, such that manual manoeuvring of the control system was possible. Thus, once the final control system development has been completed, later this year, it will be possible to validate it with the connected model, in order to virtually commission the system.

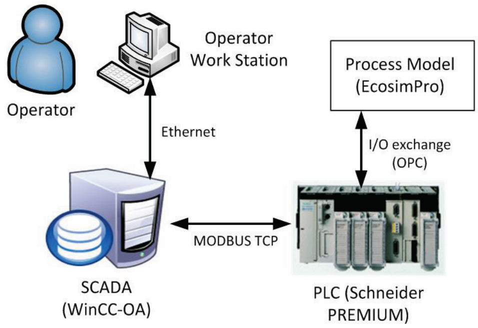

Figure 14: Dynamic simulation architecture.

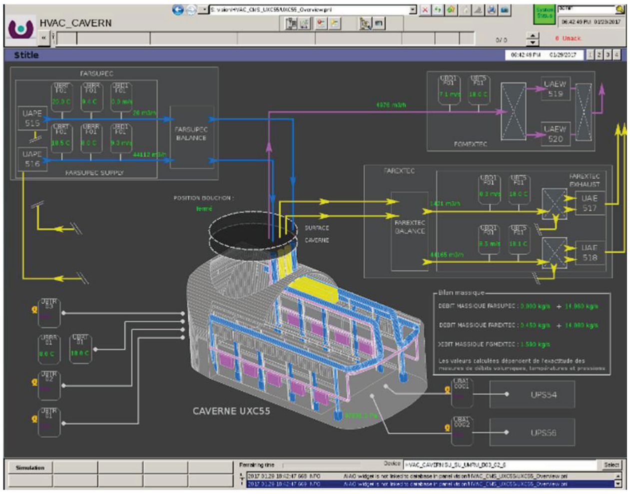

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Figure 15: Preliminary WinCC OA Supervision of HVAC CMS Cavern simulation.

CONCLUSIONS

The successful development of the CMS HVAC simulation model was the result of nearly 2 years project work, including improving and validating the HVAC library, simulating simple HVAC plants, and ultimately building the UXC55 model from first principles. The choice of this model instead of a black-box version based on pure data was clear as it provided an invaluable insight into the ventilation processes. Using EcosimPro and the HVAC library also eased the development and integration as the effort was focused on the process knowledge. The simulation model has been tested successfully under various transients including step-by-step start-ups, equipment failures, gas detection, and opening and closing of the cap, with no convergence issues. In addition the model has been connected to 3 PLCs in the lab, and manual transients can be performed. In the near future, this plant model will be used to commission the soon-to-be-upgraded control system, and to validate possible improvements, from addressing thermal gradients in the cavern, to implementing automatic step-by-step starting and stopping sequences.

ACKNOWLEDGEMENTS

We would like to thank the CERN Cooling and Ventilation (EN-CV) group and especially the operation and control teams for working closely with us over the last few years to develop the model of the CMS HVAC cavern plant.

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