The use of Digital Twins in the design of the Waste Heat Recovery project for Ferney Voltaire

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Introduction to the project

Waste Heat Recovery at CERN

Modeling and Simulation: the ‘Digital Twin’

Communication with the UNICOS Control System

Project Results

Generalization and upcoming applications
Introduction to the project
Motivation

• In order to reduce its environmental impact, CERN would like to deploy Waste Heat Recovery systems at LHC surface points
• However, the cooling plants are critical for LHC operation
• It was deemed important to investigate the impact of WHR plants on the cooling plants and their control systems
• EN-CV and BE-ICS launched a project to investigate this using a simulation of the cooling plant
Waste Heat Recovery at CERN
Why is WHR important?

- CERN’s electricity consumption is around 1.2TWh a year during runs
- Much of this energy is dissipated as heat in CERN’s cooling plants
- Makes sense to try to recuperate

<table>
<thead>
<tr>
<th>Waste heat source</th>
<th>Power dissipated (GWh), 2017</th>
</tr>
</thead>
<tbody>
<tr>
<td>LHC and Experiments</td>
<td>512</td>
</tr>
<tr>
<td>SPS</td>
<td>115</td>
</tr>
<tr>
<td>North Area</td>
<td>112</td>
</tr>
<tr>
<td>PS and other equipment</td>
<td>86.9</td>
</tr>
</tbody>
</table>

Evolution of the electrical consumption at CERN (TWh)
Pilot project: LHC Point 8

- First WHR plant will be constructed at Point 8, supplying heat to Ferney Voltaire.
- Together with geothermal facilities, the recovered heat will supply around 8000 houses.
Pilot project: LHC Point 8

- The recovery plant will require 2km of piping from Point 8
- Maximum heat recovery capacity is 10MW
- Testing in 2021, operational in 2022
Operational Challenges for CERN

- Cooling plants critical for LHC operation
- WHR plant will be operated by 3rd party
- Disruptions in WHR plant will affect CERN’s cooling plant
- Would like to be sure that an unexpected stop in WHR plant does not lead to a problem with CERN’s cooling
- If an issue is identified, it should be addressed in LS2
How to analyze these issues?

- Need to specify some failure scenarios
- Need a representation of the process
- Need to be able to interface the existing control system to this representation to check its behaviour
Modeling and Simulation: the ‘Digital Twin’
Dynamic Process Model as a ‘Digital Twin’

• The term ‘Digital Twin’ is currently popular in industry, but it can have many interpretations
• Here we take it to mean a virtual representation of aspects of a process’ behaviour
• As we are interested in the transient response of the cooling plant to a WHR plant failure, we will need a dynamic representation
A Closer Look at Cooling Plant SF8

- 5 main cooling towers, 2 backup
- Provides ‘primary’ cooling water to secondary circuits
The process: Cooling Towers

- Return water \((T_1 \sim 30^\circ C)\) enters through nozzles at top
- Fan driven by VFD can be used for additional airflow
- Cooled water \((T_2 \sim 22^\circ C)\) collected in basin
Mathematical Model

- Heat transfer occurs at water-air interface, and due to evaporation
- Want a dynamic model of the heat dissipation rate $Q$ of the tower
- Can model as a heat exchanger $Q = \frac{T_1 - T_{wb}}{R}$
- ($T_1$ is returning cooling water temperature, $T_{wb}$ ambient wet-bulb temperature, $R$ thermal resistance)
Mathematical Model: Steady State

- Thermal resistance consists of air and water components $R = R_w + R_a$
- Related to mass flows as $\frac{1}{R_w} = b_1 \dot{m}_w$ and $\frac{1}{R_a} = b_2 \dot{m}_a$
- Steady state heat dissipation is then:

$$Q = \frac{b_1 \dot{m}_w \cdot b_2 \dot{m}_a}{b_1 \dot{m}_w + b_2 \dot{m}_a} (T_1 - T_{wb}) = \frac{c_4 \dot{m}_w}{1 + c_3 \frac{\dot{m}_w}{\dot{m}_a}} (T_1 - T_{wb})$$

(1)
Mathematical Model: Dynamic

• We would like to have a dynamic model, that regards the inlet and outlet temperatures as time varying
• With a bit more math and a few assumptions, we can get:

\[
\frac{dT_2}{dt} = c_1 \phi(t)
\]

where

\[
\phi(t) = -\frac{c_4}{c_{pw}} \dot{m}_w(t) \left[ T_1(t) - T_{wb}(t) \right] - \dot{m}_w(t) \left[ T_2(t) - T_1(t) \right]
\]

\[
1 + c_3 \left[ \frac{\dot{m}_w(t)}{\dot{m}_a(t)} \right]
\]
Implementation, Parameter Estimation and Validation

We have some equations, now we need to:

- Identify the model parameters from historic or experimental data
- Implement the model in a simulation tool
- Validate the model against historic data of the real plant
Implementation: EcosimPro

- Multidomain modeling language and simulation tool
- Supports Differential Algebraic Equation (DAE) solution

- Used at CERN for Cryogenics and HVAC simulation
Cooling Tower Model Implementation

- Single tower component created
- Cooling plant modeled by instantiating 5 towers
- Individual parametrization
SF8 Plant Model

- CERN cooling clients and WHR plant modeled as simple heat sources/sinks
Parameter Identification

• Model parameters need to be obtained from process data
• Can use historical data (LHC logging)
• May also need to make experiments on the plant

• For our model, identification was done in two steps:
• Steady state identification (3 parameters)
• Dynamic identification (1 parameter)
## Parameter Identification: data used

<table>
<thead>
<tr>
<th>Measured variable</th>
<th>Symbol</th>
<th>Range (unit)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Status</td>
<td>STATUS</td>
<td>0-6</td>
</tr>
<tr>
<td>Speed signal</td>
<td>SPEED</td>
<td>0-100 (%)</td>
</tr>
<tr>
<td>Basin temperature</td>
<td>$T_2$</td>
<td>15-25 ($^\circ$C)</td>
</tr>
<tr>
<td>Flow to user 1</td>
<td>$F_1$</td>
<td>0-300 ($m^3$/h)</td>
</tr>
<tr>
<td>Flow to user 2</td>
<td>$F_2$</td>
<td>0-300 ($m^3$/h)</td>
</tr>
<tr>
<td>Flow to user 3</td>
<td>$F_3$</td>
<td>0-300 ($m^3$/h)</td>
</tr>
<tr>
<td>Return temperature</td>
<td>$T_1$</td>
<td>24.0-32.0 ($^\circ$C)</td>
</tr>
<tr>
<td>Dry-bulb temperature</td>
<td>$T_{db}$</td>
<td>0-35 ($^\circ$C)</td>
</tr>
<tr>
<td>Relative humidity</td>
<td>RH</td>
<td>0-100 (%)</td>
</tr>
<tr>
<td>Pressure</td>
<td>$P$</td>
<td>950-1050 (mbar)</td>
</tr>
</tbody>
</table>
Parameter Identification: Steady State

• LHC logging data for several years extracted using TIMBER
• Need to identify periods of steady-state operation to use for parameter identification
• R script created to heuristically detect steady state periods
• Steady state periods are divided into two sets, one for identification, one for validation
Parameter Identification: Steady State

• Recall the steady state equation

\[ Q = \frac{c_4 \dot{m}_w}{1 + c_3 \frac{\dot{m}_w}{\dot{m}_a}} (T_1 - T_{wb}) \]

• Three parameters to find: \( c_3, c_4 \) and \( l \)

• We use nonlinear optimization (Levenberg-Marquardt) to find estimates of these from the data sets
Parameter Identification: Dynamic

- We have one parameter left to find, $c_1$ in
  $$\frac{dT_2}{dt} = c_1 \phi(t)$$
- $\phi(t)$ contains the three parameters we’ve already found, and some measured signals, so we can use it as a regressor
- Can then apply least squares regression
- However, we need decent dynamic data
Step Response Tests

• Unfortunately, the TIMBER data proved difficult to use for dynamic identification
• Luckily, we were allowed to perform some step response tests on the cooling plant
• We performed step tests of the fan speed
Step Response Tests

(a) ETR-880

(b) ETR-881
Model Validation

• With all parameters identified, we enter them in the EcosimPro model

• Validation datasets fed to model
Model Validation

Fan speed signal

Cooling tower status

Primary cooling water temperatures

November 29, 2019
Communication with the UNICOS Control System
SF8 Control System
SF8 Controls: Lab Setup

- SF8 controls is a UNICOS CPC application running on a Schneider Premium PLC

- We can put a copy of the production system on a lab PLC

- If we can replace the PLC IO with values from the simulation model, we can make closed loop simulations

- How to do this?
OPC-UA

- Open protocol for industrial controls
- Integral data model
- Widely supported by PLC vendors and simulation software providers

- TCP based
- Supports multiple platforms
OPC-UA: Servers

- Schneider offers OPC Factory Server (OFS)
- Runs on engineering station

- EcosimPro allows compilation of models into an executable with an embedded OPC-UA server
- User just needs to define what the inputs and outputs of the simulation are
OPC-UA: Clients

• For this project we use the Free OPC-UA Python package to create a client

• The client will perform the data exchange between the PLC and the simulation model

• It will also be in charge of running the simulation (controlled by OPC-UA methods)
The Details...

- In the PLC program, we just need to disable the IO addressing, to allow the OPC server to overwrite inputs
- Otherwise, the program is unchanged
- Our simulation has to run in real time or faster
- The client runs the simulation for a fixed time and then exchanges signals
- No problem for slow processes (5 second period used here)
Project Results
Simulation Scenarios

• The EN-CV team defined a set of operating conditions, for which sudden failure of the WHR plant should be studied.

• The key operational conditions are the ambient wet bulb temperature, the heat load from the CERN processes, and the power recovered by the WHR plant.
## Simulation Scenarios

| $T_{wb}$ (°C) | Client | | WHR |
| | $Q$ (MW) | $\Delta T$ (°C) | $Q$ (MW) | $\Delta T$ (°C) |
| 10 | 10 | 4.8 | 10 | 3.2 |
| 12 | 20 | 6.4 | 6.3 | 2.0 |
| 21 | 20 | 6.4 | 1.6 | 0.5 |
| 21 | 10 | 3.2 | 1.6 | 0.5 |
Performance Requirements

Cryogenics is the most ‘sensitive’ client of the cooling plant
Loss of flow is the primary concern, but a sudden large temperature rise is also problematic
A temperature rise of less than $2^\circ C$ within 10 minutes was deemed to be acceptable
Closed Loop Simulation Results

- \( T_{wb} = 12^\circ C \)
- Heat load 20MW
- WHR recovered power 6.3MW
- WHR stops at 00:40
- Basin temperature only rises 1\(^\circ C\), returns to setpoint after 30 minutes
Project Conclusions

- All simulated scenarios indicated that the existing cooling plant and control system will be capable of dealing with a sudden stop of WHR plant operation.
- Project indicated that no change of the cooling plant or its controls would be necessary to accommodate the WHR plant.
- However, the project highlighted the potential usefulness of a feedforward control action, since the water temperature exiting the WHR plant is measured.
Generalization and upcoming applications
Other uses of the Digital Twin

- Once a validated process model is available, there are a wide range of possible applications.
- We can make further simulation studies of different operational aspects (energy usage of the plant, etc).
- We can even make use of the model for doing the control (Model Predictive Control).
Model Predictive Control

- With a process model, we can ‘predict the future’ given a current state, and try to find the best control input.
Model Predictive Control

- Need to set up an optimization problem, then solve it each time a new control signal is to be calculated
- Has been applied to the 1.8K cooling loop
Cryogenics Process Simulator

- Process simulator used to train operators and test control strategies
- Based on OPC DA

- BE-ICS working with TE-CRG to migrate to OPC-UA
- Key difference to SF8 project: time-dependent code moved from PLC to EcosimPro
- Can run faster than real time
CORA CO2 Cooling Process Simulator

- CORA (CO2 Research Apparatus) developed by EP-DT
- Process is modeled in EcosimPro
- Want to interface the complete control system with model
Generic UNICOS-Simulation Interface

• Currently working on a way to connect any UNICOS application to a simulation supporting OPC UA simply by modifying spec file
• Client will be automatically configured
UNICOS Application testing using OPC-UA

• We also leverage OPC-UA communication to create automated test suites for PLC applications
• Python client extended with a UNICOS object abstraction layer
• Standard Python testing packages can then be used (pytest)
Credits

- Matias Olavi Peljo (Aalto University, tech student at BE-ICS)
- Paul Pepinster (EN-CV)
- Will Booth (BE-ICS)