The Innovation Hub

for Affordable Heating and Cooling

Technology Evaluation Report

Healthcare Living Laboratories: Fernhill Residential Aged Care – Synengco HVAC Plant Digital Twin

V2 - 19 November, 2021

Queensland University of Technology (QUT)

About i-Hub

The Innovation Hub for Affordable Heating and Cooling (i-Hub) is an initiative led by the Australian Institute of Refrigeration, Air Conditioning and Heating (AIRAH) in conjunction with CSIRO, Queensland University of Technology (QUT), the University of Melbourne and the University of Wollongong and supported by Australian Renewable Energy Agency (ARENA) to facilitate the heating, ventilation, air conditioning and refrigeration (HVAC&R) industry's transition to a low emissions future, stimulate jobs growth, and showcase HVAC&R innovation in buildings.

The objective of i-Hub is to support the broader HVAC&R industry with knowledge dissemination, skills-development and capacity-building. By facilitating a collaborative approach to innovation, i-Hub brings together leading universities, researchers, consultants, building owners and equipment manufacturers to create a connected research and development community in Australia.

This Project received funding from ARENA as part of ARENA's Advancing Renewables Program.
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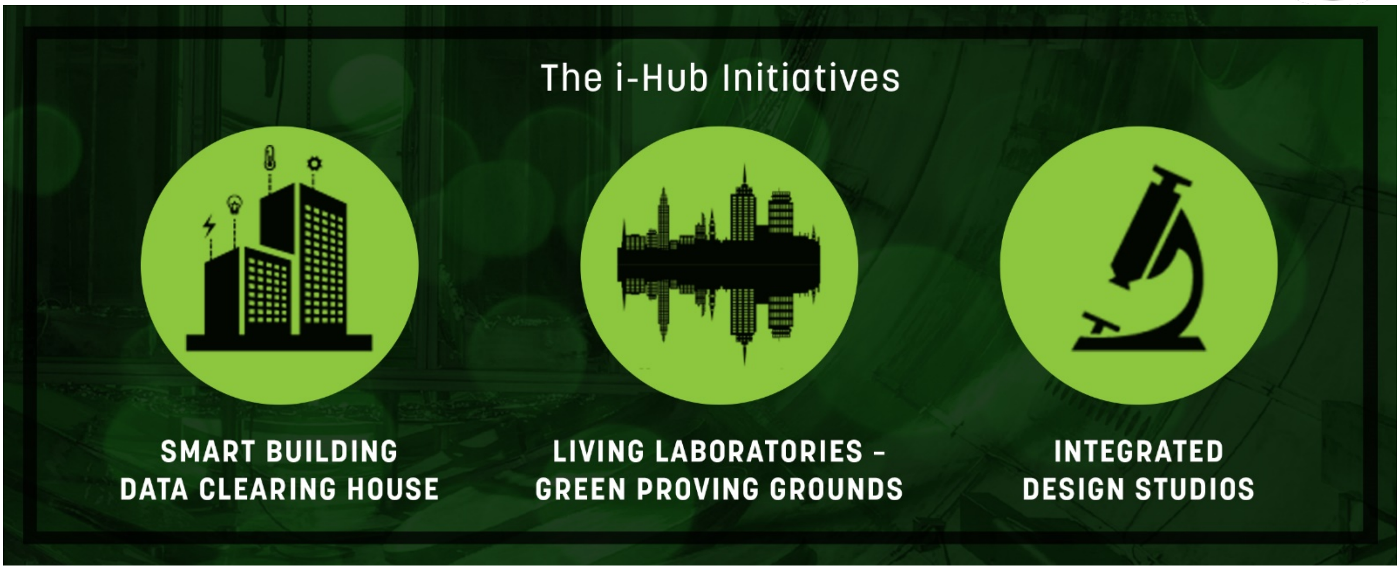

Healthcare Living Laboratories: Fernhill RAC – HVAC Plant Digital Twin

The Living Laboratory in Bolton Clarke's Fernhill RAC in Caboolture will support the healthcare sector to transition to a net-zero energy/demand future. In particular, it will validate the impact of emerging technologies in demand reduction, demand management, renewable energy and enabling technologies, in terms of core health services (residents and worker health and comfort), building maintenance and operations, environmental impact and financial management (including participation in energy markets).

Heating, ventilation and air conditioning system (HVAC) is often the largest energy user and peak demand contributor for commercial buildings and electricity networks. A main component of the HVAC system at Fernhill is a chiller system of 3 chillers. Fernhill's HVAC plant and building information was modelled with SentientSystem to build a precise digital twin of Fernhill's HVAC plant. This digital twin allowed monitoring the chiller performance compared to its design, predicting the plant performance via machine learning, and identifying control improvement opportunities that can reduce energy consumption.

Lead organisation

Queensland University of Technology (QUT)

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VERSION HISTORY

ID & Version #	Prepared By	Revision Date	Approved By	Approval Date	Reason
1.0	*Sherif Zedan*	*<14/05/2021>*			TER Stage 1: Synengco's digital twin monitoring and comparing of chillers' performance
2.0 **2.2**	Sherif Zedan	19/11/2021			TER Stage 2: Synengco's digital twin, predictive fault detection, and early warning system
3.0					
4.0					

EXECUTIVE SUMMARY

I. Technology overview

Synengco's digital twin platform, SentientSystem is a technology that can automate and continuously improve asset-intensive operations based on theoretical, empirical, and operational data. The digital twin can find areas of improvements, predict faults, assist decision makers in operating the HVAC plant, allow for continuous commissioning of the building, improve comfort, and optimise energy use and cost.

II. Objectives

A digital twin for the HVAC plant at Fernhill was created and an early system warning (EWS) was configured and deployed for two objectives:

1- Compare design to actual performance of the plant
2- Monitor and predict how the plant will perform under certain circumstances and produce alerts at an early stage.

III. Methodology

The digital twin technology was applied to Bolton Clarke's Fernhill Residential Aged Care HVAC Plant. The plant consists of one air cooled chiller (Chiller 1), and two air cooled reverse cycle chillers (Chillers 2 and 3; Heater 1 and 2). The HVAC plant operation and performance is monitored through the BMS, with automated alerts produced at pre-set conditions.

SentientSystem was applied to the plant using four steps: Model, Monitor, Predict, & Optimise.

- Model: The digital twin of the HVAC plant was created using real operational and design data that was generated from the building's BMS. Machine learning algorithms were then utilised to accurately represent the original system's behaviour.
- Monitor: Analysis techniques were used for real time plant and process monitoring of abnormal operation and/or performance.
- Predict: Using machine learning, SentientSystem predicts how the plant should perform under different circumstances, raising alerts when potential issues or opportunities emerge, while accounting for normal variations in operation. The Early Warning System (EWS) is activated when the actual operation does not match the predicted one.
- Optimise (for future work if approved by LL host): The digital twin can replicate the effect of changing operation's behaviour to find improvement opportunities. SentientSystem modules can evaluate equipment performance to support decision making based on monitored performance and learned behaviour.

IV. Findings of Objective one: Model and Monitor

BMS is very useful technology that can aid in accurately building the digital twin. However, two main issues that made building the digital twin more accurately are 1) Data availability issues, and 2) Security issues.

The missing BMS data issues can make it more difficult to understand the reasons behind low performance, and can hinder the prediction accuracy. Examples of the data issues are:

- BMS sometimes does not report COP and kWe data, due to quick cycling of the chillers which does not allow for the water to chill properly, resulting in higher water out temperature than water in, which results in invalid COP and negative kWr. The same issue happens in heating.
- The highest resolution for data reporting in the BMS is 5-minute intervals, which is often too long to determine what happened in certain events.

Some discrepancies in reporting time between meters and plant sensors, and time mismatch between kWe and kWr result in unrealistically high COP. Aligning time steps of all sensors is required to reflect accurate performance and optimise operation accordingly.

The security issue is related to the high risk of giving control access to external parties, which can result in making the data extraction and full utilisation of the digital twin capabilities more difficult and lengthier. For best outcomes, Digital twin should be integrated with the BMS from an early stage, to set the required data outputs, time intervals, alert systems, etc. than can facilitate building the digital twin. The Digital twin outputs (e.g. EWS, and optimisation) should also be integrated with the BMS system for continuing automated decision making that can improve the performance of the plant.

Comparing Actual against design performance findings:

Performance charts were created for each chiller and heater comparing the design against actual for all relevant data points. Performance findings include:

- Chiller 1 was the least utilised, only being turned on twice in 5 months
- Chiller 1 was mostly lower than design, except at high loads where the chiller performed better than design.
- Chiller 2 had the highest utilisation
- Chillers 2 and 3 consistently underperform when compared with design COP.
- Heater 1 is frequently operated at lower loads than what it is designed for, hence making it inefficient
- Heater 2 use slightly less energy (~5%) than designed. The remaining chillers and heaters all consumed over 25% more than design.
- Overall, the systems used 13.6 MWhs more than they are designed to which is equivalent to 10,940 kg CO2-

Reasons for deviation from design

It is common for HVAC plants' performance to be different from its design. COP can be affected by kWr, ambient temperature, and mass flow. However, manufacturers test performance under ideal conditions, with a constant ideal mass flow and outlet temperature set point. The humidity and microclimate conditions of the actual plant can also increase the deviation from design. Possible reasons for the performance deviation of the plant at Fernhill are

- Ambient temperature is a variable that is usually not considered accurately in design performance tables. The COP for the heater drops when the weather gets colder at a constant kWr since kWe becomes higher (more load is required to heat).
- Higher mass flow of water through the heater to reach a certain kWr will also result in lower COP. Design performance tables do not factor in the fluctuation in mass flow as it is assumed that the recommended design mass flow is being used, which can lead to differences between designed and actual performance.
- Another factor that can cause deviation is incorrect meter reading or mismatch in measurements time steps.

Potential reasons for underperforming could be :

- Chillers are oversized (run 25-75% of the capacity most of the time), which reduce their COP that is normally at its highest when chillers run at full capacity.
- Mass flow rate is often higher than its design, which participate in dropping the COP down. Currently all temperature setpoints are constant across Fernhill which increase the mass flows.
- Unshaded cooling fan on the roof can reduce performance since the air going through the cooling fan might be higher than the ambient temp measured by shaded sensors.
- Continuous on/off cycling of the chillers and heaters leads to inefficiencies and wasted energy, since turning the air conditioner for a short period will consume energy but will not provide enough heating or cooling.

V. Findings of objective two: Monitor and Predict

EWS (Early Warning Systems) was established for Fernhill's the HVAC plant and components. EWS can produce alerts for any abnormal behaviour prior to the occurrence of events based on predictions of the plant behaviour under certain conditions. This is different from the BMS alert system that raise the alerts after the occurrence of events only once threshold setpoints are reached, if at all. The predictions and EWSs were established for the following:

- Chiller energy consumption for each chiller
- Chiller COP for each chiller
- Chiller kWr for each chiller
- Chiller plant/building cooling load (total cooling produced by HVAC plant for the building)
- Bypass valve positions for each valve.

Examples of generated alerts are:

- Actual cooling load to the building is much lower than predicted. The reason was that the actual load lagged and did not follow the trend of the ambient temperature; therefore, it reflected less load than predicted.
- High increase in the cooling load that suddenly drops down. This event happened due turning on chiller 1 to meet the peak demand after it had already occurred. The external temperature was cooling down rapidly, but the HVAC was still trying to cool the building as per the high temperature.
- Hot water being pumped to the building while the heater is off, causing hot water to lose heat, and failure to turn heaters on to meet demand.

Recommendations to enhance performance are:

- Comparing actual to design performance shows that all systems are experiencing lower COP than expected, except for Heater 2 that can often perform better than expected. It would be much better for example to run one chiller at 100% than two at 50%. So it is recommended to increase a chiller or heater to 100% capacity before turning another one on

- Mass flow fluctuation through the chillers and heaters is high. It would be more efficient to try to keep the mass flow constant at its designed flow rate and only adjust temperature setpoints if required to keep the flow rate constant.
- Shading the cooling fan and ensuring that there are no obstructions to ventilation around it, will reduce the discrepancies between the actual air temperature going through the fan and the measured ambient temperature, which will enhance performance.
- On hot days pre cooling can reduce cooling loads that occur when chiller starts to operate at a high temprature, and continues to consume energy even when external temprature is lower.

VI. Discussion and conclusion

Evaluation of the digital twin highlight its potential in alerting on performance issues and events within the HVAC system of the building. Comparing the actual to design performance of the plant shows that there is a potential of 25% improvement in performance.

The modelling, monitoring, and predicting of the HVAC performance can allow for the investigation of control strategies and to develop and test continuous commissioning routines that can help optimise the performance of the HVAC system.

The digital twin is considered a low cost easy to implement technology, providing that all sensors and equipment are implemented to the plant, and required data is available and accessible.

The existing BMS at Fernhill made it easier to implement the digital twin, since no additional sensors or equipment were required, and all activities were able to be performed remotely.

The cooperating BMS provider committed timely effort in setting up remote access and data collection for the project team. However, due to security restrictions, Synengco were only granted limited access, with weekly reports developed and sent on a weekly basis through the BMS provider. The generated data reports were customised based on the digital twin requirements and were not part of the original BMS data outputs. This highlights that an early integration of the digital twin with the BMS can maximise the potential of both technologies and reduce the amount of time and effort required to implement digital twins.

The integration of the digital twin with the BMS can also provide better alert systems that incorporate the EWS with the maintenance and control alert system that is already provided in the BMS. The EWS can alert maintenance officers about anomalies and unexpected behaviour in the HVAC system so that they can prevent inefficient performance in a timely manner. The digital twin defined algorithms can control the HVAC plant and optimise for efficiency performance in real time ensuring the highest COP possible is being achieved.

iHub Initiative: Living Labs
Fernhill Residential Aged Care

Synengco Stage 2 – Progress Report

Created for: Queensland University of Technology

Written by: Dr Talara Berry, Ed Cabrero and Romane Bernard

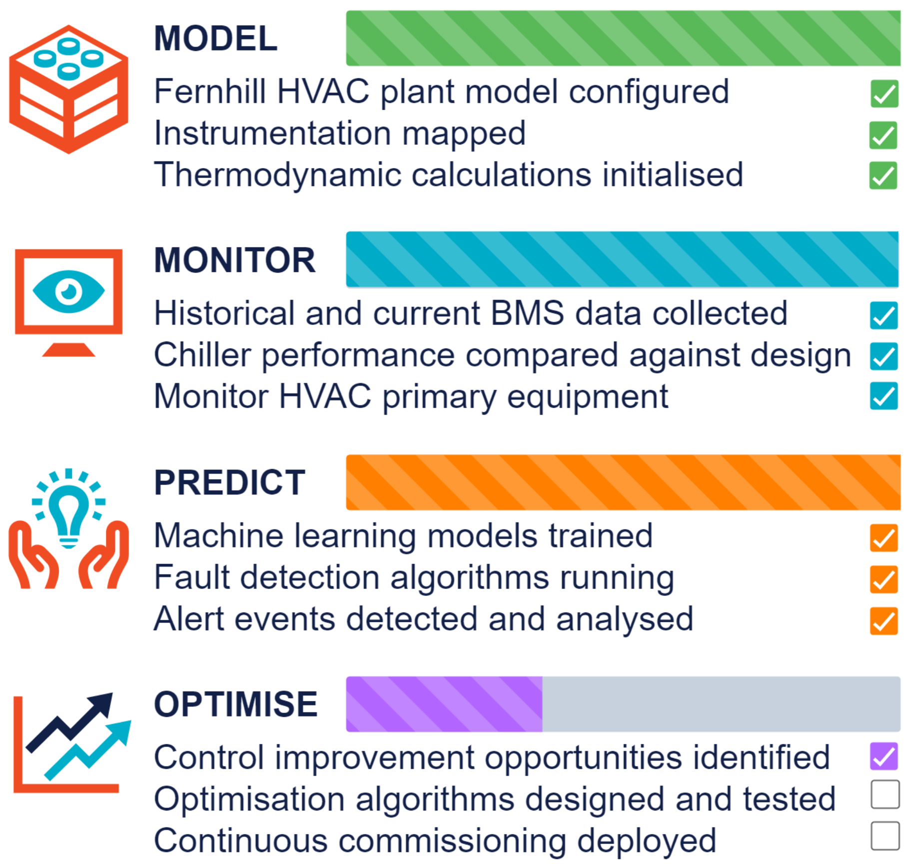
Date: 15/10/2021

Executive Summary

In Stage 1 Synengco had successfully configured a digital twin of Bolton Clarke's Fernhill Residential Aged Care Living Lab, and performance monitoring was established. Within the Stage 2 period the digital twin has continued to monitor historical and current performance compared against designed performance of the three air conditioners in the HVAC plant. The SentientSystem predict step has also been completed and was used to configure an early warning system (EWS), with alerts being evaluated in this report. From these monitoring and prediction steps control improvement opportunities have been identified and reported.

At the completion of Stage 2 Synengco's software platform, SentientSystem, has been configured for the building's HVAC plant completing the first three steps of the Model, Monitor, Predict, & Optimiser methodology.

Fernhill Living Lab Digital Twin Status Summary



Contents

1- INTRODUCTION

Synengco is an Australian-based technology provider that looks for opportunities to automate and continuously improve asset-intensive operations. They are participating in the iHub Living Lab Initiative by working with QUT on the Bolton Clarke Fernhill Residential Aged Care Living Lab.

Synengco's responsibility for the project is to apply the commercial software product, SentientSystem, for both supporting QUT's analysis of the building energy performance and testing how well SentientSystem's optimisation models and algorithms perform on a large residential building.

Commercial buildings are high energy consumers, and their operations are often complex and distributed, with HVAC plants accounting for 84% of the sectors CO2 emissions [1]. Deficiencies in operations and asset management decision-making due to these complexities can have significant environmental and economic impacts.

***HVAC plants in commercial building account for 84% of the sector's annual CO2 emissions** [1].*

At the same time, there is increased data and knowledge upon which to make better decisions and an increasing number of new innovations that can have a significant impact on an operation.

The availability of data, knowledge and state-of-the-art technology, machine learning can be used to help building owners and facility managers make faster and better decisions. A significant change management process is required to transition towards machine supported decisions. Synengco has many years of experience and proven successes in this area.

Applying this technology within commercial building market is a particular interest to Synengco given their passion for making sustained reductions in society's carbon footprint. This report outlines the software used for the project, describes the asset that it is applied to, summarises the work progress to date, and makes recommendations for the next project stages.

2- TECHNOLOGY OVERVIEW

The technology being assessed in this report is Synengco's digital twin platform, SentientSystem. Fernhill's HVAC plant and building information will be modelled with SentientSystem to build a precise digital twin of Fernhill's HVAC plant. In addition to this SentientSystem's early warning system (EWS) will also be configured and deployed for Fernhill.

SENTIENTSYSTEM

SentientSystem® (by Synengco) is a sophisticated software platform built to support decision-makers who aim to improve the performance of their assets.

Based on theoretical, empirical, and operational data, it provides a digital twin of complex asset systems, thus enabling optimisation of a customer's assets over their whole life cycle.

Capabilities

- Actionable insights into assets behaviour
- Costs reduction and mitigation
- Risks management
- Emissions monitoring
- Energy Efficiency

Features

Digital Twin Modelling	✓ Replicate your assets portfolio in a virtual environment ✓ Freely explore parameters for operations over various timeframes ✓ Compare your assets behaviour across your portfolio
Real-time Recommendations	✓ Real-time assets performance ✓ Monitor your consumptions and emissions ✓ Continuously updated industry knowledge bank
Early Warning & Fault Detection	✓ Get alerted to potential faults before they occur ✓ Prevent costly downtime through predictive maintenance
Self-learning System	✓ What-if analysis ✓ Improve predictions through machine learning ✓ Optimise your assets on their whole life cycle

DIGITAL TWINS

A digital twin replicates a real-world operation in a virtual world. They typically use real-time data to stay aligned with what is happening in the actual operation.

Data can come from many sources including internal systems – BMS (Building Management System), SCADA (Supervisory Control and Data Access), DCS (Distributed Control Systems), CMMS (Computerised Maintenance Management System) and other management systems – and external systems such as weather data and electricity supply.

Digital twins encapsulate a model of an asset's behaviour which has the ability to contextualise all data and information associated with the asset's operations. To achieve this, digital twins leverage state-of-the-art machine learning and artificial intelligence techniques.

The technology lends itself to improvement of the energy efficiency of commercial buildings and reduce their environmental impact. In this context, they can be used for:

- predictive fault detection & diagnosis,
- asset management decision analysis,
- continuous commissioning of the building,
- improving comfort, and
- optimising energy use.

EARLY WARNING SYSTEM

Faulty operation of HVAC systems can waste vast amounts of energy and CO2 emissions, with faulty operation accounting for up to 20% of commercial HVAC operation cost [2].

The large amount of data being captured by a building BMS contains the information to diagnose faults, but it can be difficult and time consuming to analyse manually. Current upper and lower limit thresholds incorporated into a BMS can be triggered if there is a major fault, but it is difficult to set thresholds for good performance at every operating condition.

With BMS sensor data available in real-time, it is possible to apply machine learning and prediction techniques to delivery high accuracy results, producing an alert as soon as something starts behaving differently than expected. SentientSystem's early warning capability detects equipment faults based on short term statistical changes in process variables compared against their predicted behaviour. This enables personnel to act quickly to mitigate the harm of failures and helps speed up root-cause analysis when faults do occur.

Case Study: Early Warning of an Equipment Fault

An example of SentientSystem's early warning capability is shown in Figure 1. An alert on an air inlet fan was detected and notified after a change in behaviour.

Unfortunately, in this case, the lack of action led to the alerted problem causing an equipment failure a month later, resulting in significant loss of generation. When acted upon, these alerts can significantly reduce costly failures and loss of production.

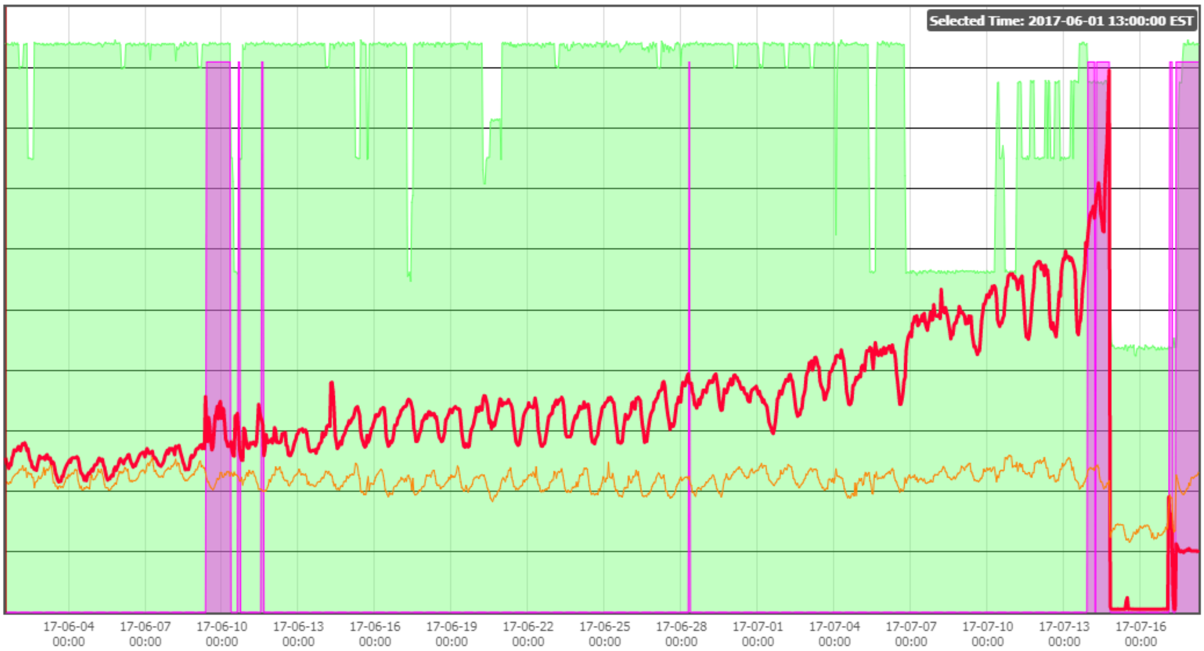
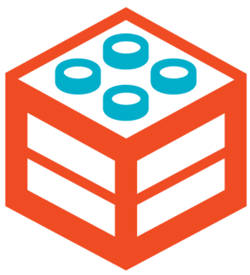


Figure 1 – Alert of change in behaviour more than a month before equipment failure.

3- METHODOLOGY

Synengco configures and applies SentientSystem using the four steps: Model, Monitor, Predict, & Optimise.

MODEL



SentientSystem is initialised by creating a detailed digital twin of the asset systems. It uses real operational data from the assets and high precision first principle-based model to calculate non instrumented points. Then using embedded algorithms with the ability to self-learn and adapt it tunes the twin to accurately represent the original system's behaviour.

For SentientSystem, the model is the digital representation of the real operation. It is the interface between the real world, where value is generated and the digital world, where management takes place.

Two of the key interface points are:

- Measurement sensor points: measurement of real world assets and translated to a digital representation
- Control points: control actions from the digital representation to the real world (human actions and process control actions)

The model explicitly aligns the domains between the real world and the digital world. It does so through a common information model, common units of measure, and control actions.

MONITOR

SentientSystem connects to the asset system's devices and sensors to collect operational data. It uses a variety of analysis techniques to keep an eye on the performance of assets and derive extra information about the current operation.

This means that SentientSystem is capable of real time plant and process monitoring of abnormal operation and/or performance.

Having a performance monitoring system that provides detail at a component level as well as the impact at a system level provides a common means of evaluating scenarios in the digital world as well as the real world.

This allows optimisation to be carried out using a digital replica of an operation or the actual operation.

PREDICT

With some fundamental knowledge and historical data about operations, SentientSystem predicts how systems and assets should perform under different circumstances, raising alerts when potential issues or opportunities emerge while accounting for normal variations in operation. Synengco's prediction models stand out from the crowd with the ability to continuously self-learn, meaning it has the ability to recalibrate and adjust limits without needing to be retrained. Predictions can also extrapolate to beyond the learn behaviours in training so the model will continue producing predictions without interruption.

Predictions are used to encapsulate and reconcile available knowledge and experience. Predictions are continuously monitored against actual measures associated with the prediction to trigger corrective actions. For example:

- The actual operation has changed from the best available knowledge and experience suggesting a potential threat or opportunity within the real operation.
- The prediction does not accurately represent the way the actual operation behaves suggesting a potential threat or opportunity to improve the encapsulated knowledge and experience within the model.

OPTIMISE

The modelled system is optimised following a set of instructions that aims to efficiently operate assets, based on previous performance, external factors, modelled scenarios, and advanced analysis techniques.

Once there is an accurate digital replication of an operation's behaviour, it can be used to find opportunities to improve. This can be done at:

- An operations level: *What if I changed this operational set-point or mode?*
- An asset level: *What if I changed the behaviour of this asset through maintaining, repairing, refurbishing, replacing or renewing with new technology for the asset?*
- A system level: *What if I changed the configuration of my system?*

Synengco has been using SentientSystem to deliver the Model, Monitor, Predict, & Optimise methodology to critical infrastructure customers for over 14 years.

Digital twins of complex systems and the environment they operate within are configured in SentientSystem as self-learning fundamental models, made up of equipment components and process connections. These are used to monitor the asset's performance in real time. As well as this, dynamic baselines, tuned from historical operation and design data, are used to predict equipment performance. Using predictions and machine learning, alerts can be triggered when actual starts deviating from predicted in the Early Warning System (EWS).

Performance improvements are achieved by various SentientSystem modules that analyse monitored and predicted equipment performance to aid short-, medium- and long-term decisions.

The most established and proven application of SentientSystem has been in the power generation industry, for which it was originally developed. Its real-time monitoring and optimisation capabilities are used by power generation customers to achieve significant and sustained performance improvements across their asset portfolios.

Through iHub, these technologies will be applied for the first time to a commercial residential building, Fernhill Residential Aged Care. This by undertaking the following activities:

1. Model: A model of Fernhill's HVAC plant, chilled and hot water circuits, and building conditions will be created in SentientSystem.
2. Monitor: Data for all related points will be processed into the model so that performance can be modelled and analysed.
3. Predict: Data science techniques will be used to find the relationships between variables and apply machine learning models to learn the system behaviour so that long- and short-term changes can be quantified, and corrective actions triggered.
4. Optimise: Advanced control algorithms will be implemented based on the monitored performance and learned behaviour.

The modelling of the system was completed in Stage 1 as well as the first stages of monitoring covering the months from October 2020 to April 2021. In this Stage 2 report, the performance monitoring stage was completed for the May 2021 to September 2021 time period and SentientSystem's early warning system (EWS) was configured and built for Fernhill. Once the EWS was deployed in SentientSystem alerts triggered by the EWS from October 2020 to September 2021 and were reported and analysed in this report.

4. TESTED ITEM DESCRIPTION (THE HVAC PLANT)

Bolton Clarke's Fernhill Residential Aged Care building will be one of two Queensland based Living Labs where the testing of SentientSystem to enhance energy efficiency will be carried out.

Fernhill is a five-story building housing 162 rooms for residents. With a HVAC plant consisting of:

- 1 x Air cooled chiller with a 448 kW cooling capacity (Kappa Sky Xi 43.1) referred to as Chiller 1 in this report
- 2 x Air cooled reverse cycle chillers (Omicron Rev LN 22.4) with 227 kW cooling capacity (referred to as Chillers 2 and 3 in this report) and 230 kW heating capacity (referred to as Heaters 1 and 2 in this repport)
- 3 x Chilled water VSD pumps
- 2 x Hot water VSD pumps
- 2 x Chilled water bypass flow valves
- 1 x Hot water bypass flow values
- 3 x Air handling units (AHUs)
- 4 x General exhaust fan (GEF) units
- Fan coil units (FCUs) for every room and common area

Diagrams of the mechanical services were provided such as the primary water schematic in Figure 2.

The three chillers are arranged in parallel, each with a VSD pump, that provide chilled water to the three AHUs on the roof top and all of the FCUs throughout the building. Two chilled water bypass valves are installed so water can be redirected back to the chillers when not required by the building load to maintain the required minimum flow through the chiller.

Differential pressure is monitored across the supply and return lines to the building. The BMS will vary the speed of the VSD pumps to maintain this differential pressure at setpoint.

Similarly, the two reverse cycle chillers are arranged in parallel to supply hot water to the AHUs, though no hot water is supplied to FCUs. The same controls as the chilled water apply with a hot water bypass valve, differential pressure across the supply and return lines and VSD hot water pumps.

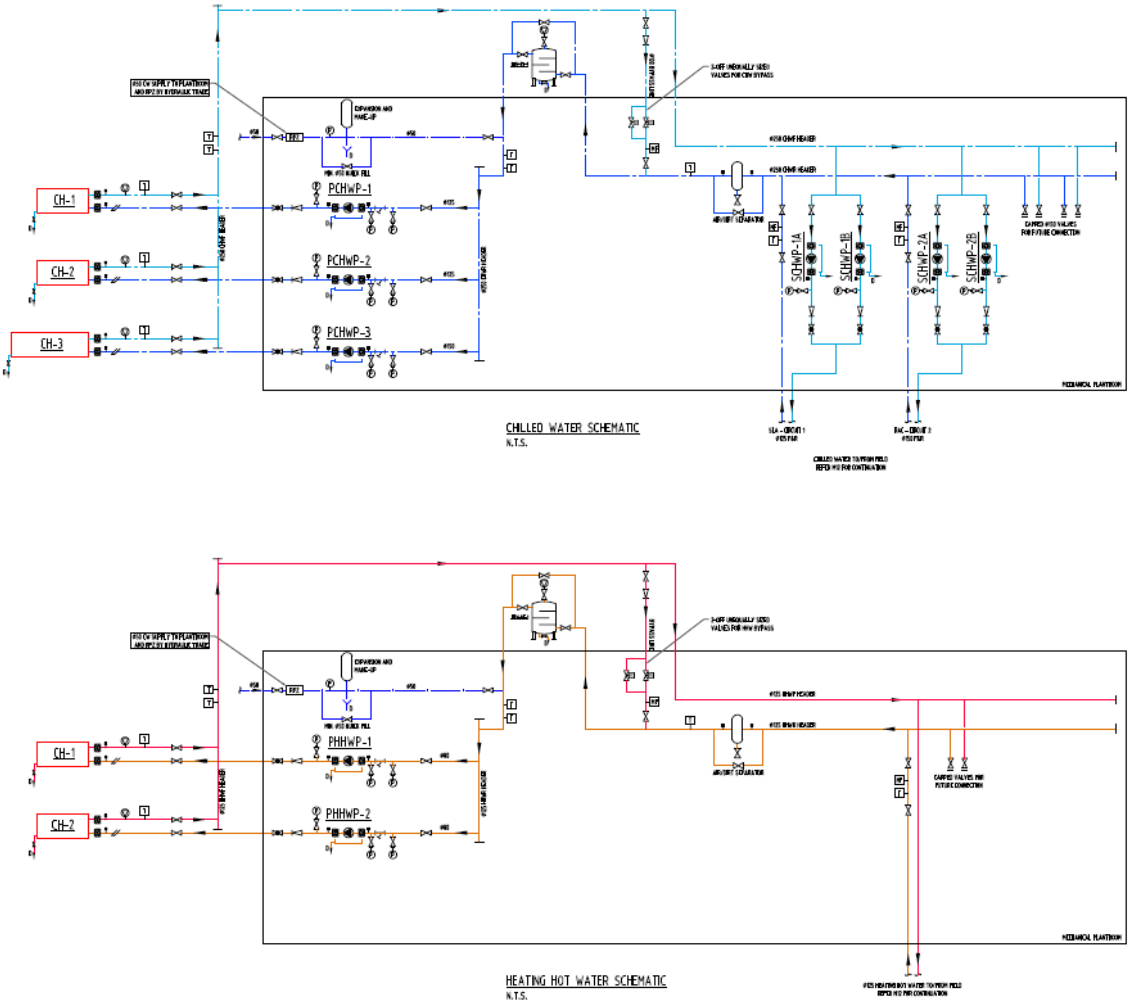


Figure 2 Mechanical services primary water schematic

Outside air at ambient conditions is sucked in through the three AHUs on the rooftop of the building. This air is cooled or heated through a heat exchanger with either the chilled or hot water, depending on whether cooling or heating of the building is required.

If the building is in cooling mode, the precooled air is then pushed with fans down to the building. Fan coil units are controlled independently in each room, if they are on, the precooled air from the AHUs will be passed over a heat exchanger with the chilled water again within the FCU and pumped into the room. Air from inside the rooms is also recycled through the FCUs, so that the cooled air pumped into the rooms is a mix of precooled air from the AHUs and return air from the room itself.

Exhaust fans in bathrooms, kitchens, and vents pump air up to the four GEFs on the roof top and out to the environment, maintaining pressure in the rooms.

Parameters and set points used for controlling the HVAC and any alarms were set during commissioning. These are all static setpoints that apply for all conditions.

Currently installed BMS alerts for the HVAC include:

FDD alarm	Alarm Condition
Chillers not maintaining leaving water set point	>3° above setpoint for 5 minutes
Chiller plant not maintaining minimum flow through vessels	-15% below low flow threshold for 10 seconds
Chiller plant not maintaining differential pressure across system	+-10 kPa above or below setpoint for 10 seconds
VSD speed control and speed indication mismatch	+- 15%

Table 1 An example of current alerts configured in Fernhill's BMS

5. TEST RESULTS

Following the methodology set out in the previous section, Stage 1 encompassed the first steps, Model and Monitor. Stage 2 continues monitoring, and completes the Predict step.

MONITOR

Key instrumentation has either been collected directly from the BMS or received in a weekly report of current instrument data.

The data received from the BMS then became the inputs into SentientSystem, the model could then run the thermodynamic solver and prediction models for each time collected, generating outputs. These inputs and output trends could then be displayed in SentientSystem's TrendView Web App.

Data Issues

After data collection the following issues were uncovered while completing the monitoring step.

Sometimes the chillers are cycled so quickly on and off that the water does not get to chill properly and sometimes the water out is a higher temp than water in resulting in a negative kWr and invalid COP. So, COPs and design kWe are missing for these times and are not included in design verses actual comparisons. This is also true for the heaters. With the highest resolution data being 5 minutes it is also hard to determine what is going on between these times and so some events are missed.

There were also several gaps of missing data over the last five months highlighted in Figure 3. These were due to BMS issues and so these times are not included in any analysis.

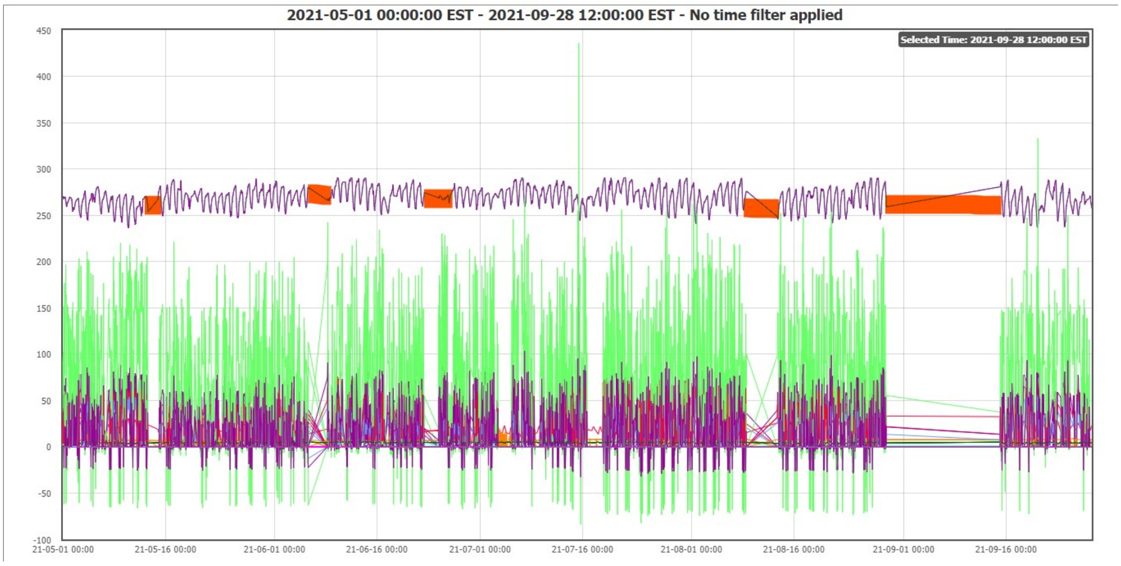


Figure 3 - Sentient TrendView showing gaps in data highlighted in orange

It is also worth mentioning there are inadequate measurements around the AHU and FCUs for a complete thermodynamic model to solve and so the main focus of this report is the HVAC plant.

Comparing actual against design performance

Design performance tables for the two types of air conditioners installed were provided by the Australian distributors Eurothermal. Data from these tables was configured into SentientSystem with some interpolations so that design COP for current conditions could be tracked in real time with actual COP if the chiller were being operated within design constraints.

Performance charts were created for each chiller and heater comparing the design against actual for all relevant data points. These performance issues will then be quantified and discussed.

Chiller 1 (CH-L05-01) results are shown in Figure 4 was the least utilised only being turned on twice in the last 5 months and so it has the least data points. The COP achieved for this chiller was mostly lower than design, except at high loads where the chiller actually performed better than design.

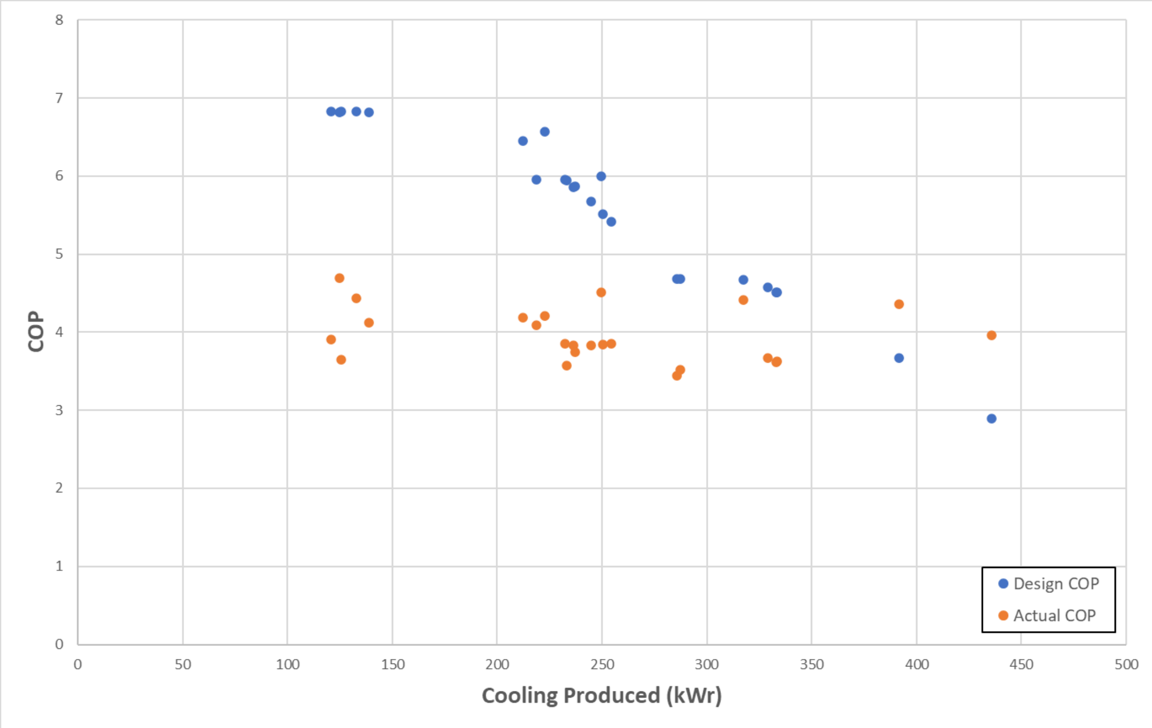


Figure 4 - Chiller 1 design vs actual performance

Chiller 2 (CH-L05-02) had the highest utilisation and as Figure 5 shows it consistently under performs showing much lower COP than expected from design.

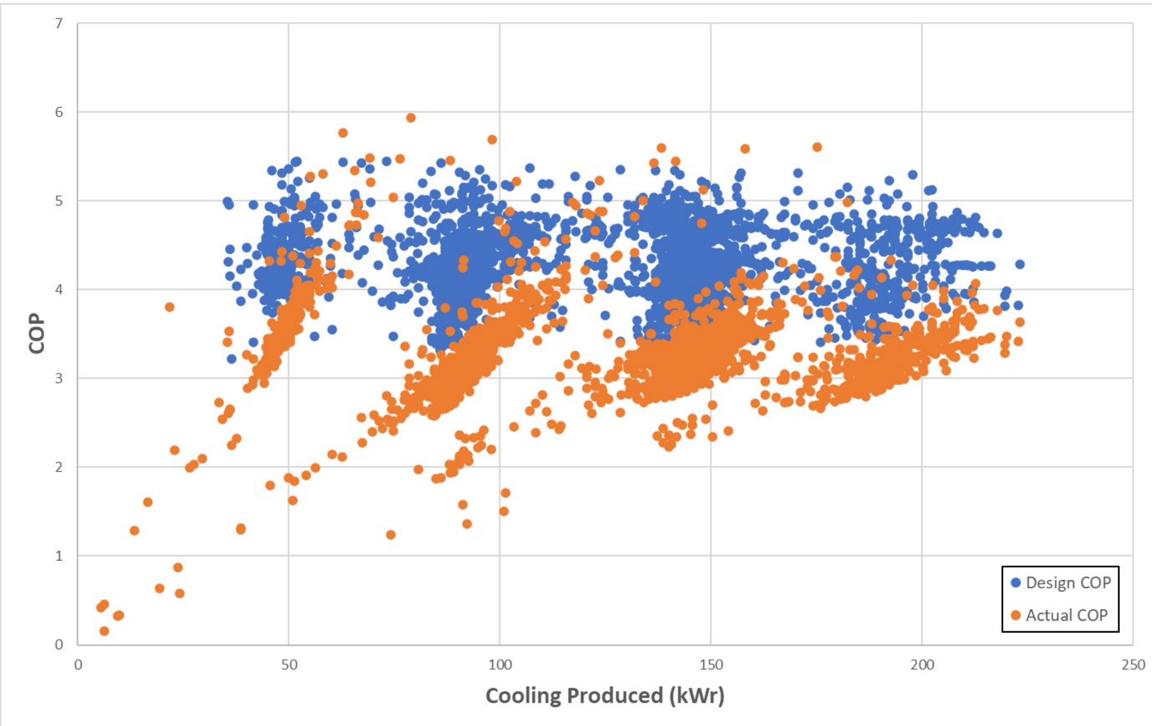


Figure 5 - Chiller 2 design vs actual performance

Chiller 3 (CH-L05-03) is very similar in its performance consistently having a lower COP than expected as shown in Figure 6.

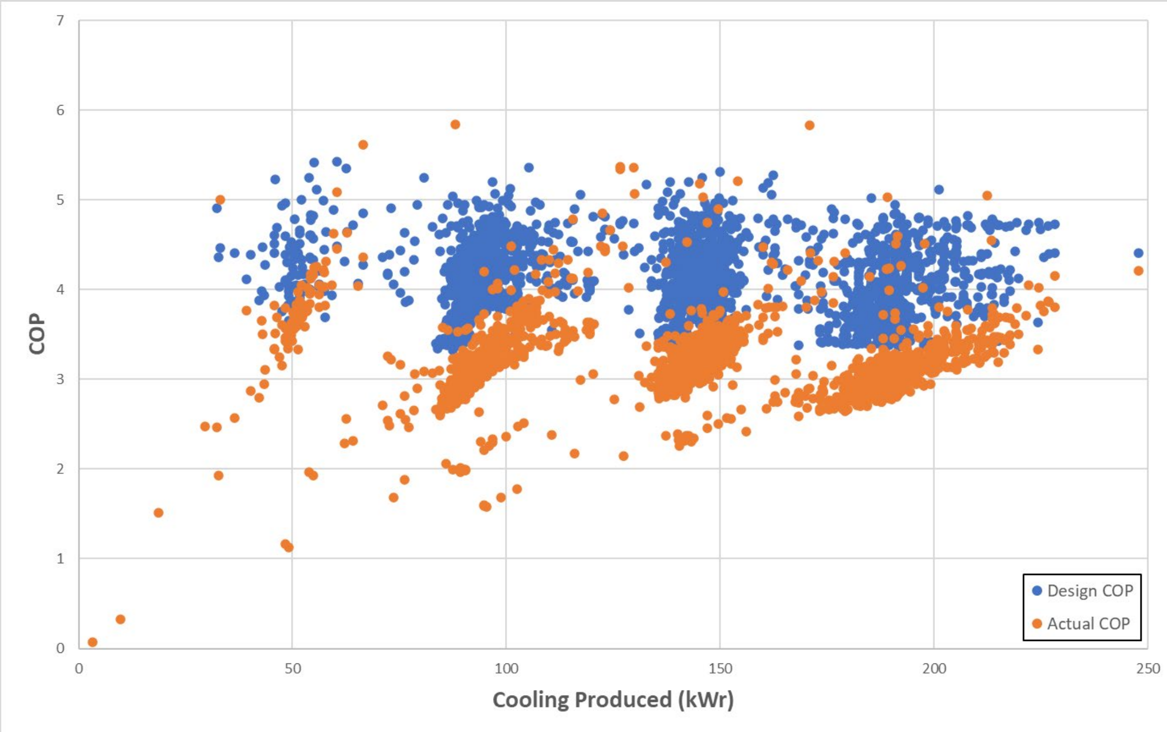


Figure 6 - Chiller 3 design vs actual performance

The performance comparison for Heater 1 (CH-L05-02) is shown in Figure 7, with this heater also under performing. Performance curves for the heaters are slightly different and the heater is frequently operated at lower loads than it is designed for making it inefficient. Instead of having one curve it also seems to have relationship groupings around each load where performance drops off as the load is lowered.

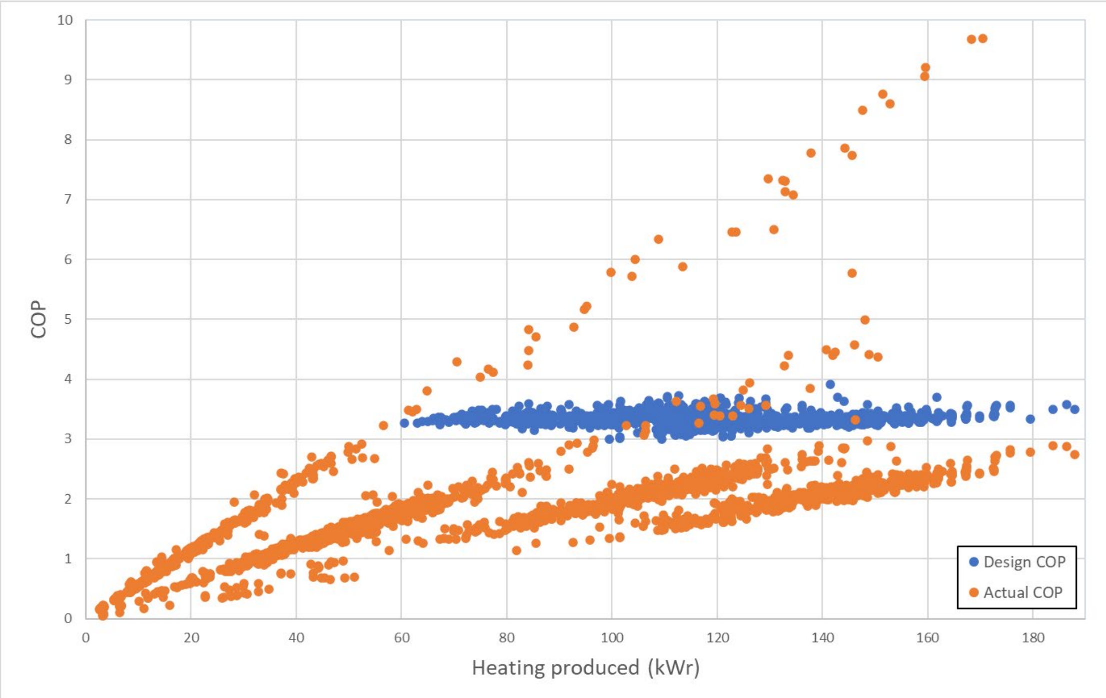


Figure 7 - Heater 1 design vs actual performance

Heater 2 (CH-L05-03) shows similar grouping patterns to Heater 1, but Heater 2 seems to be achieving much higher COP. With the first linear grouping having extremely high COPs that don't seem feasible.

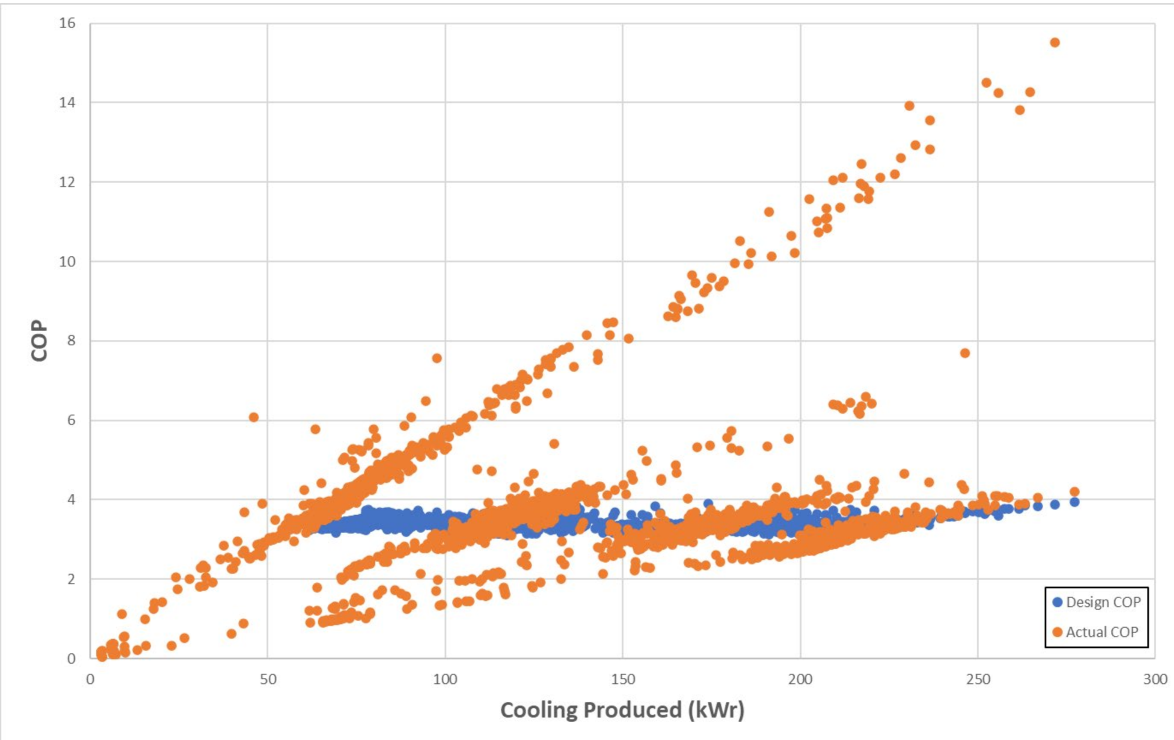


Figure 8 - Heater 2 design vs actual performance

To help explain this, Figure 9 shows how the COP relates to the electricity (kW) being drawn by the system for Heater 2. As shown the higher COPs are when the electrical kilowatts are very low. Checking back on Heater 1 in Figure 10 shows the same thing.

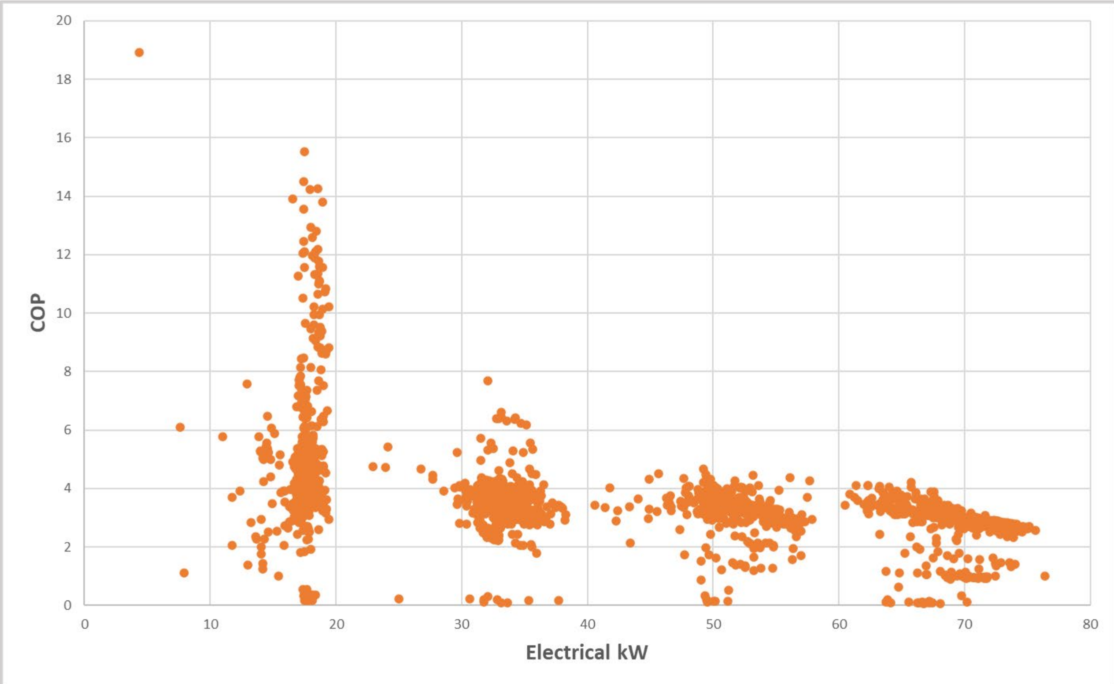


Figure 9 - Heater 2 COP vs kW of electricity

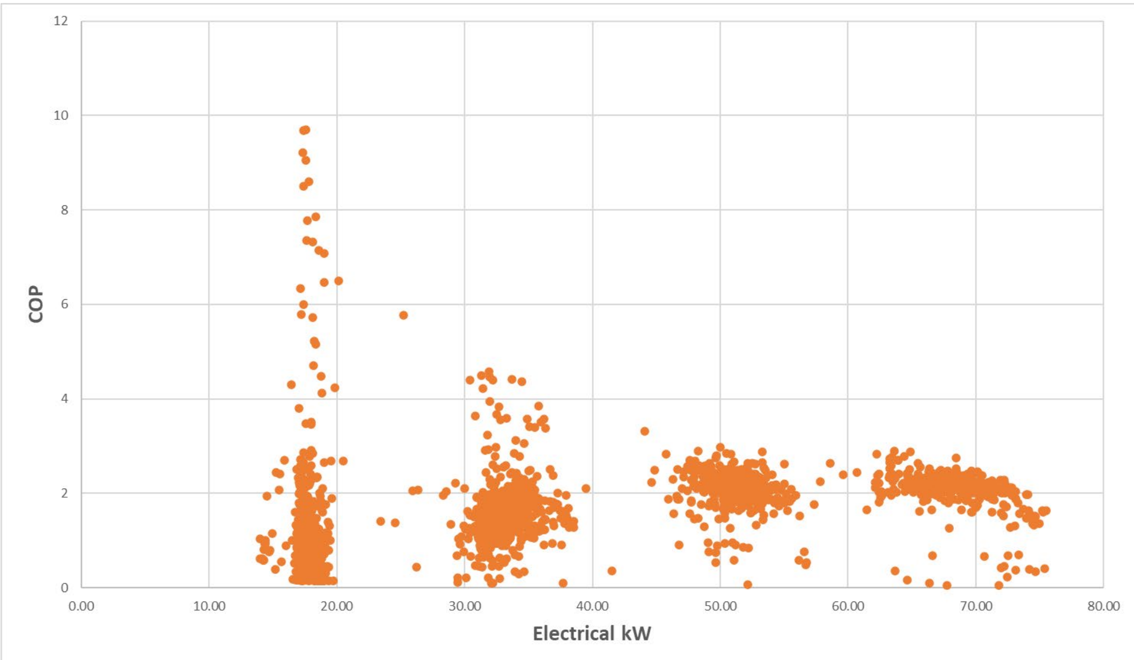


Figure 10 - Heater 1 COP vs kW of electricity

Looking at this closer in TrendView in Figure 11 there seems to be a mismatch between kWr and kWe, at this time in particular heating produced is 202.57 kW while the electricity is only 17.5 kW resulting in a COP of 11.57. But the kWe seems to be shifted forward a time step meaning the peaks are not aligning resulting in impossibly high COPs.

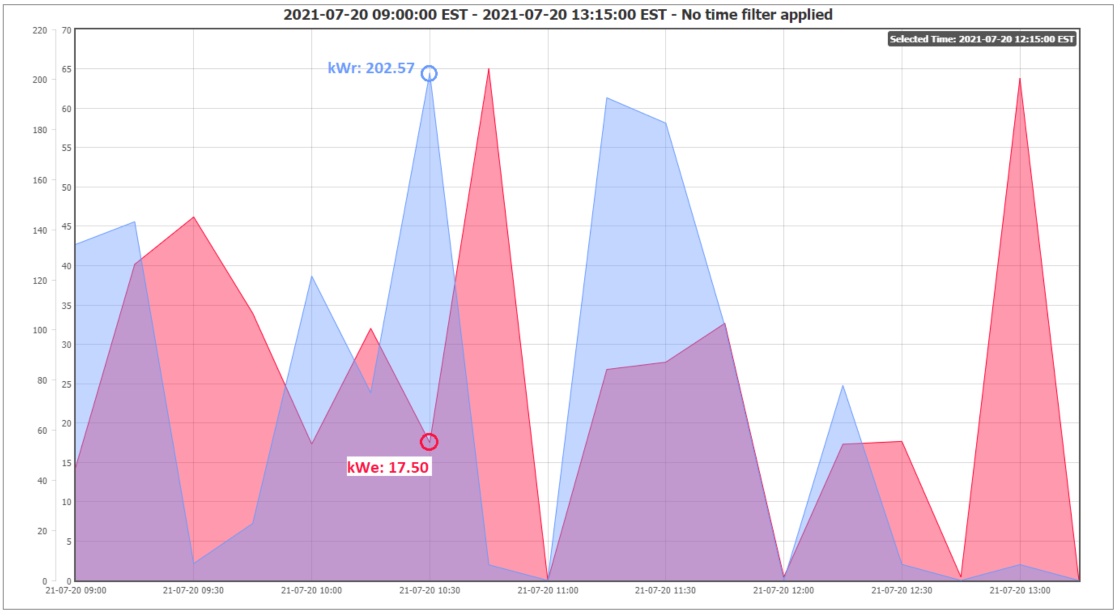


Figure 11 - Heater 2 kWr of heating and kWe of electricity on TrendView

The same thing was occurring on both heater 1 and 2 and if filtering the data by these high COP it shows that they all occur between the 19/07/2021 and 08/08/2021. Where there are frequent mismatches between kWr and kWe causing incorrect COPs. This could be due to an instrument miscalibration, most likely being the electrical meter.

By removing these dates from the analysis the abnormally high COP are now gone from the performance charts shown in Figure 12 and Figure 13. These figures also show how the different groupings of data are from different electrical kW ranges as found in Figure 9 and Figure 10.

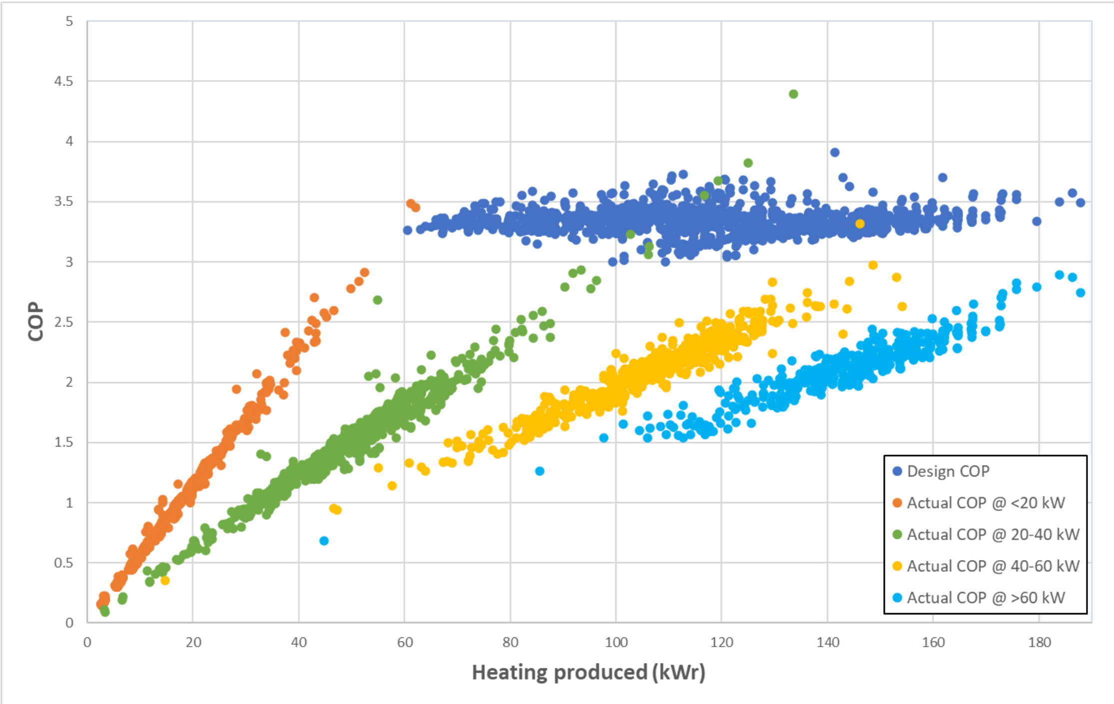


Figure 12 - Heater 1 design vs actual COP

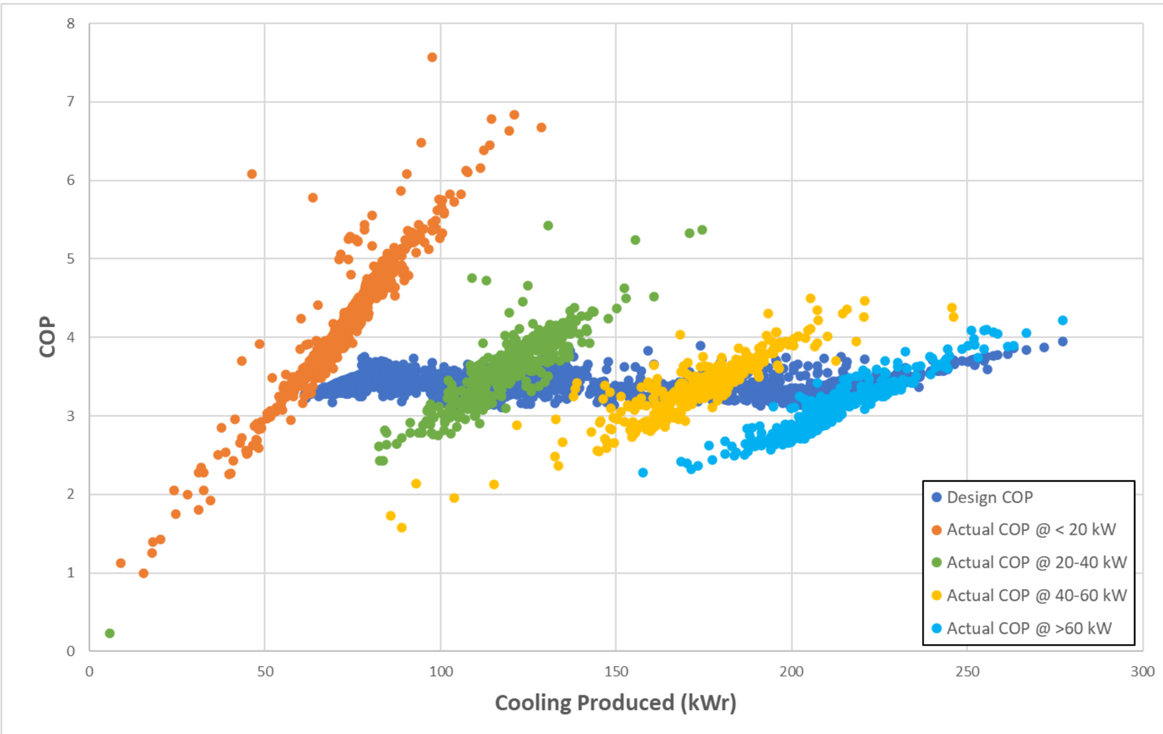


Figure 13 - Heater 2 design vs actual COP

From these figures it can be seen that for the same kWr of heating produced there are often two ranges of electrical kWe resulting in a range of COPs for the same kWr. For example, results for Heater 1 in Figure 12 show at 120 kWr there are COPs of about 2.4 using 40-60 kW of electricity as well as COPs of about 1.7 using over 60 kW of electricity. These differences can be explained by other factors effecting the COP such as mass flow of the heated water and ambient temperature.

The relationship between COP and the ambient temperature becomes clear when only looking at results with the same kWr (~120 kWr) as shown in Figure 14. Which is to be expected as when the system is trying to produce heat it makes sense that the performance is affected as temperatures outside drop. Ambient temperature is also a main factor in the designed performance.

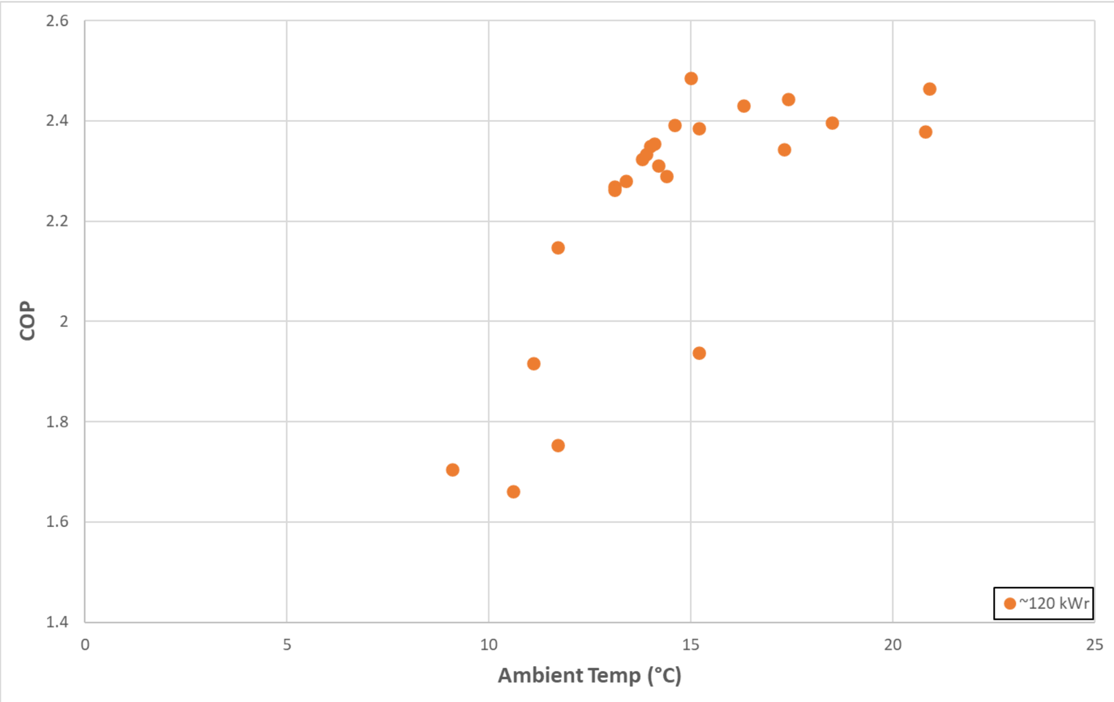


Figure 14 Heater 1 relationship between COP and ambient temperature at ~120 kWr

Another relationship that effects COP that isn't often considered in the mass flow of the water through the heater. Taking results for Heater 1 where kWr of heating produced is approximately 120 kWr and looking at the relationship between COP and mass flow in Figure 15 shows how the higher mass flow results in lower COP.

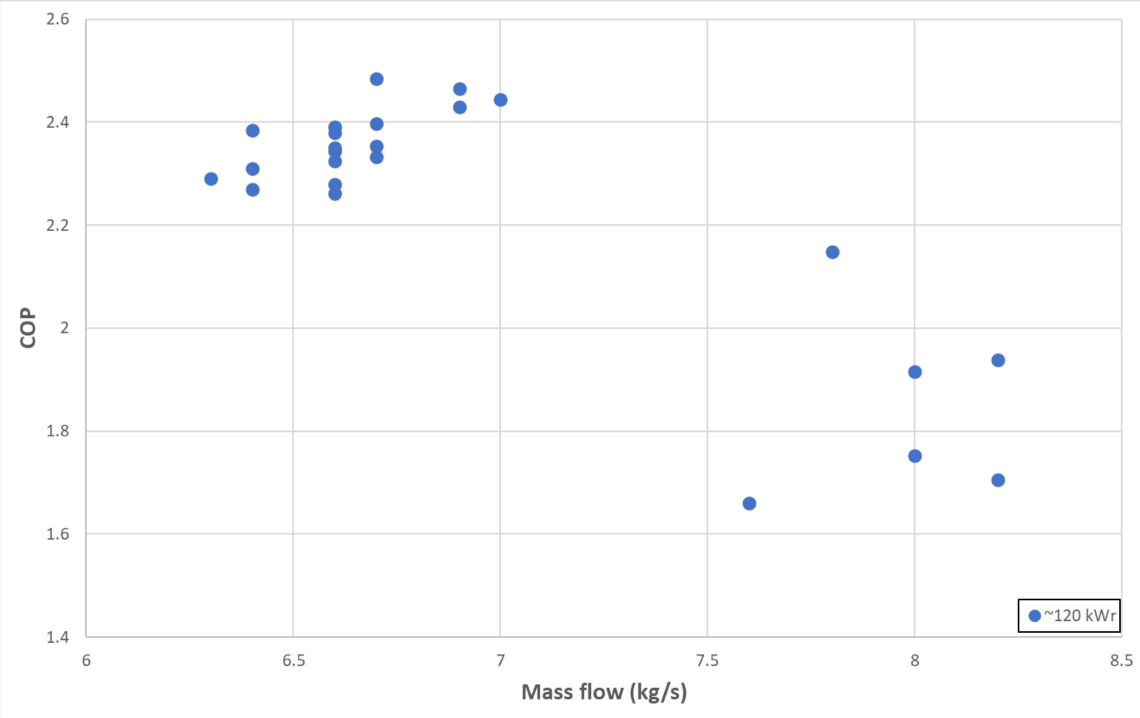


Figure 15 - Heater 1 relationship between COP and mass flow at ~120 kWr

To understand this further two times have been selected with similar ambient temperatures and the same heating produced (119.4 kWr), but the second time the outlet temperature has been reduced. It is often thought that reducing the outlet temperature set point for a heater or increasing the setpoint for a chiller is more efficient. But if the system still needs to produce the same amount of heating or cooling then the mass flow needs to increase to make up for the decrease in temperature. This makes the system less efficient. Shown in Table 2 at the second time (24/08/21) the outlet temperature is reduced lowering the temperature pick up across the heater, but so the system can still produce ~120 kWr of heating the mass flow must then increase. This higher mass flow (8.2 kg/s) drops the COP down to 1.93. So, comparing these two times the first case where the outlet temperature is higher the electricity is at 48.9 kWs, but in case 2 with a lower exit temperature and a higher mass flow the system needs 61.6 kW of energy which is 26% more energy being consumed.

Date	COP	kWr	KWe	Temp ambient	Mass flow	Temp in	Temp out	ΔT
26/06/21 16:20	2.44	119.4	48.9	19.2	6.9	32.6	36.7	4.1
24/08/21 21:35	1.93	119.4	61.6	21.1	8.2	32.2	35.7	3.5

Table 2 - Comparing two times with the same kWr but different mass flows for heater 1.

This illustrates that there are many factors that affect the COP of the system which have resulted in the performance curves of the chillers and heaters being quite spread. Design performance tables do not factor in different mass flows as it is assumed the recommended design mass flow is being used. So this is a significant factor that leads to differences between designed and actual performance.

Sometimes there also seems to be no explanation for differences in COP when kWr, ambient temperature and mass flow are all similar, yet there still seems to be differences in kWe being used.

For example, Table 3 shows two times where kWr, ambient temperature, mass flow and temperature pick up across the hot water are all very similar for Heater 2. Yet there is a big difference in electricity being drawn (kWe) and therefore COP.

Date	COP	kWr	KWe	Temp ambient	Mass flow	Temp in	Temp out	ΔT
22/09/21 06:05	3.12	99.5	31.9	11.3	7.97	34.8	37.8	3
16/09/21 06:00	5.66	100.2	17.7	10.7	8.03	35.2	38.2	3

Table 3 - Comparing two times with similar factors but different COPs

Looking at these times more closely Figure 16 shows the first time in Sentient Trendview where the system looks to be behaving as expected with kWe and kWr increasing at the same time and the COP being acceptable at 3.12.

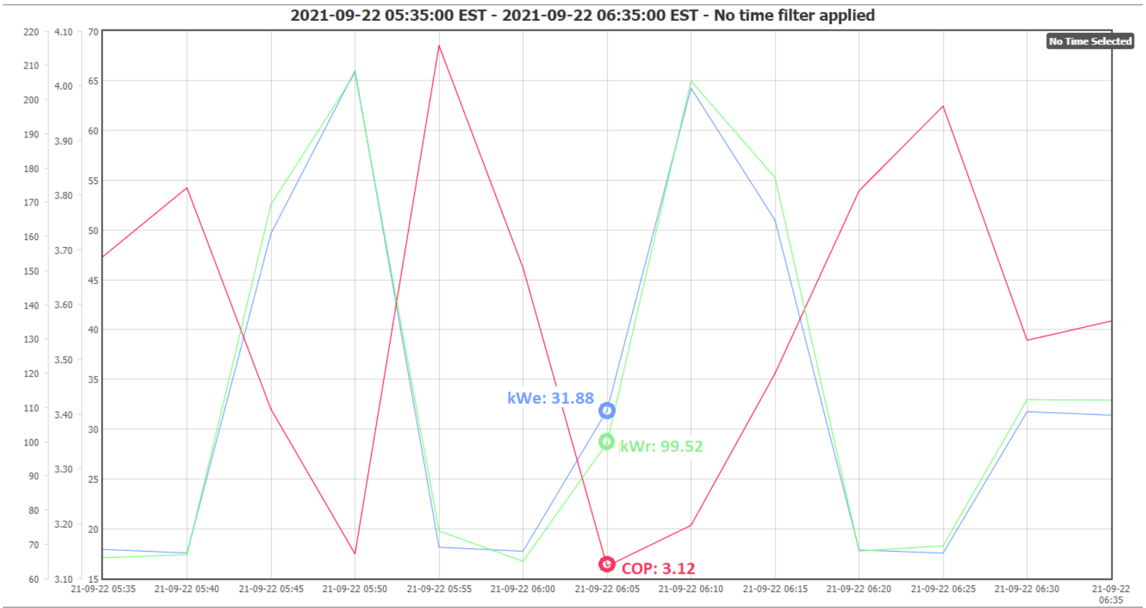


Figure 16 - TrendView showing time on 22/09/21 where COP is normal

However, Figure 17 shows at this time the kWe and kWr are out of sync. Where the kWr is increasing the kWe is decreasing and doesn't sync back with kWr until the next time step. This results in a very high COP of 5.66 and is likely more examples of instrument issues. Most likely the electrical meter is incorrect or is being measured at a different time.

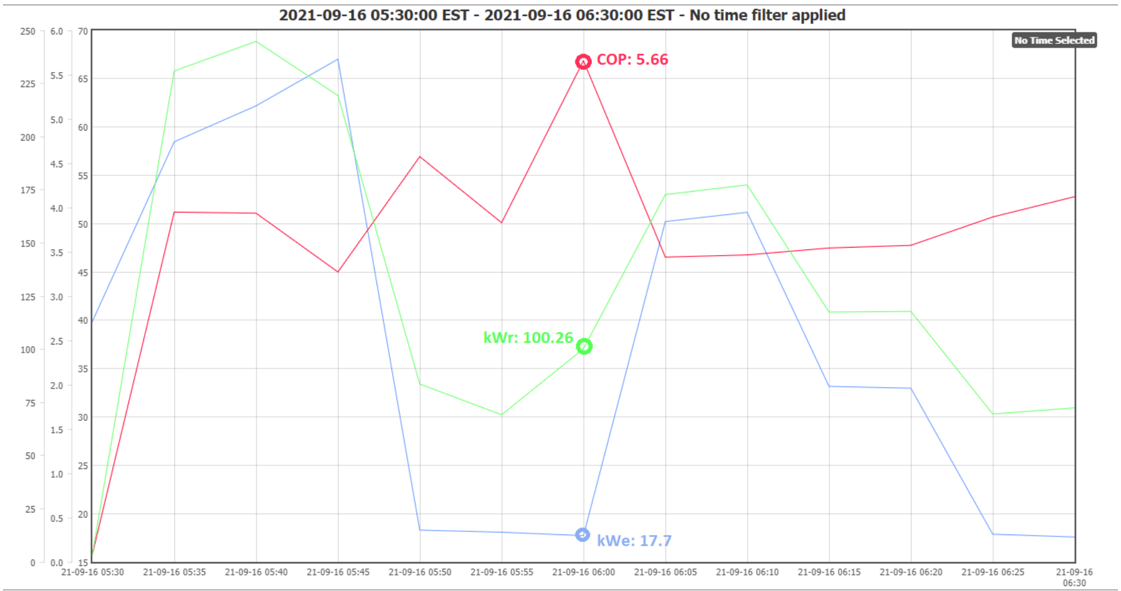


Figure 17 - TrendView showing time on 21/09/21 where COP is high

From these results all systems are experiencing lower COP than expected, except for Heater 2 that can often perform better than expected. Although this could be results from instrument issues, especially since heater 2 has the highest COPs when kWe is less than 20 kW which is normally when out of sync issues like above occur.

It was also found the spread of the performance curves are from several factors including ambient temperature, mass flow of the hot water and temperate increase/decrease in and out of the chiller/heaters, and sometime just from instrument errors. But overall, the chiller/heater systems are underperforming and using more than expected electrical energy.

Reasons why actual performance is lower than design

When the chillers and heaters are tested by the manufacturer to produce performance data it is normally done so under ideal conditions, with a constant ideal mass flow and outlet temperature set point. As shown previously, in actual usage the mass flow and outlet temperature are varied and significantly impact performance. It is also not clear what the ambient humidity was at testing and so it could be different to Brisbane's humid climate.

The chillers for this building were also oversized and so the chillers and heaters mostly run at around 25-75% of capacity. Air conditioners are most efficient and produce the highest COP at full capacity, so there is a lot of inefficiency in using these low loads. It would be much better for example to run one chiller at 100% than two at 50%. So it would be recommended to increase a chiller or heater to 100% capacity before turning another one on.

Mass flow is also a major factor in performance, the designed mass flow for Chiller 1 is 13.35 kg/s and for chillers 2 and 3 and heaters 1 and 2 the design flow rate is 6.79 kg/s. But often actual mass flow is higher than this dropping the COP down. Practices discussed in the previous section of reducing the chillers temperature set point or increasing the heaters set point often result in higher mass flows decreasing performance. It is recommended to try to keep the mass flow constant at its designed flow rate and only adjust temperature setpoints if required to keep the flow rate constant.

Other factors of underperformance could be the positioning of the chillers/heaters on the roof. The cooling fans supplying the condensers are critical to the system performance and in testing conditions the system would have been kept cool with ample ventilation. However, in reality the systems are roof-mounted and are likely to be in full sun and may also have other equipment causing obstructions to good ventilation. The temperature of the air going into the cooling fan may well be higher than the ambient temperature being measured and so this would also reduce performance.

There also still seem to be a mismatch between supply and demand for cooling and heating the building as mentioned in the stage 1 report. There seems to often be times where chillers and heaters are continuously cycled on and off, which leads to inefficiencies. Sometimes energy is being consumed without any cooling or heating being produced since the time on was not long enough for the system to do so, which is wasted energy. An example of this is shown in Figure 18 where kWe is toggling on and off too quickly for any useful cooling to be established (positive kWr). A more advanced way of controlling this would need to be investigated and implemented to reduce the excess energy usage.

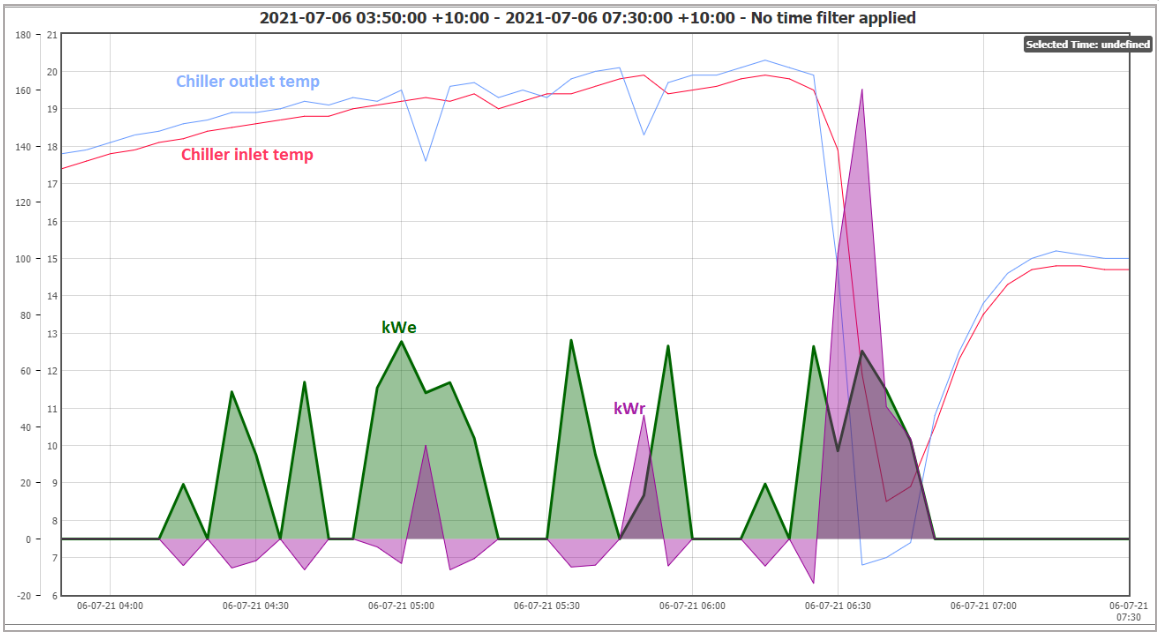


Figure 18 - Example of Chiller 2 not turning on long enough for any useful cooling to be produced

Accumulating Energy Consumption Deviation from Design

SentientSystem is continuously tracking actual COP and energy consumption as well as designed. As seen in the previous section the actual COPs are mostly less than designed so this results on more energy being consumed than expected. In this analysis Synengco was able to accumulate these differences and realise them into a total cost.

Table 4 shows these cumulative results for the 5 months of 1st of May to 30th of September, and Heater 2 is actually using slightly less energy (~5%) than designed. Chiller 1, as mentioned before, was only used twice for short periods. The remaining chillers and heaters all consumed over 25% more than design. Overall, the systems used 13.6 MWhs more than they are designed to which is equivalent to 10,940 kg CO_{2-e} emissions.

	Chiller 1 (kWh)	Chiller 2 (kWh)	Heater 1 (kWh)	Chiller 3 (kWh)	Heater 2 (kWh)	Total
May	-	2,520.3	336.6	2,316.5	-173.6	4,999.8
June	-	1,340.1	804.4	844.0	-158.7	2,829.8
July	- 1.0	1,159.1	637.3	455.7	-86.2	2,164.9
August	-	739.9	495.7	760.0	2.5	1,998.1
September	27.9	857.0	140.0	745.4	-88.9	1,681.3
Total Excess (kWh)	**26.9**	**6,616.4**	**2,414.0**	**5,121.5**	**-504.9**	**13,673.9**

Total Excess emissions (kg CO_{2-e})	**20**	**5,290**	**1,930**	**4,100**	**-400**	**10,940**
Total usage overall (kWh)	174.3	24,988.7	8,749.2	19,772.2	9,282.2	62,966.6
% Excess	**15.41%**	**26.48%**	**27.59%**	**25.90%**	**-5.44%**	**21.72%**

Table 4 - Accumulated kWh of deviation between actual and designed energy consumption

Based on common electricity usages charges in South East Queensland, the estimated cost of this deviation from designed performance has been calculated based on publicly available prices. This is deviation cost for the 5 months of May to September 2021 and is summarised in Table 5.

Charges	Usage	Unit price (c/kWh)	Amount ($)
Peak	6,662.4	9.0	599.61
Off peak	7,011.6	6.0	420.69
Environmental schemes	13,673.9	2.0	273.48
Network charges	13,673.9	2.0	273.48
Market operator charges	13,673.9	0.07	9.57
Total			$1,576.84

Table 5 - Cost of the actual vs design deviation based on current electricity use charges

PREDICT

For Fernhill, Synengco also established EWS (Early Warning Systems) for the HVAC plant and components. For each EWS a prediction is established, which is the tag that needs to be monitored and to generate alerts from. This prediction is based on the value of related tags (features), with machine learning algorithms used to establish relationships between tags and to decide which features would be best for each prediction while maintaining the balance between over or under fitting the model.

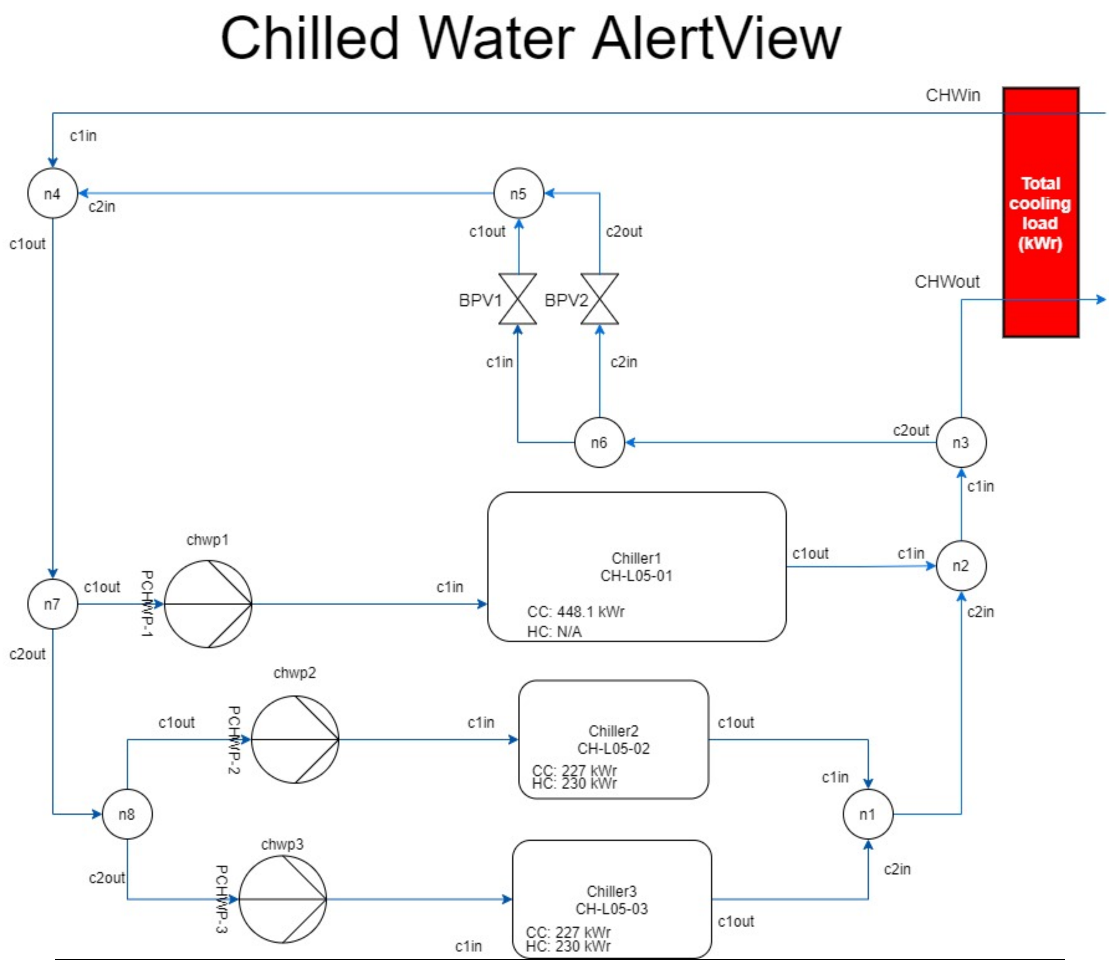
Once features are picked and the model is trained and producing predictions the EWS then monitors the predicted and actual value for each tag and uses self-learning to monitor the relationship between the predicted and actual over long- and short-term periods to assess if there is an issue. If the algorithm assesses that there is a significant enough change in the relationship an alert will be generated.

The predictions and EWSs were established for the following:

- Chiller energy consumption for each chiller
- Chiller COP for each chiller
- Chiller kWr for each chiller
- Chiller plant/building cooling load (total cooling produced by HVAC plant for the building)
- Bypass valve positions for each valve.

The following sections will show various alerts that were generated from these and the analysis of each.

Cooling load



No.	Alert Description	Plant Area	Date	Severity
0024	Cooling load kWr	Chilled water	30/12/2020	Monitor
0028	Cooling load Kwr	Chilled water	16/01/2021	Monitor

Figure 19 - Sentient AlertView and valid alerts for HVAC cooling load

30/12/2020

Figure 20 shows a building cooling load event alerted on the 30/12/2020, being the actual cooling load to the building is much lower than predicted, following this the cooling load supplied to the building then proceeds to oscillate and spike before settling back to the predicted load.

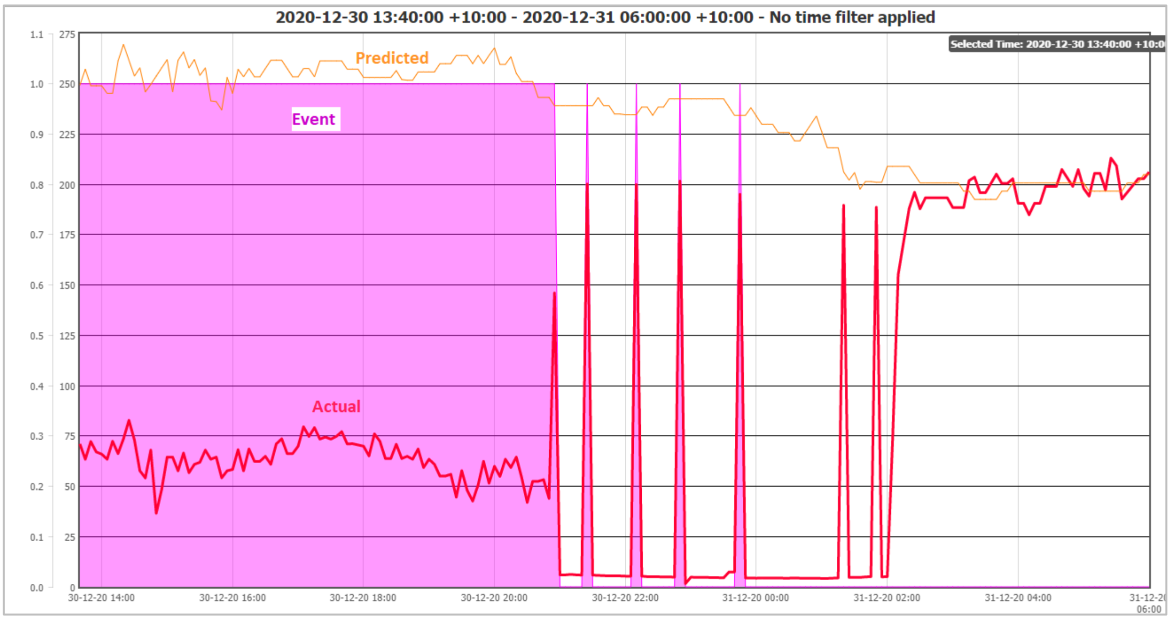


Figure 20 - Sentient Trendview showing EWS event from actual and predicted building cooling load 30/12/2020

The tags related to the cooling provided to the building are shown in Figure 21 and it can be seen that the leaving and return temperatures from the HVAC plant to the building are not spiking but the mass flow of chilled water to the building is.

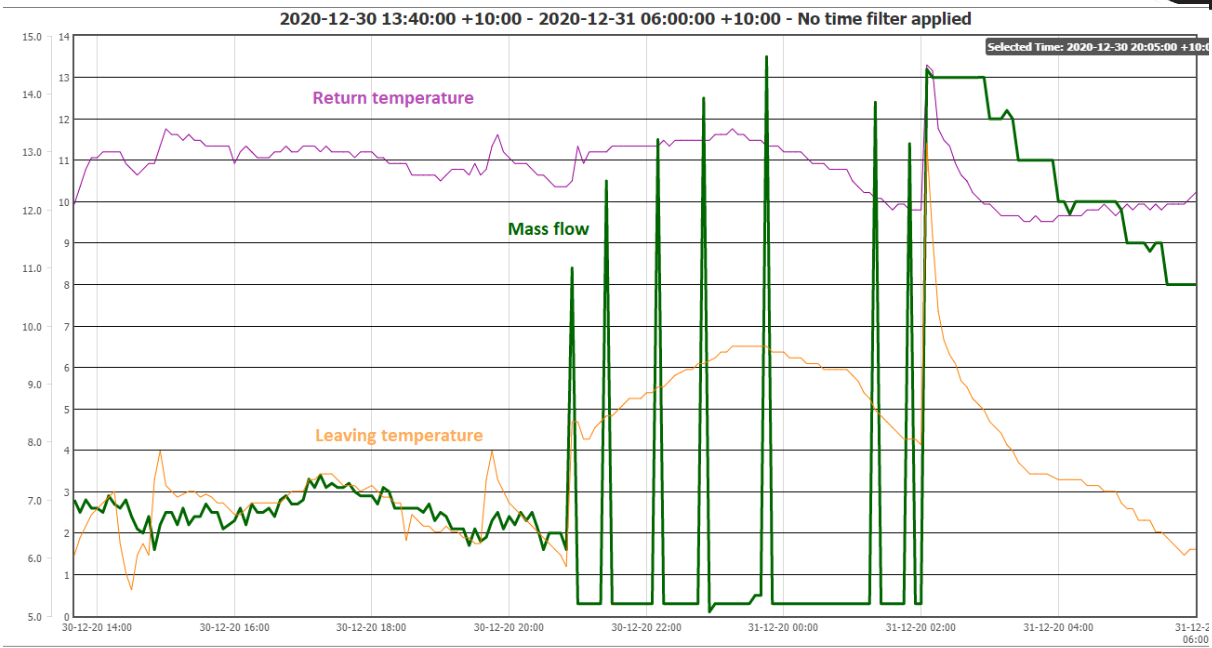


Figure 21 - Sentient Trendview showing HVAC plant supply and return conditions during EWS cooling load event 30/12/2020

Looking closer at the individual chiller operation Figure 22 shows that Chiller 2 is exhibiting some strange behaviour. First the system starts with Chiller 3 on, consuming electricity and producing a mass flow. But during this time Chiller 2 is also recording electricity consumption but has no mass flow. Then when Chiller 3 turns off Chiller 2's electricity consumption increases, but the mass flow starts turning on and off. Something is definitely wrong here either with plant operation or equipment failure.

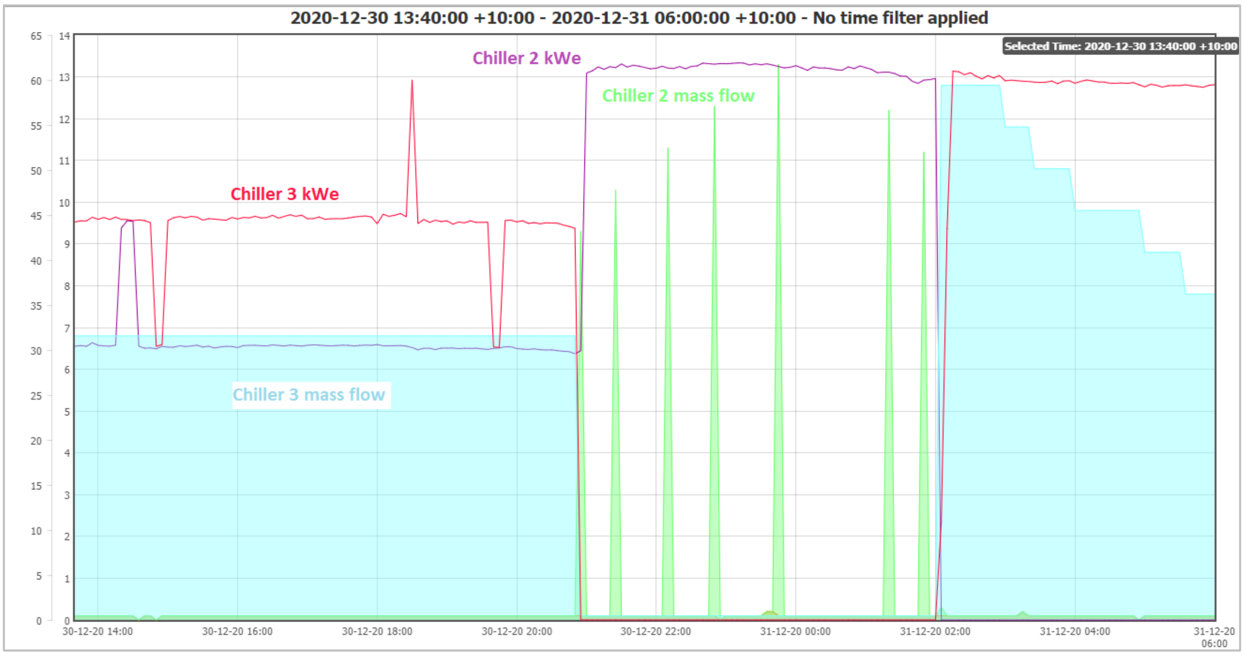


Figure 22 - Sentient Trendview showing chiller operation during EWS cooling load event 30/12/2020

16/01/2021

The below event for building cooling load in Figure 23 shows the load suddenly increasing to quite a high load for a period before suddenly dropping back down. With the increased load occurring while the ambient temperature is cooling down instead of following a similar trend to the predicted cooling load which rises and falls with ambient temperature.

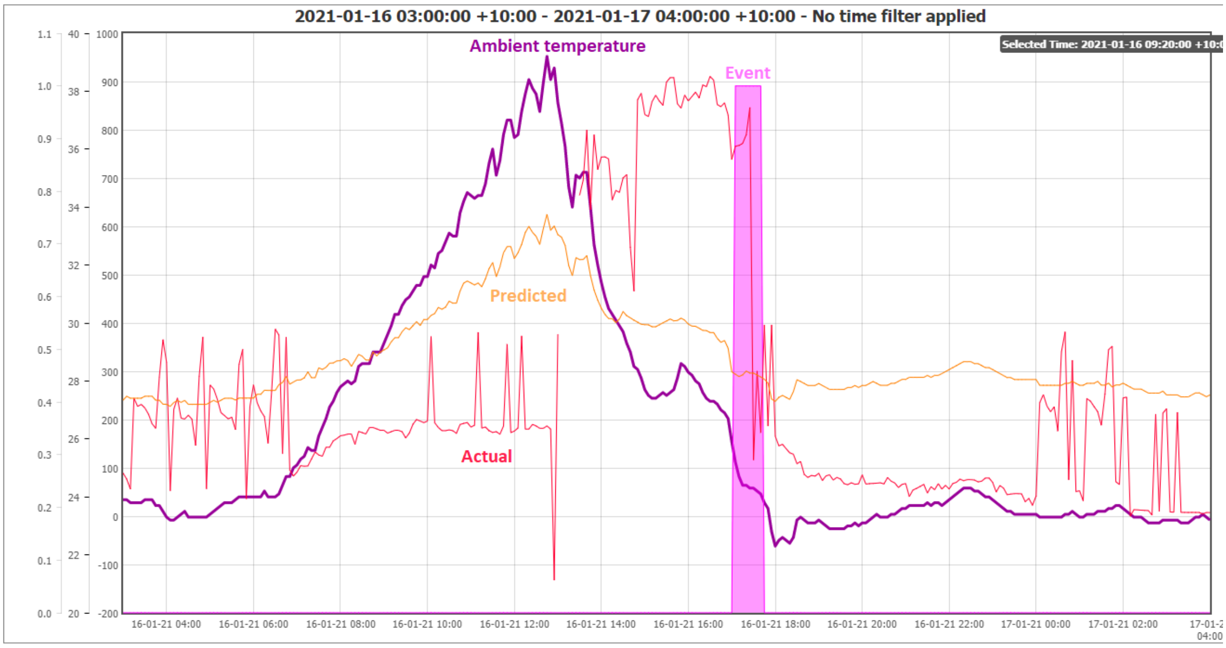


Figure 23 - Sentient Trendview showing EWS event from actual and predicted building cooling load 16/01/2021

From Figure 24 it can be seen that this high cooling load comes from chiller 1 being turned on to meet demand at about 1pm. By this time the peak temperature outside (nearly 40°C) had already occurred, and it was actually cooling down quite rapidly outside, but the HVAC system was still trying to cool the building down. A better way to manage a hot day like this would have been to do some precooling before peak temperature was reached, similar to the predicted cooling load trend, so that the chillers wouldn't have to work so hard in the afternoon to catch up using a lot more energy.

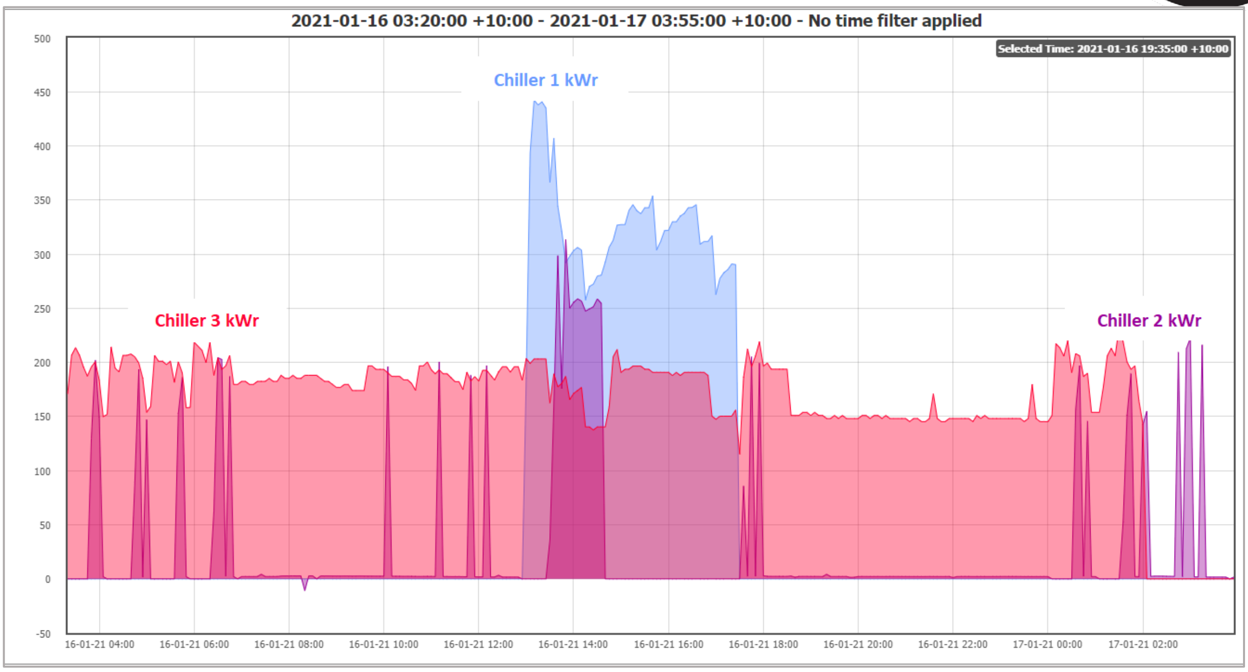
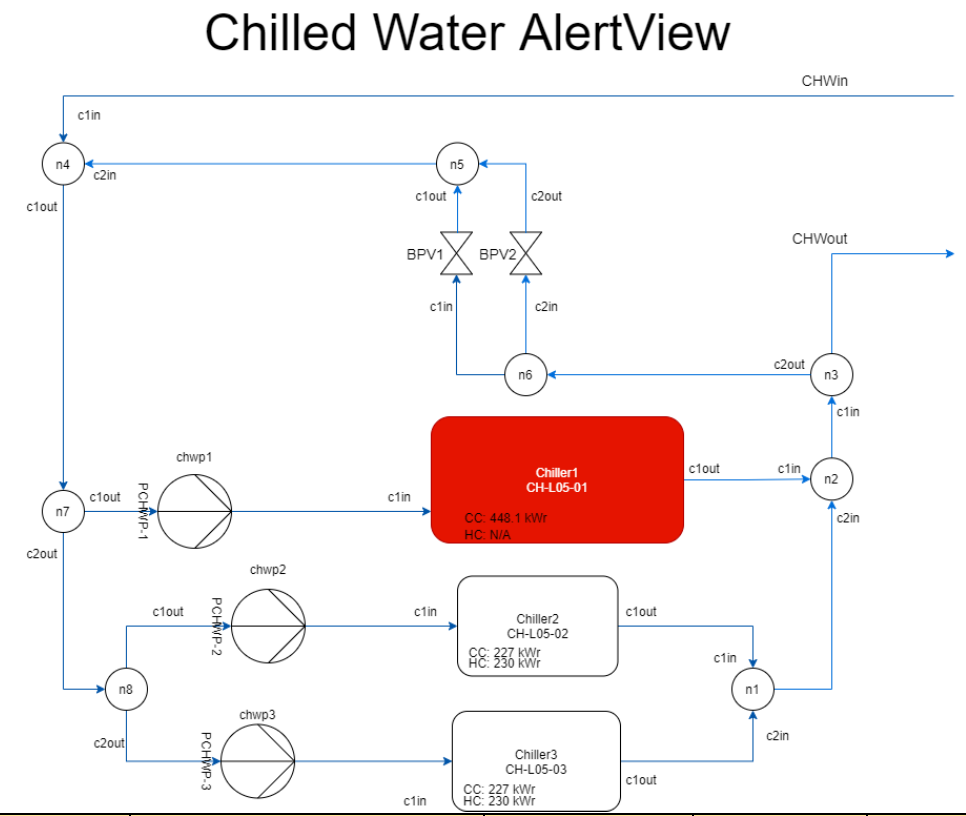


Figure 24 - Sentient Trendview showing chiller operation during cooling load event 16/01/2021

Chiller 1



No.	Alert Description	Plant Area	Date	Severity

0009	hvac_Chlr1_kw	Chiller1	20/11/2020	Monitor
0037	hvac_Chlr1_kw	Chiller1	23/02/2021	Monitor

Figure 25 - Sentient AlertView and valid alerts Chiller 1

20/11/2020 - kW

The event depicted in Figure 26 is for Chiller1 electricity consumption during November 2020. The duration of the alert is 3hrs which is the same as the period of 'cooling load' on the building, which may allow this event to be classified as a 'startup' event.

However, if this 'startup' event classification is ignored, and the focus is on the kWe of the Chiller on the 20/11/20 versus the period of operation ~3 days prior on the 17/11, it can clearly be seen that the chiller load is almost 20kW less for an equivalent building cooling load. Also, checking the kWr of the chiller it can be seen that this figure is substantially higher than the operation on the 17th. This suggests the chiller is potentially performing either much better than designed (i.e. allowing for a significant kWr for minimal kWe) or the chiller was being under powered which may explain the short period of operation (i.e. resulting in the chiller forced shutdown).

Alternatively, it could be that the kWr figure is much higher than the 17th operation due to the rise of the CHW inlet Temp just before Chiller1 loads on. Looking closely this temperature rise can be explained by the outage of all the chillers prior.

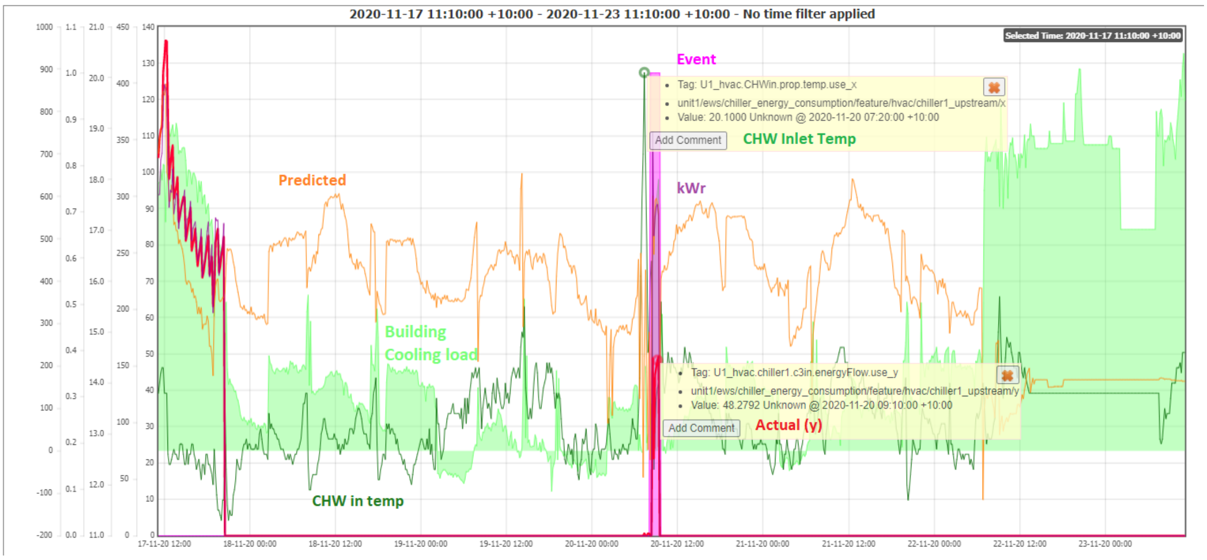


Figure 26 - Sentient Trendview showing EWS event for Chiller 1 electricity consumption (kWe) on 20/11/2020

Figure 27 below shows the detail of SentientSystem's cause for alerting. Note that the predicted kWe for the respective building cooling load is at ~90kW vs the actual of 42kW.

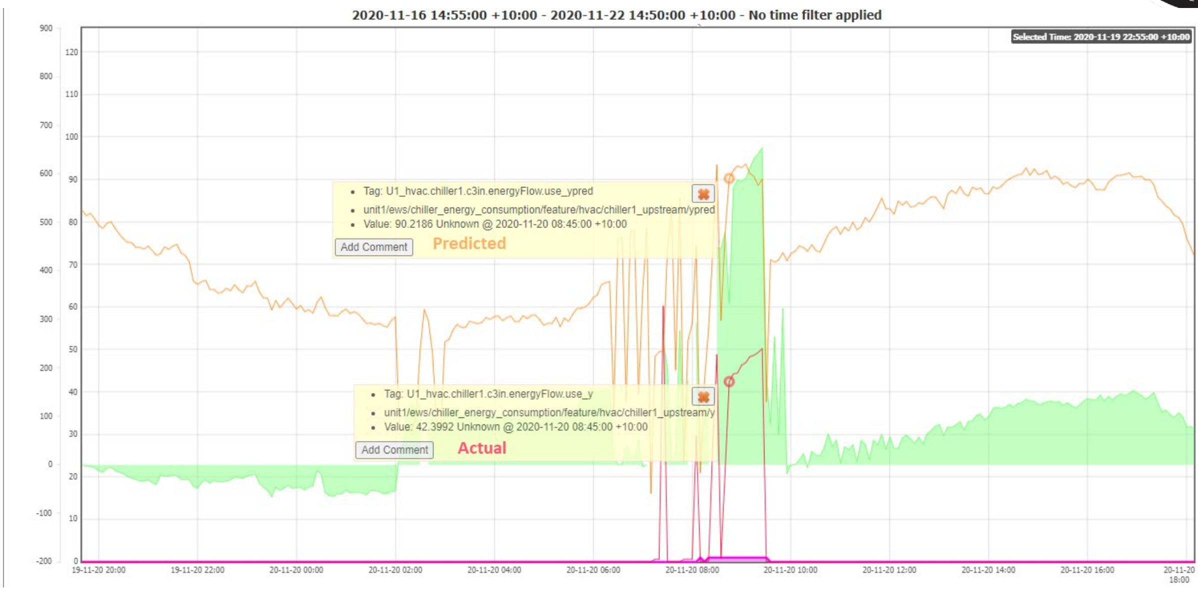


Figure 27 - Sentient Trendview showing actual and predicted kWe for chiller 1 for EWS event on 20/11/2020

23/02/2021 - kW

The below event in Figure 28 for Chiller 1 electrical consumption (kWe) shows that Chiller 1 went through a period of being off yet continued to have mass flow pumped through it. This is an unusual occurrence, as you can see in the previous times leading up the event on the 21/02 and 22/02 when the chiller was off and actual kWe was zero, the mass flow is also zero. It is unclear why this would occur or if it is an operation or instrument error or a maintenance activity.

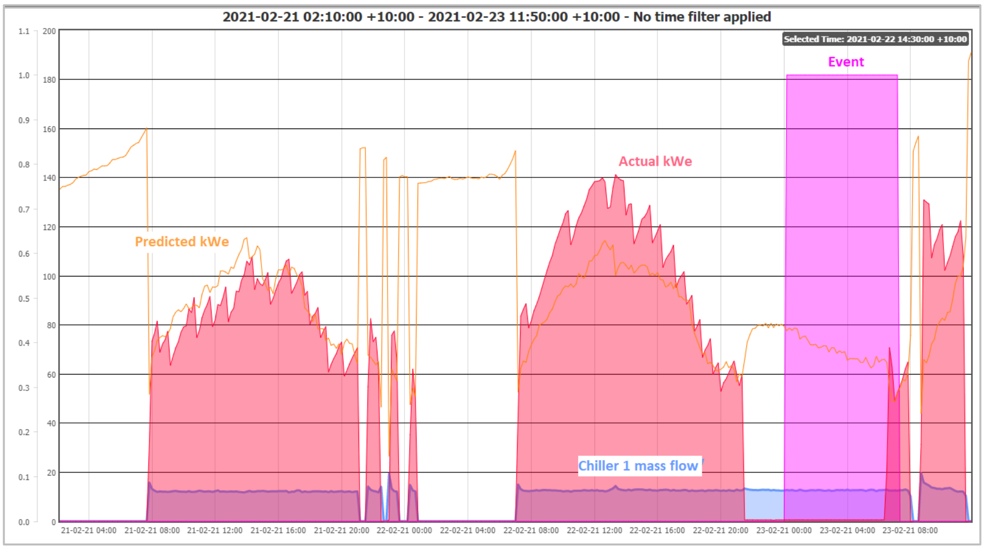
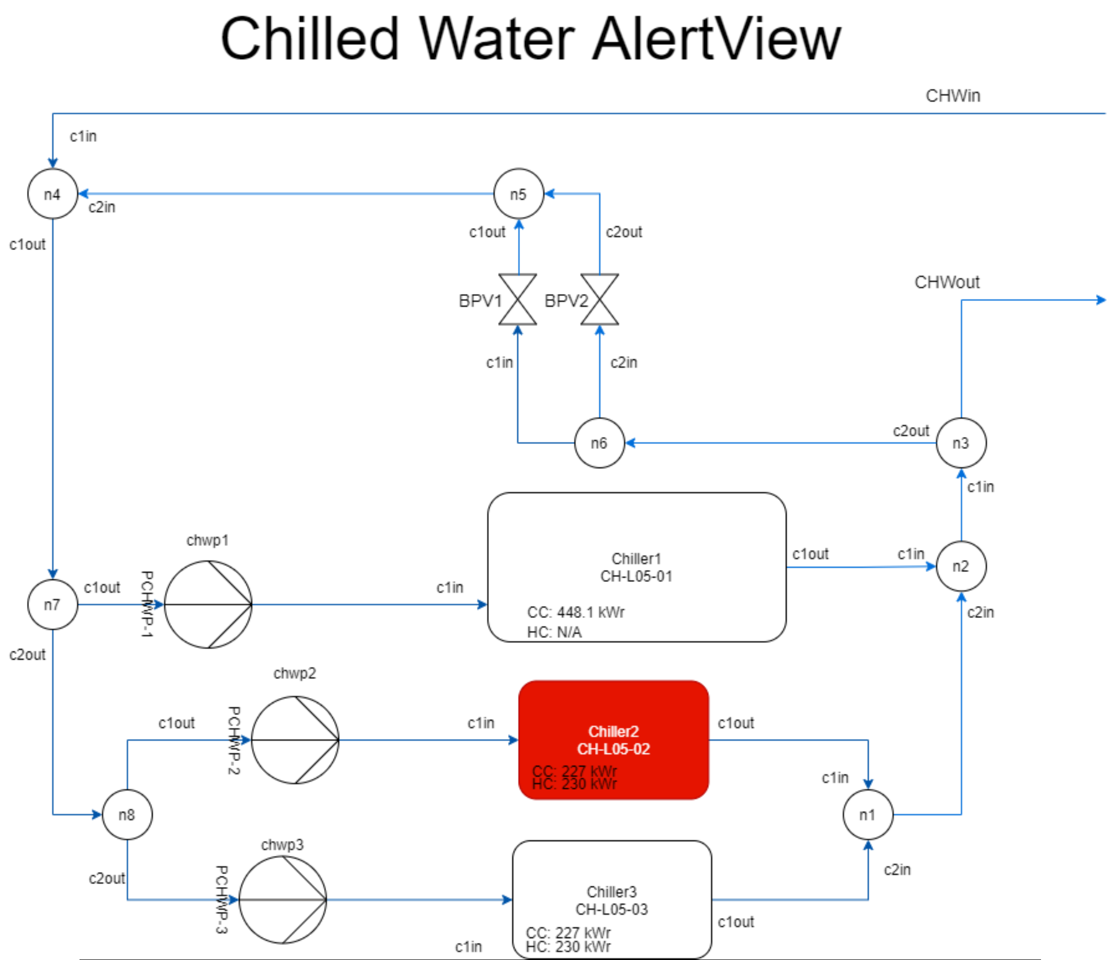


Figure 28 - Sentient Trendview showing EWs event for Chiller 1 kWe on 23/02/2021

Chiller 2



No.	Alert Description	Plant Area	Date	Severity
0002	hvac_Chlr2_COP	Chiller2	5/11/2020	Monitor
0003	hvac_Chlr2_kW	Chiller2	5/11/2020	Monitor

Figure 29 - Sentient AlertView and valid alerts for chiller2

05/11/2020 – COP

As seen in the table above there are two alerts, kW and COP, generated on the same day for seemingly the same problem. The COP alert, seen immediately below, shows rapid cycling of the chiller mass flow which is reflected by the COP calculation that causes the alert generation.

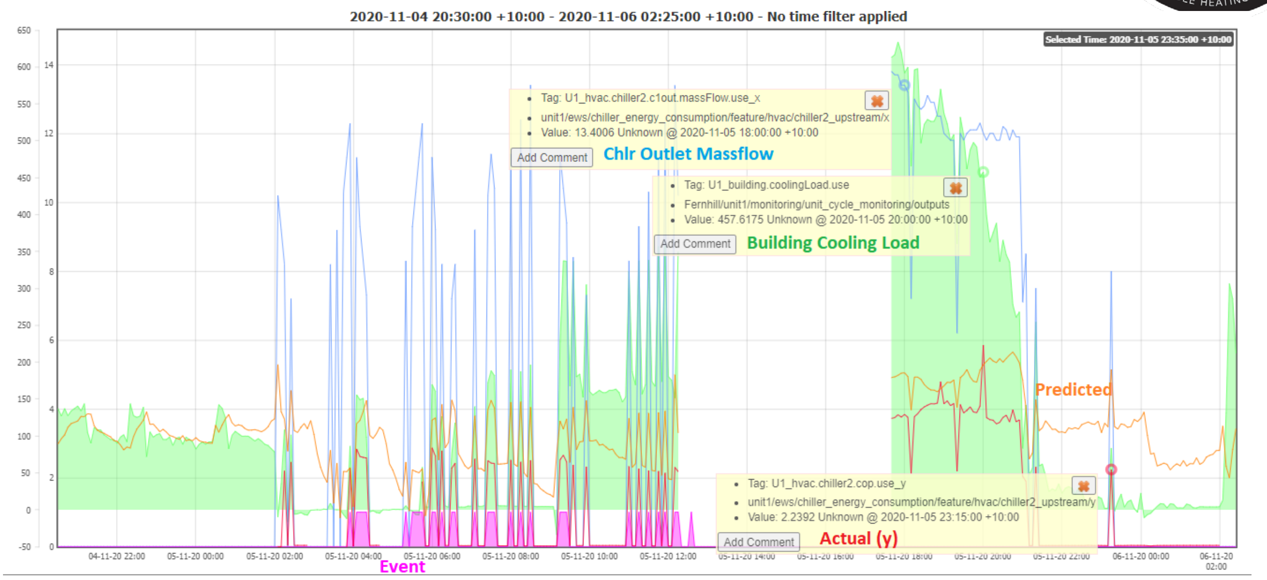


Figure 30 - Sentient Trendview EWS for Chiller 2 COP on 5/11/2021

The root cause of this is not immediately clear as this event has occurred during November 2020 which is known to be problematic for data and configuration alike. Therefore, this could be either a problem with the data collection, a system configuration or set up event, a 'flushing' of the chiller (i.e. routine maintenance) or a valid event brought on by poor control of the system. The last two theories are more likely given the duration of the event effectively lasts for almost 12hrs.

05/11/2020 – kW

Supporting the above hypothesis, the kW event alerted for chiller 2 is also due to the mass flow turning on and off yet the electrical consumption (kWe) is continuous, and it is producing cooling with temperature out being cooler than temperature in. This information suggests that the problem may also be related to data collection.

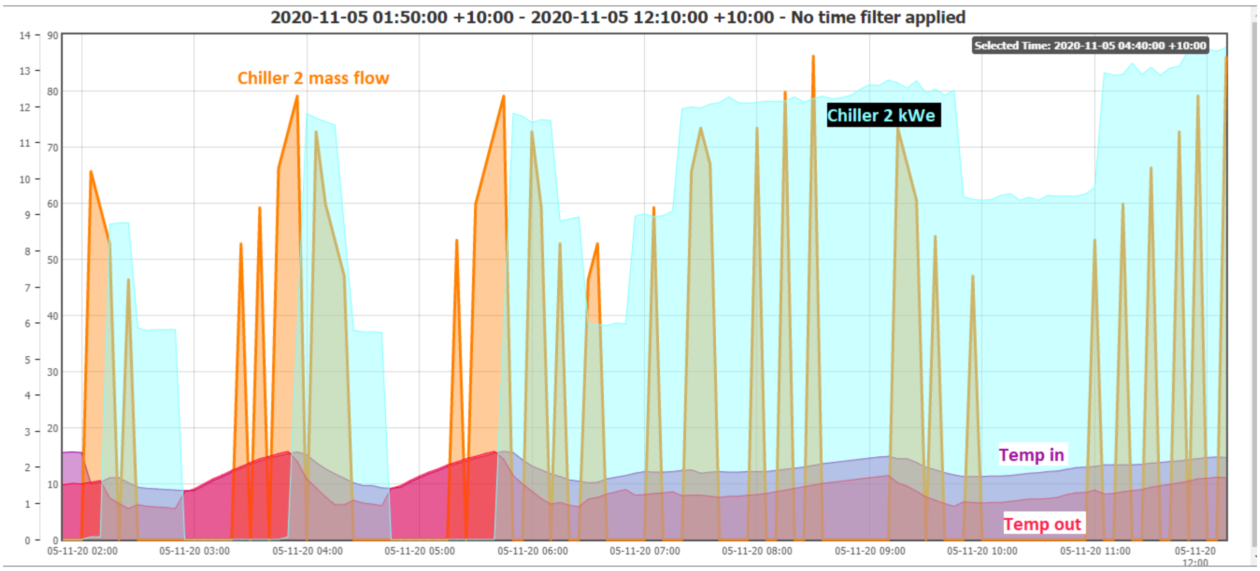
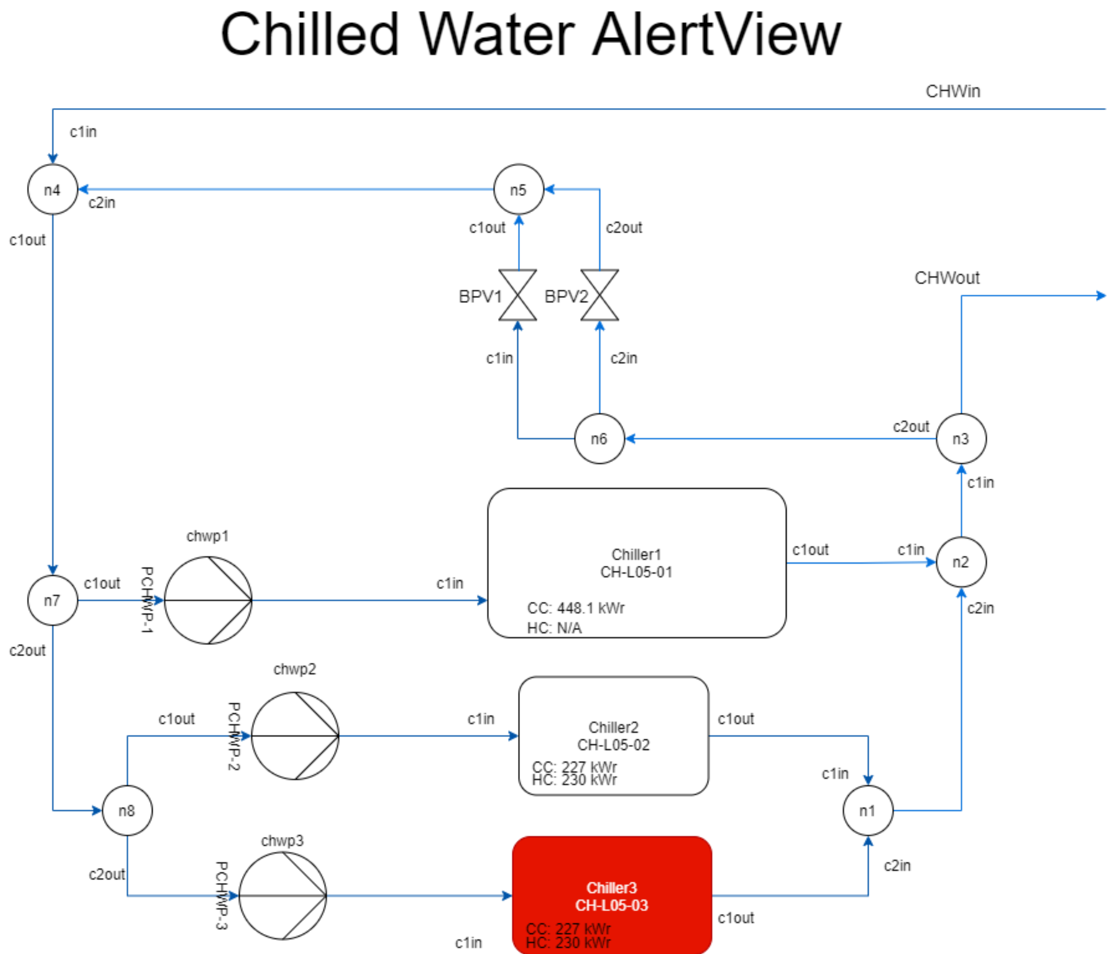


Figure 31 - Sentient Trendview showing Chiller 2 operation for EWs event on 05/11/2021

Chiller 3



No.	Alert Description	Plant Area	Date	Severity
0019	hvac_Chlr3_COP	Chiller3	11/12/2020	minor

Figure 32 - Sentient AlertView and valid alerts for Chiller 3

11/12/2020 – COP

Figure 33 shows Chiller 3 COP on the 11/12/2020 and depicts a deviation in the form of an improvement of the Actual COP from the predicted. This valid performance improvement of the chiller looks to be possible due to the better/cooler ambient conditions.

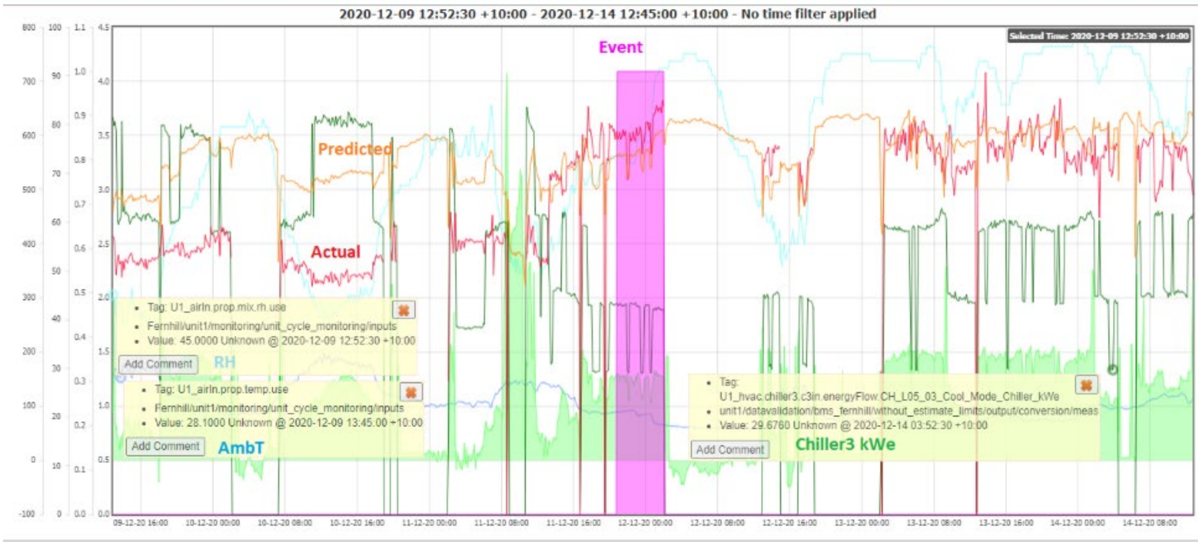
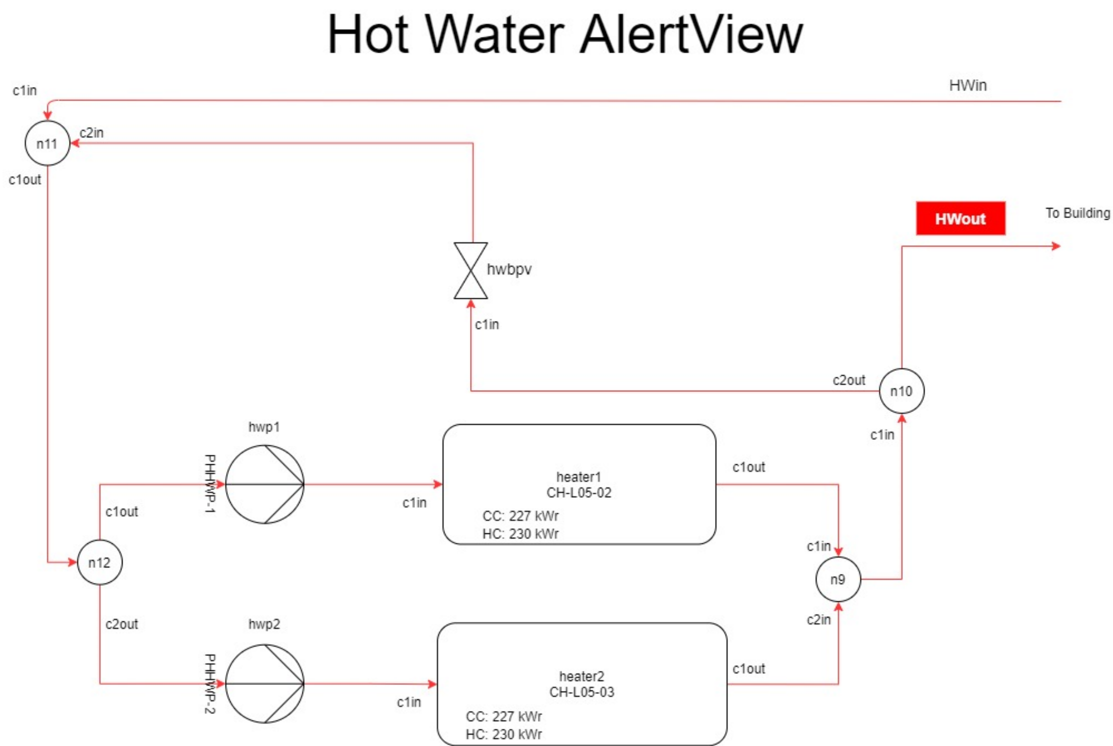


Figure 33 - Sentient Trendview EWs event for Chiller 3 COP on 11/12/2021

Heater load – HWout temp



No.	Alert Description	Plant Area	Date	Severity
0051	hvac_HW outlet	Hot water	7/07/2021	Valid
0052	Hvac HW outlet	Hot water	15/07/2021	Valid

Figure 34 - Sentient AlertView and valid alerts for hot water outlet temp

07/07/21

Figure 35 below shows an event for hot water outlet temperature on the 07/07/2021. This event seems to be caused by some data or instument issues. Firstly, there is a period of missing data for this temperature and then it comes back very low before correcting itself. Ambient temperature also drops down to zero around this time. This is most likely an instument recallibration or some other issue that caused the data to go bad for this period resulting in an alert.

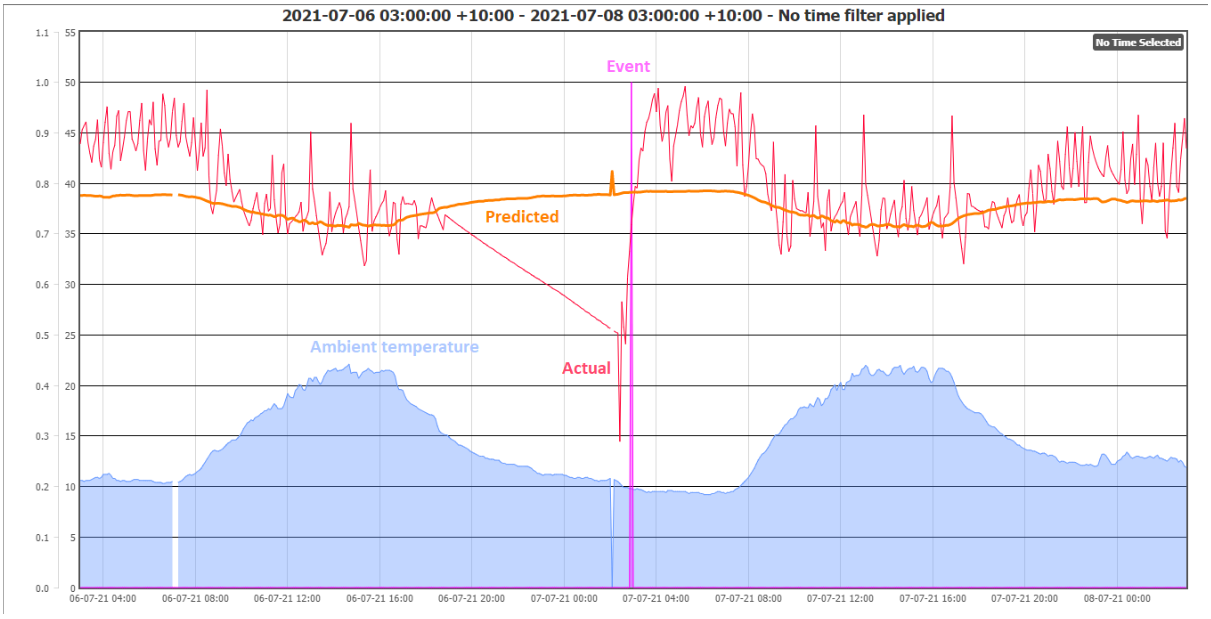


Figure 35 - Sentient Trendview showing EWS event for hot water outlet temperature 07/07/2021

15/07/2021

Figure 36 shows an EWS event for the hot water leaving temperature from the HVAC plant on the 15/07/2021. In this event the predicted heating water temperature out is predicted to be much higher than actual. It was also noticed that the mass flow of hot water also seemed to be higher than usual.

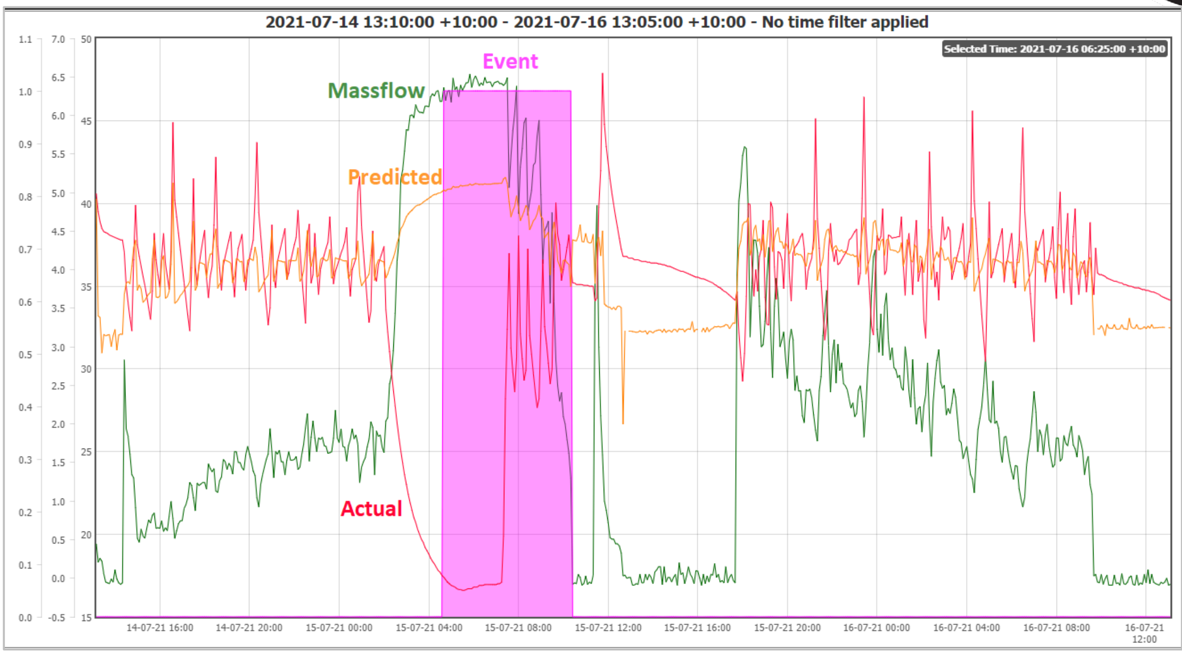


Figure 36 - Sentient Trendview showing EWS event for HVAC plant hot water leaving temperature 15/07/2021

Figure 37 shows the heater and bypass valve operation during this time. Both heaters were actually turned off at this time, yet the hot water was being pumped to the building. This is unusual operation since shortly after when both heaters are off again you can see that the hot water bypass valve is at 100% closing off flow to the building and so mass flow to the building is hovering around zero. This operation would cause the hot water to lose heat to the building hot water loop, therefore the temperature of this hot water is dropping down to environment and causing an alert. If heaters are off the bypass valve should be 100% to store the heat in the heater loop. It is also possible in this instance the heaters have failed to turn on which is a failure to meet demand which would explain the hot water mass flow being driven up in an effort to meet demand.

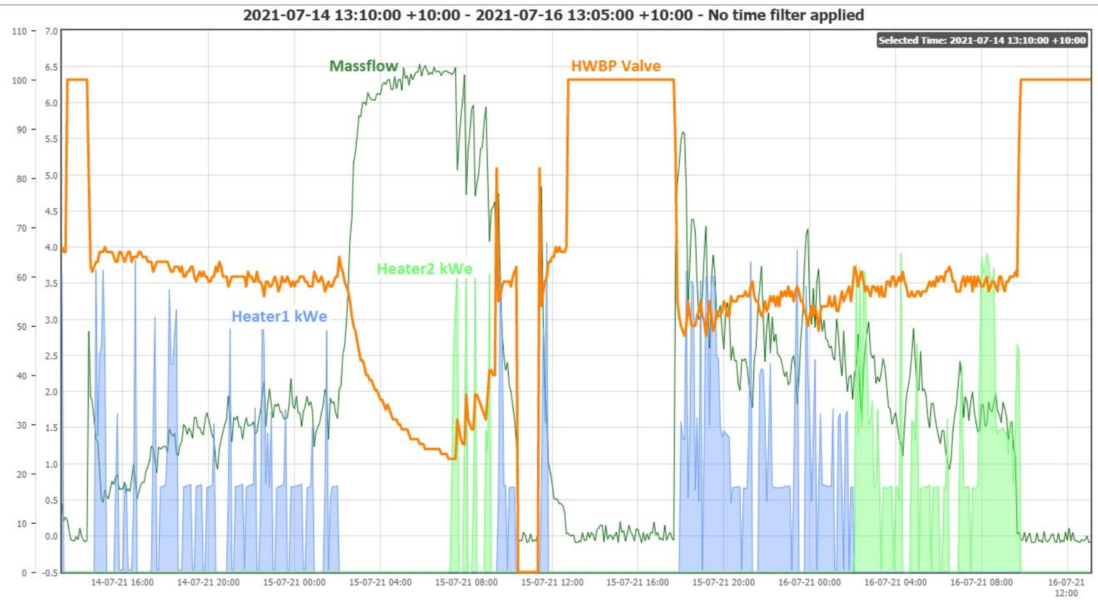
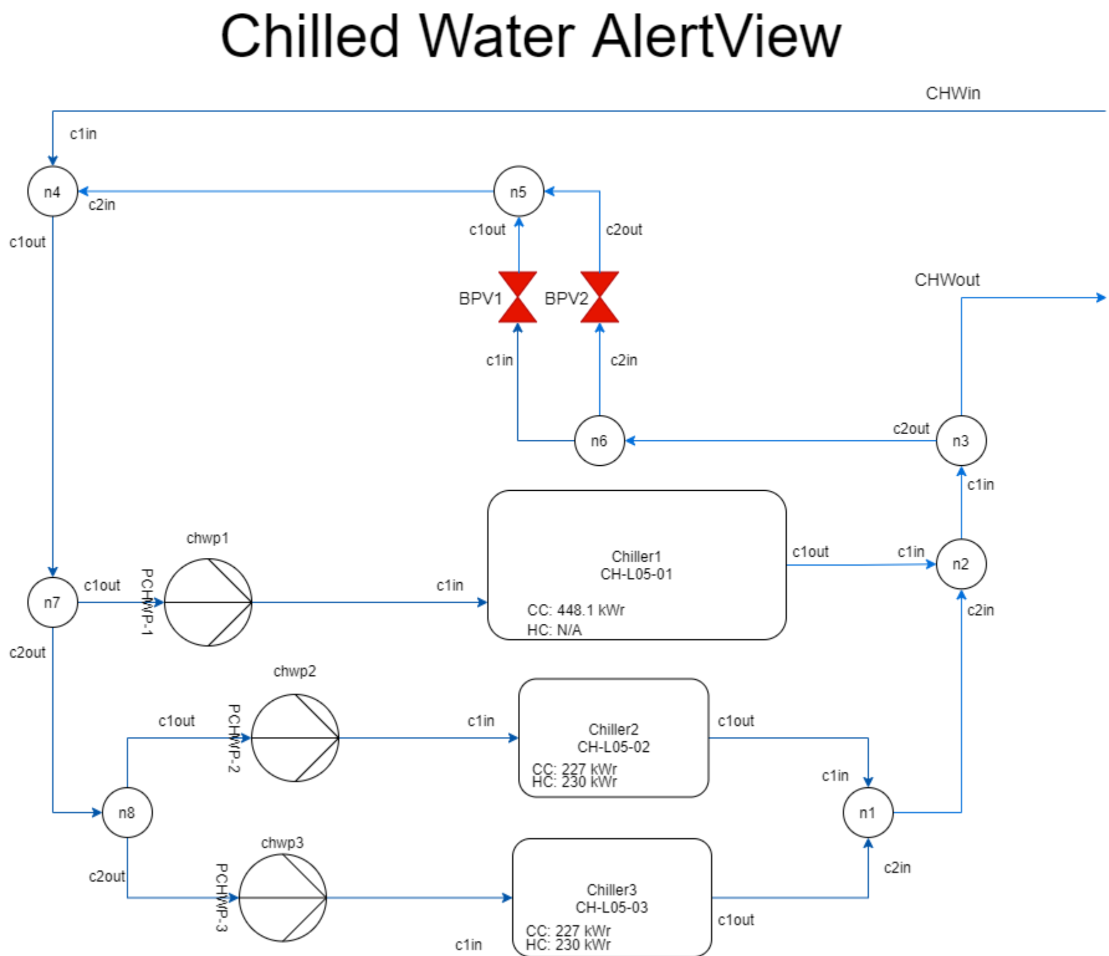


Figure 37 - Heater and bypass valve operation during EWS event for hot water temperature 15/07/2021

Chilled Water Bypass Valves



No.	Alert Description	Plant Area	Date	Severity
0048	hvac_BPV2	Building	22/04/2021	Valid

Figure 38 - Sentient AlertView and valid alerts for chilled water bypass valves

21/04/21 – Bypass Valve 2

Figure 39 displays an alert generated on the 21/04/21 on the building bypass valve 2 position. In the snapshot below the valve position is rapidly cycling from 0-100% for approximately 6hrs, where the same cycling can also be seen for bypass valve1.

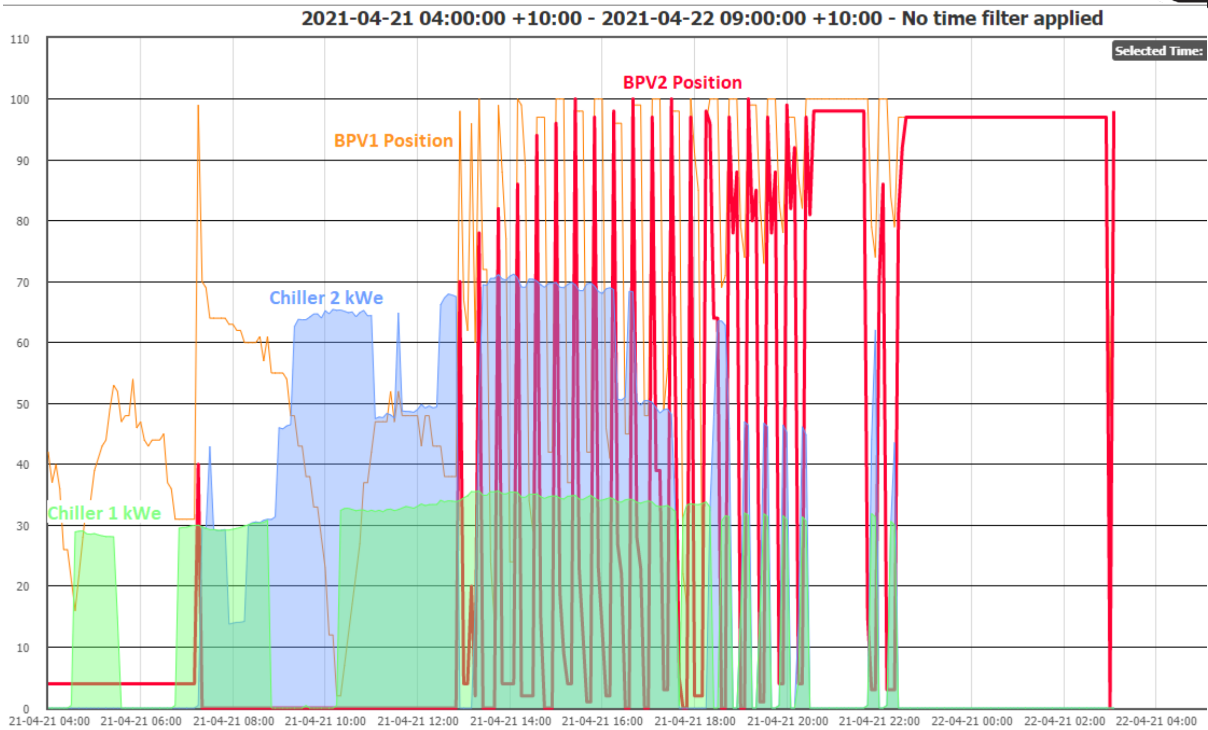


Figure 39 - Sentient Trendview showing EWS event time for CHW bypass valve 2 position

This operation is validated by the Chiller 1 pump (CWP1) cycling as seen in Figure 40, even though Chiller 1 is not on at this time. Given the cycling of the valves this may indicate the system is being "flushed" as per a routine maintenance event, however, if this were the case the Chiller load (Chiller 2 & 3) could have been reduced as the chilled water is not being delievered to the building (due to bypass) and could be considered a waste of energy.

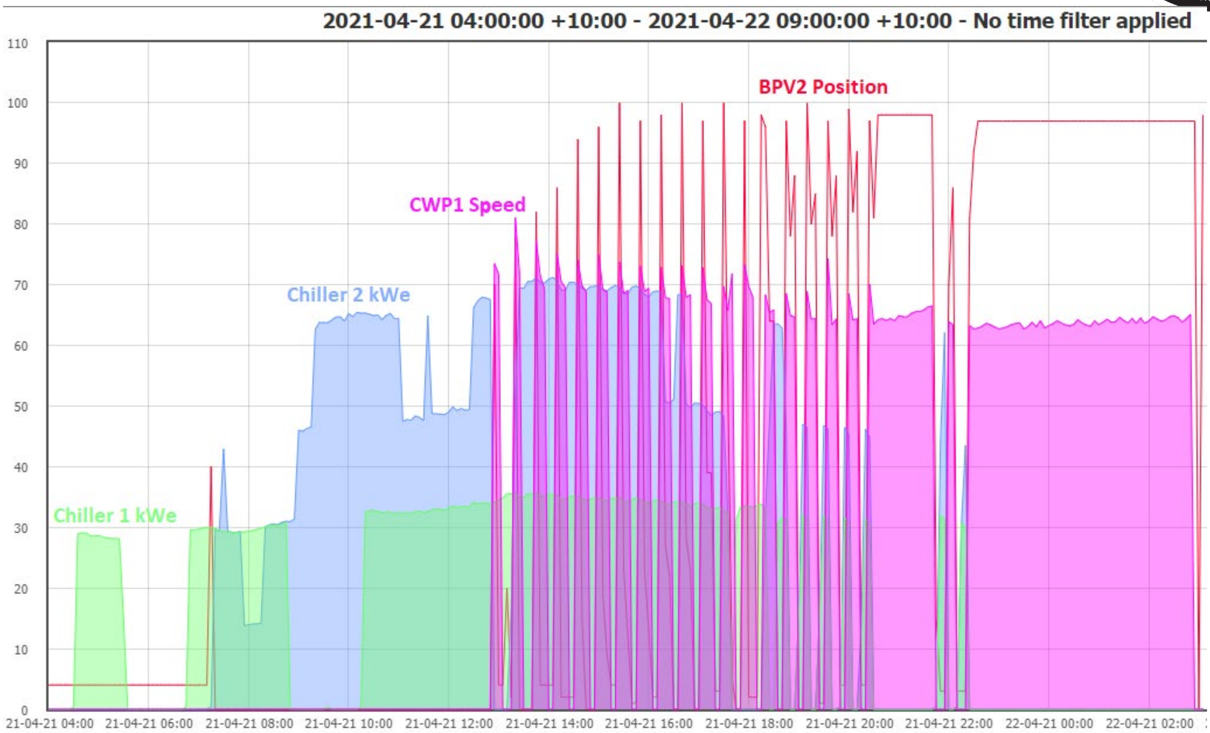


Figure 40 Sentient Trendview showing chiller 1 pump operation during EWS event 21/04/2021

6. FINDINGS AND CONCLUSIONS

Testing SentientSystem at Bolton Clarke's Fernhill Residential Aged Care Living Lab has successfully resulted in:

- a digital twin configured for the building HVAC plant
- thermodynamic performance monitoring calculations running
- comparison of actual vs design chiller performance
- accumulated deviation kW and cost over the 12 months of HVAC operation
- Early warning system (EWS) configured and deployed
- Valid alerts being generated and reported on from the EWS

This has been achieved by completing three steps of the methodology, Model, Monitor and Predict.

ENCOURAGING OUTCOMES

Results from the performance monitoring have shown a number of interesting operational effects of performance that may not have otherwise been noticed.

The comparison against design also indicated that all heaters and chillers except for heater 2 are operating beneath their designed performance. This deviation between actual and design performance was quantified in terms of accumulated excess energy consumption found to be 13.6 MWh for the five months from May to September 2021. This is equivalent to 10.9 tonnes of CO_2 emissions.

Control improvement opportunities identifies were:

- Ensuing chillers and heaters are more utilised at full load, bringing each one to 100% to meet demand before turning on another one.
- Controlling temperature set points to ensure mass flow through the chillers and heaters remains constant at the designed set points.
- More control around managing the building heating and cooling load so that chillers and heaters are not cycled on and off.

SentientSystem's EWS was also successful in alerting on valid events within the HVAC system of this building. Given this is a new building and no events were simulated to test the EWS this is a very good result and shows how useful SentientSystem early alerting systems can be for commercial buildings.

LOW IMPLEMENTATION EFFORT

SentientSystem's capabilities have been configured and deployed quickly with no additional sensors or other additional equipment required, and all activities were performed remotely.

This represents a short turn-around time and low setup cost for establishing a digital twin and receiving performance results and an EWS alerting system.

It should also be noted and acknowledged that: Fernhill is a new building with an owner/operator that has kindly provided timely access to relevant drawings of the HVAC system; the chiller supplier promptly provided design data upon request; and the cooperating BMS provider committed timely effort in setting up remote access and data collection for the project team. These factors helped streamline the digital twin establishment process.

FUTURE WORK

Based on the successful completion of stage two, now covering SentientSystem's Model, Monitor and Predict steps with some control opportunities identified. The final step would be to starting to apply these control strategies to complete SentientSystems Optimisation step. Further optimisation of the system would also involve investigation and confirmation of control deficiencies and to develop and test continuous commissioning routines

This step would include SentientSystem being integrated with the BMS so that the defined algorithms would be able to control the HVAC plant and optimise for efficiency performance in real time ensuring the highest COP possible is being achieved.

References

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[2] Y. G. X. R. W. a. J. W. S. R. West, “Automated fault detection and diagnosis of HVAC subsystems using statistical machine learning,” *12th International Conference of the International Building Performance Simulation Association,* 2011.

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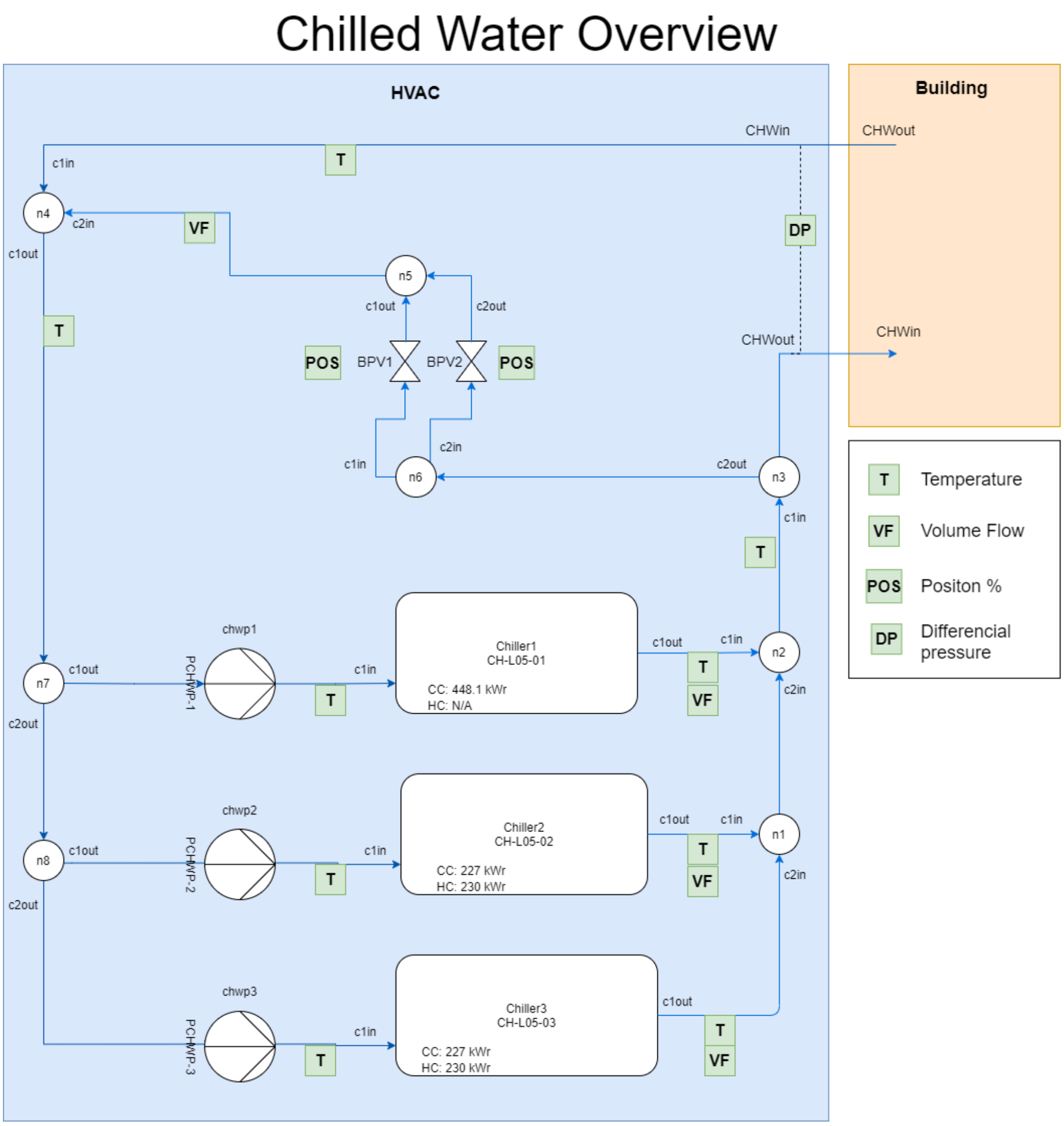
Appendices


Chilled Water Overview
HVAC
Building
CHWin
CHWout
CHWout
CHWin
T
c1in
n4
c2in
VF
c1out
DP
n5
c1out
c2out
POS
BPV1
BPV2
POS
c1in
n6
c2in
c2out
n3
c1in
chwp1
n7
c1out
PCHWP-1
c1in
Chiller1
CH-L05-01
CC: 448.1 kWr
HC: N/A
c1out
c1in
n2
c2in
VF
c2out
chwp2
n8
c1out
PCHWP-2
c1in
Chiller2
CH-L05-02
CC: 227 kWr
HC: 230 kWr
c1out
c1in
n1
c2in
c2out
chwp3
PCHWP-3
c1in
Chiller3
CH-L05-03
CC: 227 kWr
HC: 230 kWr
c1out
T Temperature
VF Volume Flow
POS Positon %
DP Differencial pressure

Hot Water Overview