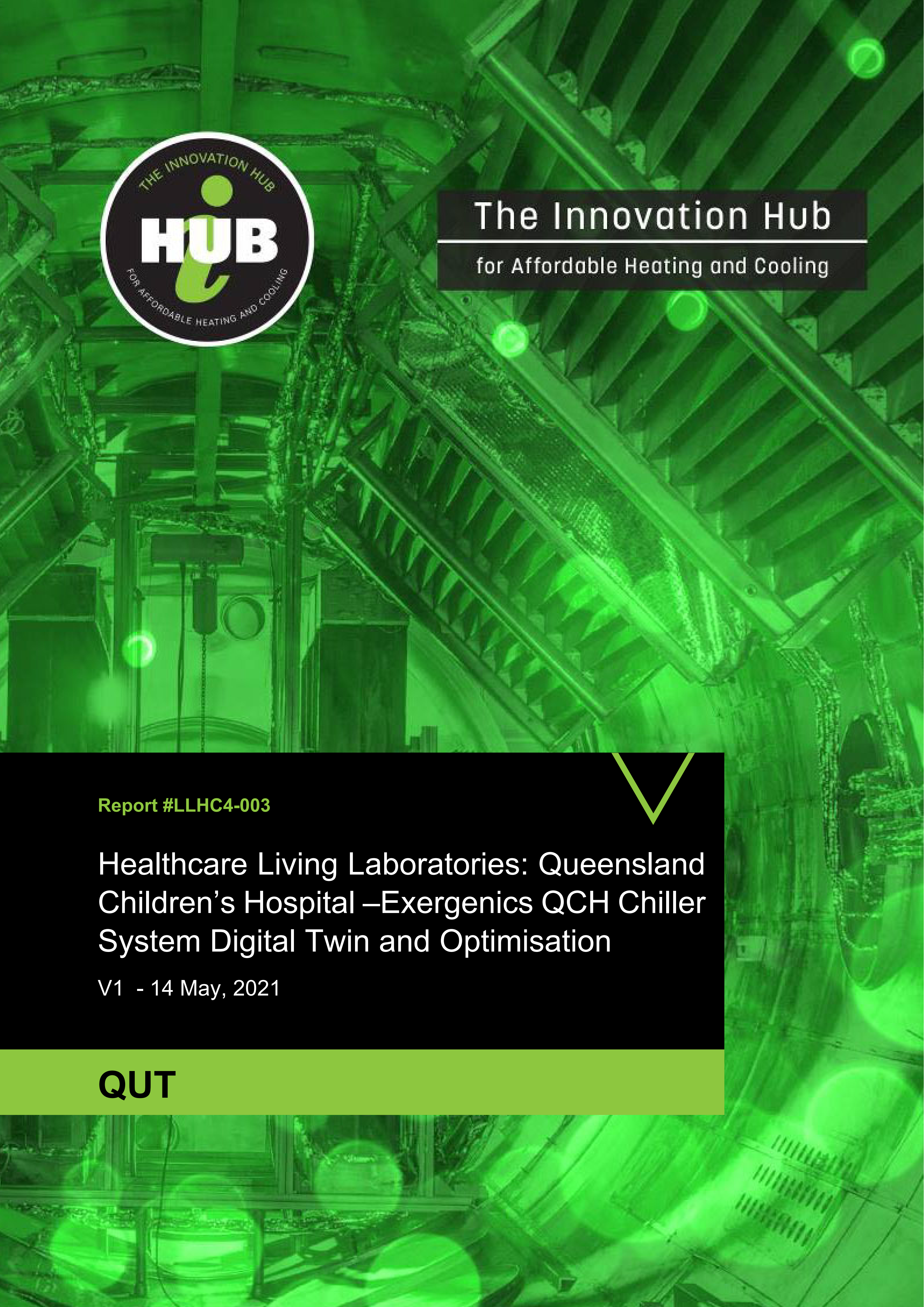

The Innovation Hub

for Affordable Heating and Cooling

Report #LLHC4-003

Healthcare Living Laboratories: Queensland Children's Hospital –Exergenics QCH Chiller System Digital Twin and Optimisation

V1 - 14 May, 2021

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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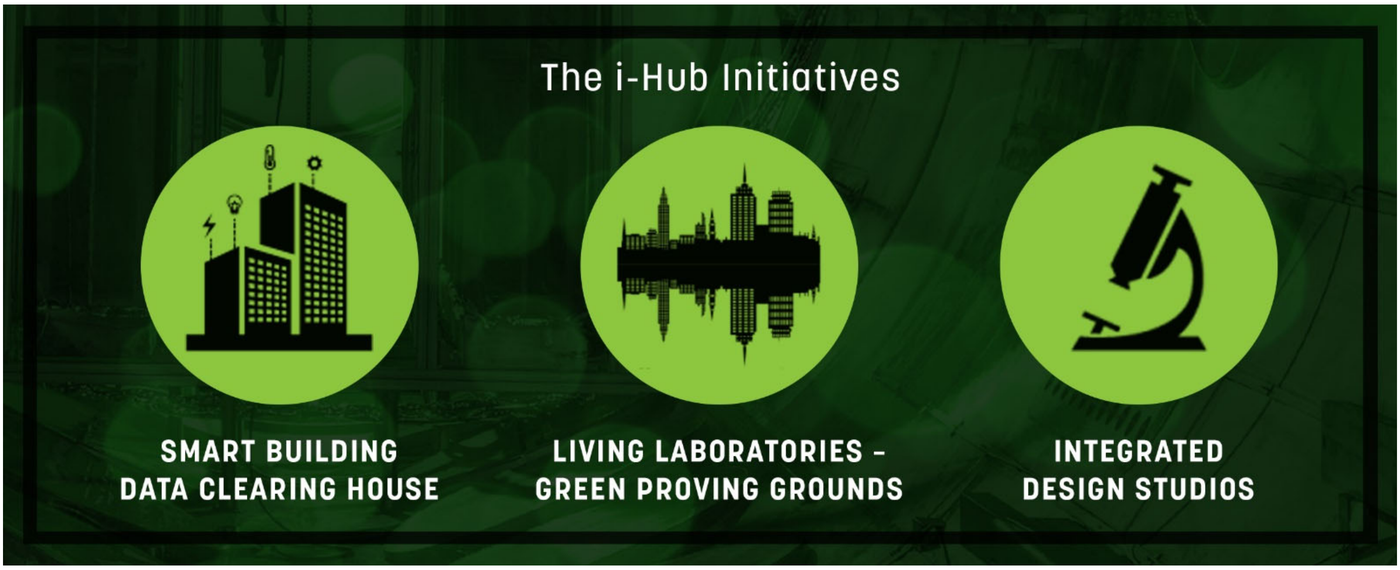

Healthcare Living Laboratories: Queensland Children's Hospital – Chiller System Optimisation

The Living Laboratory in Queensland Children's Hospital (QCH) will support the hospital 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 (patient 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 QCH is a chiller system of 6 chillers. Through the operation optimisation of the chiller system, energy use and peak demand can potentially be reduced as well as providing controlling operational cost and limiting impact to the electricity network.

Lead organisation

Queensland University of Technology (QUT)

Project commencement date

01/06/2019

Completion date

30/06/2022

Date published

14/05/2021

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1 INTRODUCTION

1.1 Background

Heating, ventilation, air conditioning and refrigeration (HVAC&R) is essential in most settings to ensure a pleasant, comfortable, and safe work environment. In commercial buildings around the world, 70% of energy usage and 63% of greenhouse gas emissions are estimated to be contributable to heating, cooling and ventilation. HVAC typically accounts for 40% to 50% of the total energy bill for businesses and commercial buildings. Inefficient HVAC&R system may lead to higher than expected electricity bills and continuous breakdowns.

HVAC system accounted for 52% of healthcare buildings energy use, based on a US study in 2012 (Figure 1, [1]). In Queensland, the main energy use of a HVAC system is for the chiller system. With optimised chillers' operation, multi-faceted benefits can be realised, e.g. cost control, energy use, peak demand and carbon footprint.

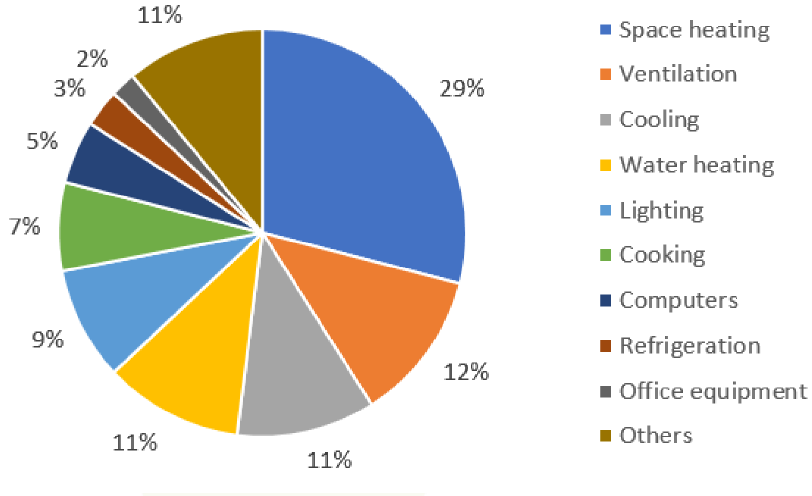

Figure 1 US healthcare building energy breakdown by end-use

1.2 Technology Overview

Exergenics' chiller system optimisation technology is named PlantScore™. As Table 1 shows, there are three major steps in the optimisation process. The first step is to acquire data for chillers, pumps and cooling towers. The data sets are temperature, flow rates, pressure and energy data. In the next step, the data will be fed into advanced machine learning algorithms to build a working mathematical model for the physical plant. The algorithms will loop through numerous possible scenarios and identify the best way to control the chiller system. In the last step, a set of control recommendations will be provided to improve the plant's efficiency. Also, potential energy and cost savings will be estimated with each recommendation.

Table 1 Exergenics optimisation process

Step	Name	Purpose
1	Data collection	Collect temperature, flow rates, pressure and energy data; site equipment drawings and layout.
2	Building a digital twin	Advanced machine learning algorithms are used to train data to build a working mathematical model of a physical plant
3	Chiller system optimisation	A set of implementable items is recommended for improving plant's operation

2 TEST DESCRIPTION

2.1 Site Descriptions

The Queensland Children's Hospital precinct is comprised of three buildings:

- the Main Hospital (MH) Building;
- the Centre for Children's Health Research (CCHR); and
- the Central Energy Plant (QCH EP) Building.

This central energy plant supplies the hospital and research facility with their chilled water needs for air conditioning. The chiller system comprises one 1,100kWr low-load swing variable-speed drive (VSD) low-voltage electric centrifugal chiller, and five VSD low-voltage electric centrifugal chillers of 3,315kWr each, with a full-load minimum coefficient of performance (COP) of 6.7. These are configured in an N+1 redundancy arrangement. Combined, the total chilled water capacity of the central energy plant is up to 20MWr.

The QCH water cooled chillers are shown in Figure 2. The six water cooled chillers are shown (partially) in the figure. Information about those chillers is provided in Table 2.

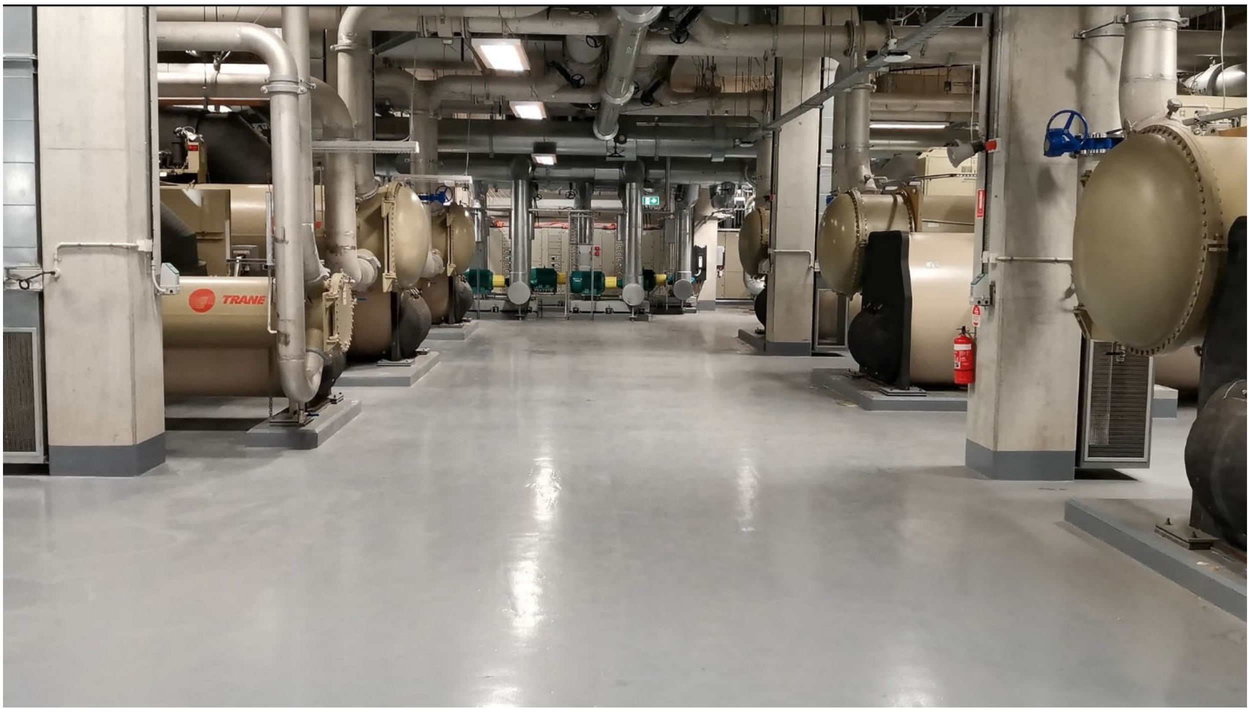

Figure 2 QCH site

Table 2 Chillers at site

Item	Description	Rating
1	VSD low voltage electric centrifugal chiller (Chiller 3)	Trane 1100kWr
2	VSD low voltage electric centrifugal chiller (Chiller 4)	Trane 3315kWr
3	VSD low voltage electric centrifugal chiller (Chiller 5)	Trane 3315kWr
4	VSD low voltage electric centrifugal chiller (Chiller 6)	Trane 3315kWr
5	VSD low voltage electric centrifugal chiller (Chiller 7)	Trane 3315kWr
6	VSD low voltage electric centrifugal chiller (Chiller 8)	Trane 3315kWr

2.2 Tested Item Description

The item to be tested is PlantScore^{TM} chiller system digital twin and optimisation technology, supplied by Exergenics. The optimisation process and description are provided in Table 1.

3 METHODOLOGY

This research uses quantitative methods, utilizing historical data, experimental data (in-situ data) and energy models.

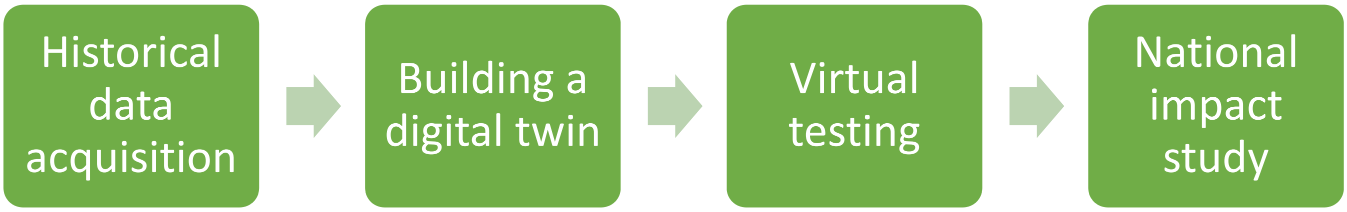

Figure 3 Test stages

The test consists of 4 steps as shown in Figure 3.

Step 1: historical data acquisition

A year of QCH chiller system data are used. The dataset includes chillers’ energy use, refrigeration, water flow rates for chillers and cooling towers etc (Item 1 in Table 1).

Step 2: building a digital twin

A set of historical data has been used to train machine learning algorithms that build a working mathematical model of the physical chiller system. Another optimisation engine looped through numerous possible scenarios (such as temperature events, load increase) that could be experienced by the chiller system, learning how to best control the chiller system (Item 2 in Table 1).

Step 3: virtual testing

A reserved randomised set of data has been used to test the accuracy of the digital twin. The reserved dataset is different from the dataset used to build the digital twin. This digital twin and optimisation results form part of the report (Section 4).

Step 4: national impact study

The QCH results are extrapolated to Australian major hospitals to reveal its national impact, considering different climate zone scenarios and to the extent possible based on available energy and demand data.

4 TEST RESULTS

PlantScore™ simulates the operations of chillers, pumps and cooling towers within a chilled water plant. Historical data is used to train algorithms which represent each piece of equipment in the plant, and then a wider model emulating energy and fluid flows is constructed.

The model is seeded with a range of conditions, and an optimisation algorithm is used to determine the ideal combination of equipment to deliver the required cooling, while maximising chilled water plant efficiency or Coefficient of Performance (COP). The results are then collated and described as controls recommendations which are listed in Section 5.2.

The optimised strategy is simulated for a full year of operation and compared to historical data to estimate the energy and peak demand reductions associated with each of the control strategy recommendations.

4.1 Quantitative Results

Estimated energy and peak demand reductions are presented in Table 3. The total yearly energy saving is around 432MWh and the largest peak demand reduction is 108.29kVA (0.9 p.f.) or 99.45kVA (0.98p.f.) for Jan 2020.

Table 3 Estimated energy and peak demand reductions

Month	Estimated kWh Saving	Estimated Peak Demand Reduction (kVA) power factor (p.f.) = 0.9	Estimated Peak Demand Reduction (kVA) power factor (p.f.) = 0.98
May-19	33,328.91	85.96	78.94
Jun-19	21,537.63	87.78	80.61
Jul-19	22,457.40	87.02	79.92
Aug-19	18,099.93	95.10	87.34
Sep-19	25,516.49	102.64	94.26
Oct-19	40,773.25	102.64	94.26
Nov-19	40,559.47	104.43	95.91
Dec-19	51,449.70	107.15	98.40
Jan-20	57,942.79	108.29	99.45
Feb-20	48,704.63	100.10	91.93
Mar-20	31,322.45	95.71	87.90
Apr-20	40,564.45	89.87	82.53
Total:	432,257.10	**Max reduction = 108.29**	**Max reduction = 99.45**
Mean Monthly	36,021.43		

4.2 Cost Effectiveness

The energy savings can be presented in terms of financial values. Considering $0.15/kWh, Table 4 shows the monthly bill savings from energy use reduction. The yearly energy charge saving is $62,581.

Table 4 Estimated bill savings

Month	Estimated Bill Savings $0.15/kWh	
May-19	$	4,999.34
Jun-19	$	3,230.64
Jul-19	$	3,368.61
Aug-19	$	2,714.99
Sep-19	$	3,827.47
Oct-19	$	3,827.47
Nov-19	$	6,115.99
Dec-19	$	6,083.92
Jan-20	$	7,717.46
Feb-20	$	8,691.42
Mar-20	$	7,305.69
Apr-20	$	4,698.37
Total:	**$**	**62,581.37**
Mean Monthly	**$**	**5,403.21**

4.3 Environmental Benefits

Table 5 presents the estimated monthly CO_2 emission reduction from May 2019 to April 2020. The yearly total reduction is around 350 tons with a mean monthly reduction of 29 tons.

Table 5 Estimated emission reduction

Month	Estimated Emissions Reduction (tC02-e)
May-19	27.00
Jun-19	17.45
Jul-19	18.19
Aug-19	14.66
Sep-19	20.67
Oct-19	33.03
Nov-19	32.85
Dec-19	41.67
Jan-20	46.93
Feb-20	39.45
Mar-20	25.37
Apr-20	32.86
Total:	**350.13**
Mean Monthly	**29.18**

The above table has used Queensland emission factor 0.81 kg CO_2-e/kWh [2].

5 SUMMARY FINDINGS AND CONCLUSIONS

5.1 Overall Technology Assessment

When building the digital twin and training the model we perform anomaly detection, and include data such as wet bulb temperature, chiller energy consumption (kW), pump and fans energy consumption (kW), cooling requirement, and chilled and condenser water temperatures and flow rates (where available).

The model takes the Cooling Requirement (from 0 kW to the system capacity, or in this case around 9000 kW of cooling since the system is oversized) and outputs optimal chiller loading and energy consumption of the plant (including pumps, fans, chillers etc). The energy consumption of the chillers themselves is calculated from their loading level and COP.

A randomised holdout portion of 20% of the complete dataset was used for validation of the model. The model's Mean Absolute Error (MAE) is 30.25 kW, which is calculated by taking the average of all predicted errors for each cooling load for the year long data set. These error values reflect the error in the chiller COP values (all model outputs), as these have the largest impact on the simulated system energy consumption.

5.2 Recommendations

Table 6 lists the control recommendations resulting from the optimisation and simulation. Each recommendation can be implemented individually, however for best results it is recommended that they be implemented together.

Table 6 Summary of control recommendations and simulated savings potential

		Simulated savings potential (%)	
#	**Recommendations**	**Energy - kWh**	**Peak Demand - kVA**
1	Chiller staging	2.8%	2.6%
2	Dynamic condenser water temperature algorithm	1.8%	1.5%
3	Chiller load balancing	2.5%	1.3%
	Total	**7.1%**	**5.4%**

The three recommendations are subsequently described in the following sections.

5.2.1 Chiller staging

'Chiller staging' involves the modulation of «stage up» and «stage down» demand setpoints to turn on and off chillers at certain cooling loads (as shown in Table 7 and Table 8).

Table 7 Stage up demand setpoints

	Stage up demand setpoints
Stage 1 **Stage 2**	Above 1100 kW$_r$
Stage 2 **Stage 3**	Above 3250 kW$_r$
Stage 3 **Stage 4**	Above 4400 kW$_r$
Stage 4 **Stage 5**	Above 6600 kW$_r$
Stage 5 **Stage 6**	Above 9900 kW$_r$

Table 8 Stage down demand setpoints

	Stage down demand setpoints
Stage 2 **Stage 1**	Below 960 kW$_r$
Stage 3 **Stage 2**	Below 2850 kW$_r$
Stage 4 **Stage 3**	Below 3850 kW$_r$
Stage 5 **Stage 4**	Below 5780 kW$_r$
Stage 6 **Stage 5**	Below 8660 kW$_r$

The staging strategy described in Table 9 only pertains to the stage up/stage down demand set points, described in terms of cooling load (kWr). All other controls should be maintained or adjusted as appropriate to align with the new staging strategy, including:

- Duty pump set enabled
- Minimum de-coupler flow, or
- Bypass valve position
- Common return water minimum temperature
- Staging runtime
- Chiller in fault or fails to start
- Pump set runtime before being disabled
- Cooling call
- Optimum start / stop

Table 9 Chiller staging strategy

	Chiller 3 (Low load)	Chiller 4 - 8 (Lead)	Chiller 4 - 8 (Lag)	Chiller 4 - 8 (Lag)	Chiller 4 - 8 (Lag)
Stage 1	Enabled	Disabled	Disabled	Disabled	Disabled
Stage 2	Disabled	Enabled	Disabled	Disabled	Disabled
Stage 3	Enabled	Enabled	Disabled	Disabled	Disabled
Stage 4	Disabled	Enabled	Enabled	Disabled	Disabled
Stage 5	Disabled	Enabled	Enabled	Enabled	Disabled
Stage 6	Disabled	Enabled	Enabled	Enabled	Enabled

5.2.2 Dynamic condenser water temperature algorithm

The 'Dynamic condenser water temperature algorithm' is a variable approach temperature, which accounts for the ambient wet bulb temperature and cooling load.

The condenser water temperature algorithm described below is a 'dynamic approach' algorithm, considering both the wet bulb temperature and cooling load.

C_t = Condensing water temperature setpoint (°C)

kW_r = Cooling load (kW)

W_t = Ambient wet bulb temperature (°C)

For $kW_r < 1150$ kW (Stage 1)

$C_t = W_t + 13.359 – (0.0032 \times kW_r)$

For $1150 \leq kW_r < 3950$ kW (Stage 2 - 3)

$C_t = W_t + 11.361 – (0.0019 \times kW_r)$

For $kW_r \geq 3950$ kW (Stages 3 - 6)

$C_t = W_t + 4$

To ensure that chillers are operating within their manufacturer specific safe operating ranges, upper and lower limits should be placed on the algorithm above to ensure that condenser water inlet temperatures do not fall outside this range. Where the plant is configured with a common condenser water header, the upper and lower bounds should be restricted to the largest possible range incorporating each chiller than is enabled in the current stage.

5.2.3 Chiller load balancing

'Chiller load balancing' utilises the demand limiting functionality of a chiller or chillers to ensure that when multiple chillers are operating, each of them is generating the correct amount of chilled water.

Load balancing is best achieved by employing the demand limiting functionality of one or more chillers. Load balancing is used when there are two or more chillers with different cooling capacities and efficiencies operating at the same time. Load balancing is intended to ensure that each chiller is generating enough chilled water to satisfy the cooling requirements, while operating at loadings which maintain the highest chilled water plant system COP. Load balancing is not required in chilled water plants containing identical chillers and is only required at high cooling loads. Chiller load balancing in this plant is required in Stage 3 (Table 10), as there are multiple chillers operating of different sizes and efficiencies.

Table 10 Stage 3 demand limits

Stage	kW_r	Demand limit
3	3300	72.8%
	3350	74.1%
	3400	75.2%
	3450	76.5%
	3500	77.8%
	3550	79.0%
	3600	80.2%
	3650	81.4%
	3700	82.6%
	3750	83.8%
	3800	85.1%
	3850	86.3%
	3900	87.6%
	3950	88.6%
	4000	89.9%
	4050	91.2%
	4100	92.4%
	4150	93.4%
	4200	94.7%
	4250	95.9%
	4300	97.1%
	4350	98.3%
	4400	99.5%

As Chillers 4 – 8 are identical, Chiller 3 is the only chiller in which demand limiting will need to be enabled to achieve the correct load balancing.

A summary of demand limits (%) for Chiller 3, based on the cooling load (kWr) is shown below. Depending on the current capability of the Chiller High-Level Interface (HLI) to select demand limiting setpoints, it may be most cost effective to only implement the number of demand limiting setpoints which are currently available.

5.3 National Impact Study

As temperature rises, there is a need of having space cooling which is often provided by chiller systems. Figure 4 shows the correlation between Brisbane cooling degree days and QCH chillers' energy use.

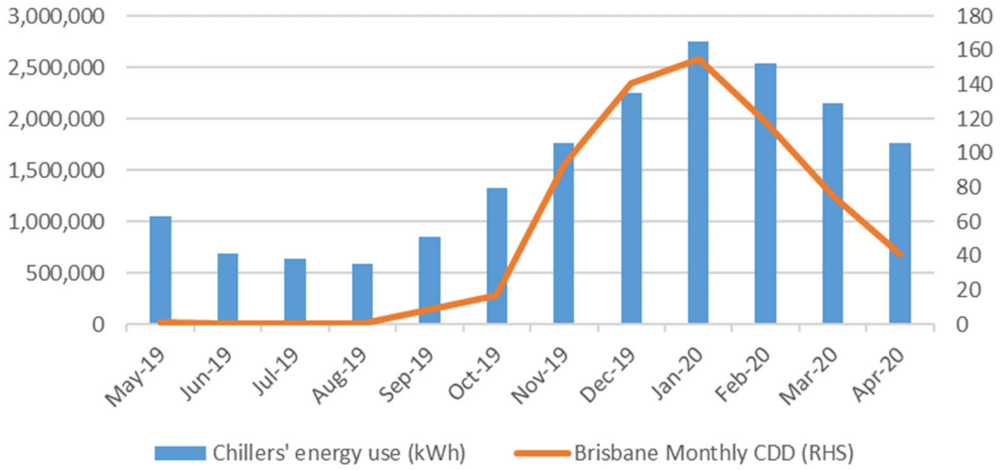

Figure 4 Monthly chiller system energy use and cooling degree days

The following facts and assumptions are used to estimate potential chiller systems' energy and environmental impact if the digital twin and optimisation technologies are applied to all Australian capital cities hospitals:

- Electricity is the main energy source for air conditioning cooling across Australia
- Cooling degree days are associated with electricity use for cooling at hospitals
- 22^{O}C is used as the reference temperature to calculate cooling degree days for capital cities
- Hospitals in Australian capital cities have similar cooling technologies
- If Exergenics digital twin and optimisation technology is applied to all hospitals at Australian capital cities, a similar level of energy saving per floor space per cooling degree day can be achieved.

Table 11 shows the national impact estimates if Exergenics digital twin and optimisation technologies are applied to all hospitals in Australian capital cities. The highest energy saving and CO2 emission reduction would occur in Sydney and Darwin due to large hospital spaces in Sydney and high cooling demands in Darwin.

Table 11 National impact estimates

	Cooling degree days [3]	**Gross floor areas ('000m^2)** [4]	**Potential electricity savings (MWh)**	**Emission factor (kg CO2-e/kWh)** [2]	**CO2-e reduction (tons)**
Brisbane	649.23	1,520	3,510	0.81	2,843
Sydney	292.95	3,075	4,263	0.81	3,453
Canberra	162.40	229	105	0.81	85
Melbourne	105.60	2,144	713	0.98	699
Hobart	26.00	160	12	0.17	2
Adelaide	206.70	897	785	0.43	338
Perth	500.60	1,400	2,336	0.68	1,589
Darwin	2,265.75	121	6,341	0.62	3,932
Total		**9,546**	**18,730**		**13,478**

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