ARBS Foundation

Dynamic Simulation Study

Comparison of Chilled Beam Systems

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CONTENTS

1 EXECUTIVE SUMMARY

The results of this research commissioned by the ARBS Foundation has led to a series of ground breaking findings. It builds on an earlier study that compared the performance of commonly used Heating, Ventilation and Air Conditioning (HVAC) systems, namely Variable-Air-Volume (VAV), Under Floor Air Distribution (UFAD) and Passive Chilled Beam (PCB) systems from an energy efficiency perspective using dynamic simulation analysis.

This current research paper provides a detailed study of Active Chilled Beam (ACB) systems, and compares the performance of two chilled water plant configurations:

1. ***Standard***: using a single Chilled Water Plant (CHWP) of multiple chiller configuration, which uses a Heat eXchanger (HX) to deliver High Temperature CHilled Water (HTCHW) to Active Chilled Beams (ACBs) at the zone level, and
2. ***High Temperature Chiller***: using a dedicated chiller to generate and distribute HTCHW to the ACBs at zone level. This chiller will run at a much higher COP for this duty, and allows the overall HVAC system to function more efficiently

Both systems use a central Air Handling Unit (AHU), that has a function similar to that of a Dedicated Outside Air System (DOAS), which delivers de-humidified and conditioned air to the ACBs at zone level. In keeping with recent design trends for such systems in Australia, the AHU is set to recirculate air and includes an economy cycle that is carefully controlled (further details are provided in the body of the report).

Since the first evaluations, carried out two years ago, the fundamental change in this exercise is the recognition of the fact that heat outputs from lighting and IT equipment, mainly computers, has decreased significantly, as outlined in the National Construction Code (NCC) 2019. Building geometry is identical to that used in the previous study, however, construction systems, window systems, internal loads (noted above), thermostat settings and infiltration rates have been changed to reflect the requirements of the National Construction Code 2019 (NCC2019) of Australia, Vol 1. The new requirements for the Verification Methods using energy simulation require a test of thermal comfort measured using PMV, to be maintained between ±1 for 95% of the conditioned floor area for 98% of operating hours, as per code definitions. These requirements required the building enveloped to be improved beyond the minimum Deemed-To-Satisfy requirements, particularly the window system performance.

The aim of the study is to take advantage of modern system design and control practise, compared to that which might have been popular a decade or so ago. The intent is to analyse the energy efficiencies available by taking advantage of improved control functionality available from modern digital control at each of the HVAC loops. Part load performance characteristics have been held the same between the two runs, as far as possible.

Table 1: Summary of predicted Chilled Beam HVAC system energy intensities

SYSTEM TYPE →	*STD HX ACB*		*Dedicated HTCH ACB*	
HVAC END USE ↓	*Electricity [kWh]*	*Natural Gas [kWh]*	*Electricity [kWh]*	*Natural Gas [kWh]*
HVAC totals	184,251	68,168	155,323	57,056
Energy intensity, kWh/m2-yr	*28.0*	-	*23.6*	-

The predicted energy efficiency outcomes for each of the two system configurations, the Standard (STD) and High Temperature Chiller (HTCH) variants are summarised in Table 1 using system configurations and control strategies detailed in this report. They have all been modelled for the Sydney climate.

The results indicate a 16% predicted reduction in system energy consumption between the Standard (STD) and High Temperature Chiller (HTCH) variations of the modelled Active Chilled Beam (ACB) HVAC system. The predicted results are logical. There are energy savings in the chiller energy consumption for the system with the Dedicated High Temperature Chiller (HTCH). Some of these savings are offset by additional pumping energy required to move larger quantities of high temperature chilled water around the system. In the following sections, this report provides a break down of the predicted energy consumption for each HVAC sub-system (eg., pumps, fans, chillers etc).

The predicted performance for both configurations of the ACB systems modelled above is estimated to be within the operational requirements of a 5 to 5.5 star Base Building NABERS rating for office buildings.

A striking result outcome of this study is the fact that the NCC2019 simulation parameters specified have resulted in the predicted hourly thermal demand being similar in quantum to that of the predicted hourly cooling loads. More detail is provided in the body of the report.

The study would be of interest to the HVAC industry in that it has been carried out by experienced practising engineers, involved in the design, specification and ongoing monitoring of HVAC systems as installed in energy efficient buildings.

2 INTRODUCTION

Chilled Beam air-conditioning systems were a rarity in Australia until around 2005 when there was heightened awareness about energy efficiency, air-quality and greenhouse gas emission reduction. There are a few examples of Passive Chilled Beam (PCB) systems with 100% once through outside air cycles, however, the majority of newer projects seem to adopting an Active Chilled Beam (ACB) configuration with recirculated air. This may be due to higher solar radiation loads in Australia compared to the European climates where Passive Chilled Beam systems were developed.

The system design configuration adopted and tested in this research project differs from many designs in Australian buildings that the authors have had the opportunity to review. The configuration presented here uses an Air Handling Unit (AHU), in a manner similar to a Dedicated Outside Air System (DOAS) to deliver dehumidified and conditioned primary air to the Active Chilled Beams (ACBs). However, it is important to note that this is not a true DOAS in that the AHU is designed to recirculate return air from conditioned zones.

Active Chilled Beams (ACBs) are installed at the zone level, and have cooling and heating coils to cater for sensible loads in their respective zones. In thermodynamic terms, the ACBs are equivalent to a four pipe Induction Unit (IU), which have been modelled with an induction ratio of three for this study. This practical configuration allows good control at zone level, and can efficiently, and simultaneously, handle zones with widely differing heating and cooling needs in different parts of the building. The configuration described eliminates potential thermal discomfort issues in differently oriented zones when heating is provided via the heating hot water coil in the AHU only.

This departure from common practise in Australia is in the fact that the DOAS AHU modelled is the primary system component catering for dehumidification. Typically, the primary air supply AHU is designed to provide neutral temperature air supply to the chilled beams, with a control strategy that varies the supply air temperature (SAT) between a wide range in response to a small change in zone air temperature. It is our view that such practise for ACB system design can create an ‘unforgiving’ control requirement, where the sudden, large SAT variation requirement can create control challenges and thermal comfort issues.

In our view, dehumidification is increasing important in many of Australia’s coastal cities, where the ocean may moderate ambient temperatures, but there can be many low temperature, high humidity hours (as in Sydney, for which this study is carried out). The challenges posed by these conditions on HVAC systems are not revealed by studying performance only at the design day condition.

Two different CHilled Water Plant (CHWP) configurations have been modelled in this study. In the first or Standard (STD) configuration the Active Chilled Beams (ACB) are supplied High Temperature Chilled Water (HTCHW) via a Heat eXchanger (HX). In the second configuration, the HTCHW is supplied by a dedicated High Temperature Chiller (HTCH). Since this dedicated chiller is able to carry out it’s cooling duty at a higher efficiency compared to the chillers in the first (HX) configuration, resulting in lower electricity consumption for the total chilled water plant.

From an academic viewpoint there are various published papers detailing the performance of Chilled Beam HVAC systems. However, from carrying out a short literature review the authors were not able to find a study with similar rigor in modelling the HVAC componentry and control descriptions, and which compared the energy intensities for variations of system configuration of the same system type, in this case an ACB system for the same building. We have modelled these

two ACB system configurations as incorporated in a hypothetical building that has been described with a high performance building envelope, internal loads and operational schedules for the Australian National Construction Code 2019 Section-J.

The study does not seek to test the impact of changes to the building envelope; therefore identical building fabric descriptions, internal loads, operational schedules and thermostat settings have been used to test the performance of both ACB system configurations. The systems have been applied to a 10 storey high tower building located in Sydney, with identical (theoretical, no amenity zones are modelled) floor plate organisation. For modelling purposes, each floor is divided into five thermal zones; four perimeter zones in each cardinal orientation, and one interior zone. These "whole building" simulation models are used to predict the annual energy performance for each of the HVAC systems. The results have been reviewed and summarised, and conclusions are reported here. The intention has been to present the energy intensities as per the modelling results without 'rating' the systems in any order.

The dynamic simulation analysis is carried out using the well respected ***EnergyPlus*** (https://energyplus.net/) simulation engine developed and maintained by the USDOE (US Dept of Energy). The simulation engine is freely available in the public domain and is extremely well documented, see https://bigladdersoftware.com/epx/docs/. EnergyPlus combines[1] the best features of DOE-2.1E and BLAST, the previous generation of dynamic simulation engines developed and maintained by USDOE from the 1970s till around 2000. Many well respected research laboratories and universities from around the world have contributed to it's development, and it is understood that well over 200 million US dollars have been invested to date. For this study we have used the DesignBuilder GUI (https://www.designbuilder.co.uk/) to access the power of EnergyPlus.

The study is also somewhat unique in that this comparison (in Australia) has been carried out by a team of practising consulting engineers with practical experience and expertise in the design, review and delivery of energy efficient HVAC systems in larger buildings. Many studies focus on the energy efficiency of the building envelope (which is the first step) but do not consider the practical limitations of systems and components when modelling environmental control (HVAC) systems. Predicted results in such cases can lead to optimistic outcomes. A concerted effort has been made to incorporate practical control strategies as far as possible, and incorporate system and component limitations into the modelled system representations. Further detail on each HVAC loop is provided in the following sections.

[1] Crawley, D. B., Lawrie, L. K., Pedersen, C. O., Liesen, R. J., Fisher, D. E., Strand, R. K., ... Huang, Y. J. (1998). *Beyond DOE-2 and BLAST: EnergyPlus, the New Generation Energy Simulation Program*. In Commercial Buildings: Technologies, Design, and Performance Analysis: Proceedings of the 1998 Summer Study on Energy Efficiency in Buildings (Vol. 3, pp. 3.89-3.104). Washington, DC: ACEEE

3 METHOD

3.1 BUILDING MODEL DESCRIPTION

A hypothetical building model (similar to the reference building type "A" used for the National Construction Code, Section-J stringency analysis developed by Team Catalyst for other projects) has been used. The general arrangement of the building model is described below:

- square floor plate, 30m on all sides
- oriented to cardinal directions
- greenfield site (no shading from adjacent buildings)
- 10 levels (ground plus 9 levels), plus an unconditioned basement floor
- a floor-to-floor height of 4.0 m, ceiling at 2.7m
- 2m high vision glazing at 700mm sill height (façade WWR = 50%)
- high performance glazing systems, SHGC=0.26 and U=3.0 W/m2-K
- external walls modelled to be R1.0
- 200mm concrete roof construction insulated to R3.7
- exposed floors modelled as uninsulated slab
- 200mm thick concrete floors

It is noted that the building envelope (or building fabric) for this hypothetical building is capable of high performance outcomes. This level of specification can allow an office 'base building' in Sydney to easily perform to a 5 star NABERS Energy rated building (see www.nabers.com.au), and may even allow performance at 5.5 stars with careful commissioning and monitoring.

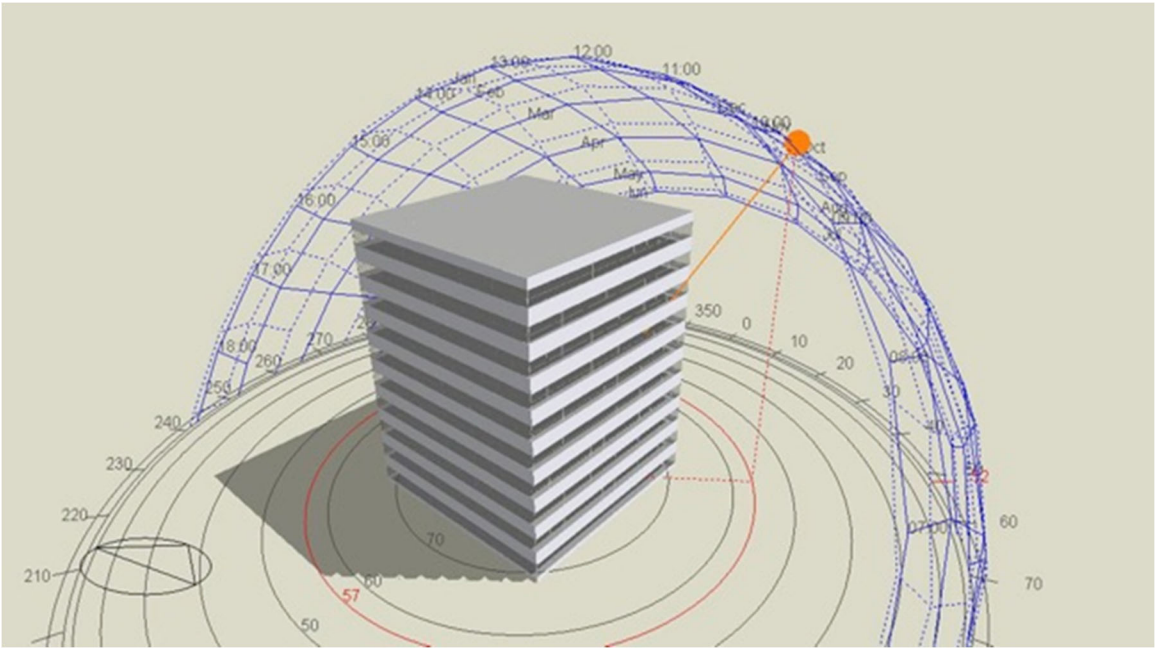

Figure 1: 3D visulation of the building with superimposition of annual sunpath for Sydney

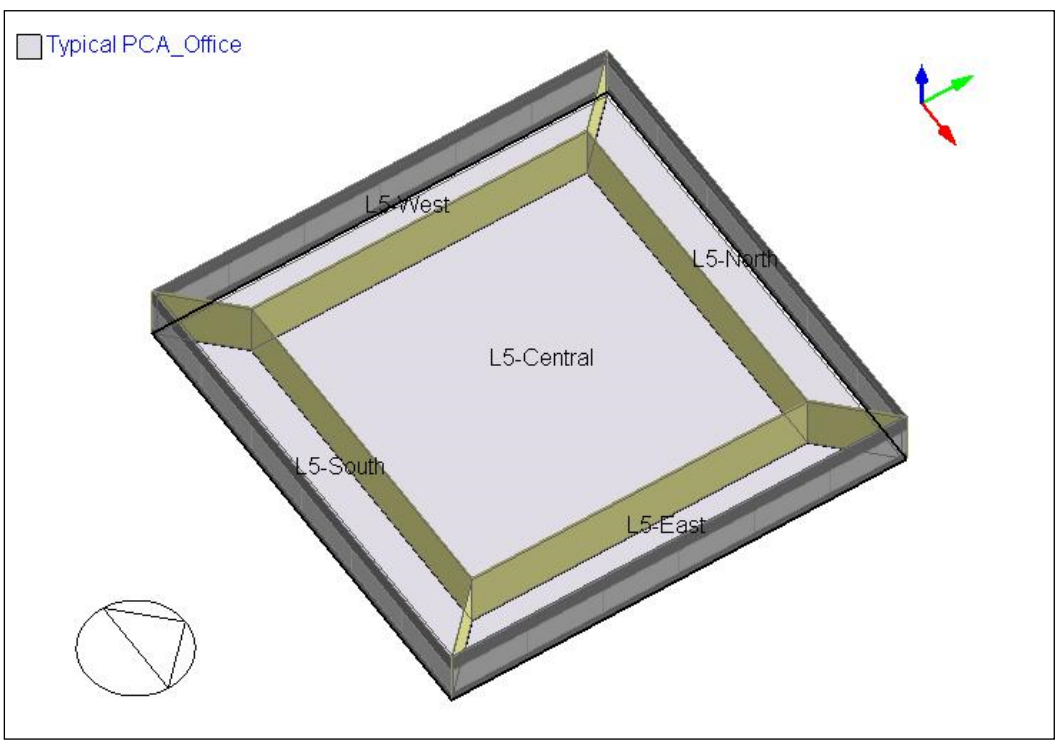

Figure 2: Zoning for typical floors; the zones are separated by "virtual walls", ie., heat transfer boundaries, typically used in HVAC design for open plan offices; amenity zones not modelled

3.2 IMPACT OF NCC2019

Since our last report was delivered to ARBS (AUG2018), there has been a considerable change to the energy efficiency provisions in Section-J of the NCC2019 upgrade. To ensure that the study is useful for Australian Engineers, modelling inputs and outputs have been aligned to these newer requirements. Table 2 list the design values (maximums) for internal loads. These values are used for sizing, and are modified by appropriate hourly schedules for the energy simulation analysis.

Table 2: Internal loads

Design Internal Load	• Occupancy density 1 per 10 m^2 as per PCA Guide (2012) Standard office occupancy * • Occupant heat load of 130 watts per person (55W latent/ 75W sensible) • *Lighting load: 4.5 watts per m^2, and* • *Equipment load: 11 watts per m^2 (as per current NCC Section-J allowance for modelling) ** *
Outside Air Rate	10 L/s per person as per AS 1668.2 without filtration for offices
Indoor Temperature	22.5C +/- 1.5 (generally 21C for heating and 24C for cooling)
Design Criteria	0.4% confidence level, ASHRAE monthly design criteria, dry bulb priority (listed in a later section of this report)

* the maximum weekday occupancy is modelled at 70% (see *Table 3*)

** loads in italics are the changes/reductions in modelling inputs required by NCC2019 Vol 1 Section-J JV3

A striking result outcome of this study is the fact that the NCC2019 simulation parameters specified have resulted in the predicted hourly thermal demand being similar in quantum to that of the predicted hourly cooling loads (see Figure-1). This is a significant change from NCC2016 simulation predictions used in the earlier study. This change is due to the combination of the drop in internal loads that reflect current practice and include:

- A 50% reduction in design lighting loads from 9 to 4.5 W/m2
- Equipment load reduction from 15 W/m2 to 11 W/m2, and
- Possible reduction in solar heat gain through glazing systems due to increased stringency (depends on building geometry)

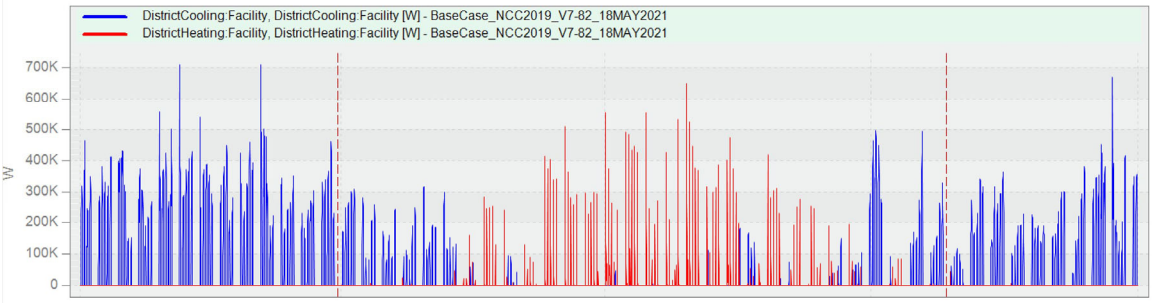

Figure 3: Predicted hourly cooling (blue) and heating (red) loads for the test building (Note: these are hourly thermal loads, and do not reflect system energy consumptions)

Table 3: Operational schedules based on NCC2019

Weekdays	NCC2019 Class 5 Schedule			
Time Period	**Occupancy**	**Lighting**	**Equipment**	**HVAC Operation**
0000-0100	0%	15%	25%	Off
0100-0200	0%	15%	25%	Off
0200-0300	0%	15%	25%	Off
0300-0400	0%	15%	25%	Off
0400-0500	0%	15%	25%	Off
0500-0600	0%	15%	25%	Off
0600-0700	0%	15%	25%	Off
0700-0800	10%	40%	65%	On
0800-0900	20%	90%	80%	On
0900-1000	70%	100%	100%	On
1000-1100	70%	100%	100%	On
1100-1200	70%	100%	100%	On
1200-1300	70%	100%	100%	On
1300-1400	70%	100%	100%	On
1400-1500	70%	100%	100%	On
1500-1600	70%	100%	100%	On
1600-1700	70%	100%	100%	On
1700-1800	35%	80%	80%	On
1800-1900	10%	60%	65%	Off
1900-2000	5%	60%	55%	Off
2000-2100	5%	50%	25%	Off
2100-2200	0%	15%	25%	Off
2200-2300	0%	15%	25%	Off
2300-2400	0%	15%	25%	Off

Weekends	NCC2019 Class 5 Schedule			
Time Period	Occupancy	Lighting	Equipment	HVAC Operation
0000-0100	0%	15%	25%	Off
0100-0200	0%	15%	25%	Off
0200-0300	0%	15%	25%	Off
0300-0400	0%	15%	25%	Off
0400-0500	0%	15%	25%	Off
0500-0600	0%	15%	25%	Off
0600-0700	0%	15%	25%	Off
0700-0800	0%	15%	25%	Off
0800-0900	5%	25%	25%	Off
0900-1000	5%	25%	25%	Off
1000-1100	5%	25%	25%	Off
1100-1200	5%	25%	25%	Off
1200-1300	5%	25%	25%	Off
1300-1400	5%	25%	25%	Off
1400-1500	5%	25%	25%	Off
1500-1600	5%	25%	25%	Off
1600-1700	5%	25%	25%	Off
1700-1800	0%	15%	25%	Off
1800-1900	0%	15%	25%	Off
1900-2000	0%	15%	25%	Off
2000-2100	0%	15%	25%	Off
2100-2200	0%	15%	25%	Off
2200-2300	0%	15%	25%	Off
2300-2400	0%	15%	25%	Off

3.3 HVAC PLANT

Large HVAC installations can be separated into the plant (or water) side, air loop and zone side systems and components. The two HVAC system configurations modelled have different chilled water plant loops, as described below. The peak thermal load for the building was estimated to be around 1,000kW.

3.3.1 CHILLED WATER PLANT

The ***Standard (STD) chilled water plant configuration*** was modelled with three equal sized chillers plumbed in parallel. Each chiller was sized to provide 350 kWr of refrigeration. The 'EnergyPlus Reformulated EIR Chiller' model was used to describe a detailed part load performance 'surface' for each chiller. Design COP was set to a conservative 5.5 value (modern chillers can achieve more than 6 at design conditions). The reference values for leaving chilled water and leaving condenser water are set to 6.67C and 35C (AHRI conditions). The chillers are not allowed to unload below 20%. The chilled water loop has been designed to a 5/13 C split. Therefore, the CHWP supplies 5C chilled water to the DOAS AHU cooling coil and to the Heat eXchanger (HX). The HX then supplies the ACBs at 14C with a 3C temperature rise at full load (a 17C return temperature). The chilled water pumping arrangement is designed as a constant volume primary flow system with a 200 kPa head. Each chiller has a dedicated chilled water pump. Figure 4 is a schematic for this loop as represented in the DesignBuilder GUI.

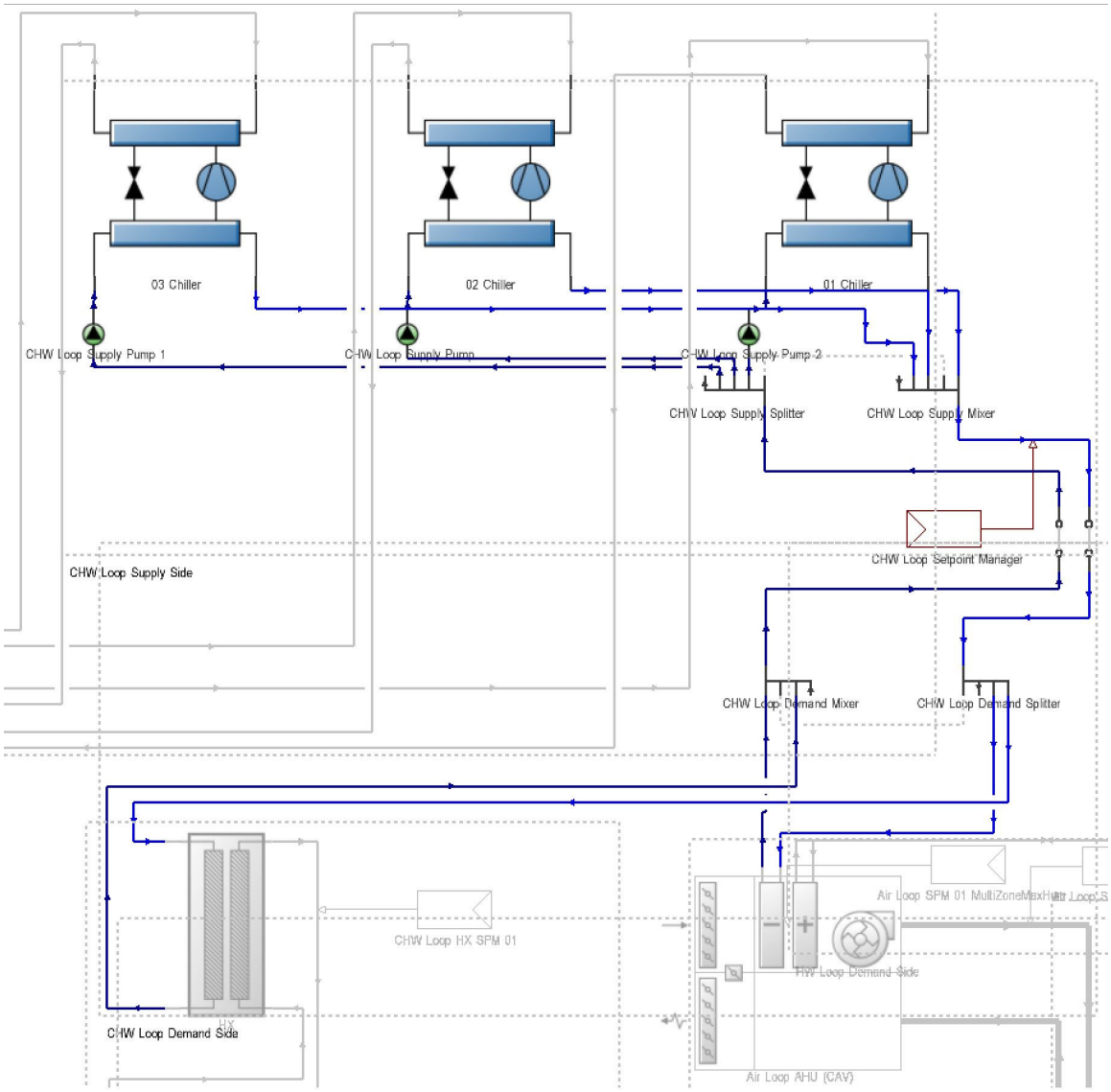

Figure 4: HVAC plant – primary chilled water (CHW) loop for Standard (STD) configuration

It is noted that the selected chiller sizes (350 kW) are probably too small for practical centrifugal machines. However, they are appropriate for the simulation study at hand, since:

- identical chiller machines are being used for each simulation analysis
- part load performance of the chillers being modelled are identical, with respect to chilled water and condenser water reset, and chiller part load ratio
- the chiller part load equations in the model are scalable, and not impacted by absolute chiller size.

Chiller sequencing for the **STD configuration** has been modelled using a sequential control strategy. The first chiller carries the building till it's capacity is exhausted, when the next is energised and so on. In the final stage all three chillers will run when required.

Supply of High Temperature Chilled Water (HTCHW) for the STD configuration has been modelled using a secondary chilled water loop that incorporates the Heat eXchanger (HX) supplying 14C water to the ACBs on demand via a variable speed secondary chilled water pump. *Figure 5* is a schematic of this loop as represented in the DesignBuilder GUI.

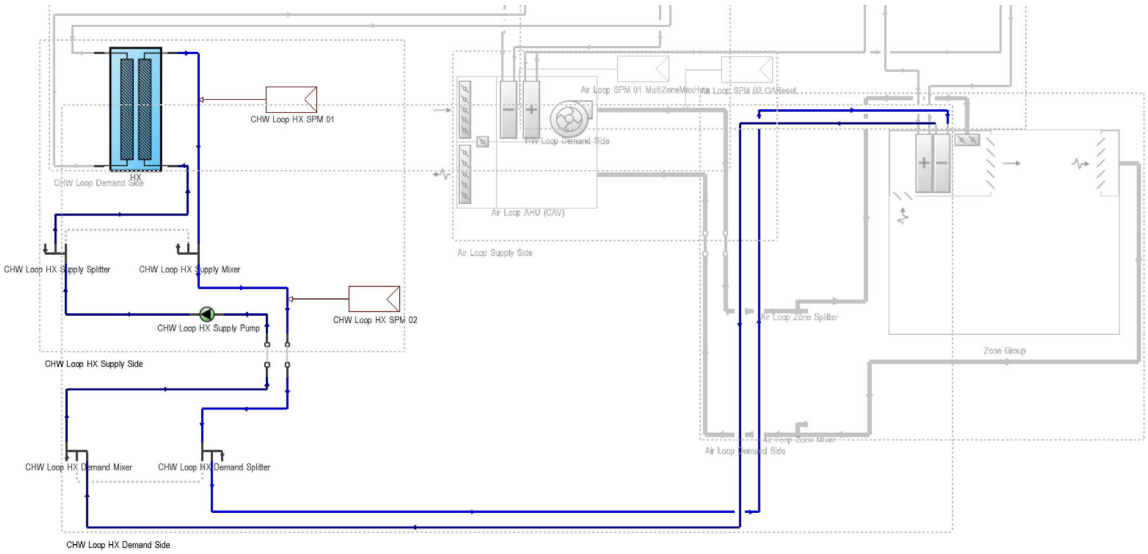

Figure 5: Heat eXchanger (HX) secondary chilled water loop supplying HTCHW to ACBs at zone level

The second ***HTCH (High Temperature Chiller) chilled water plant configuration*** is modelled with one dedicated 400 kW chiller supplying the ACBs directly with 14/17 C water. The two other 350 kW chillers, plumbed in parallel, serve the DOAS AHU cooling coil with 5/13 C chilled water.

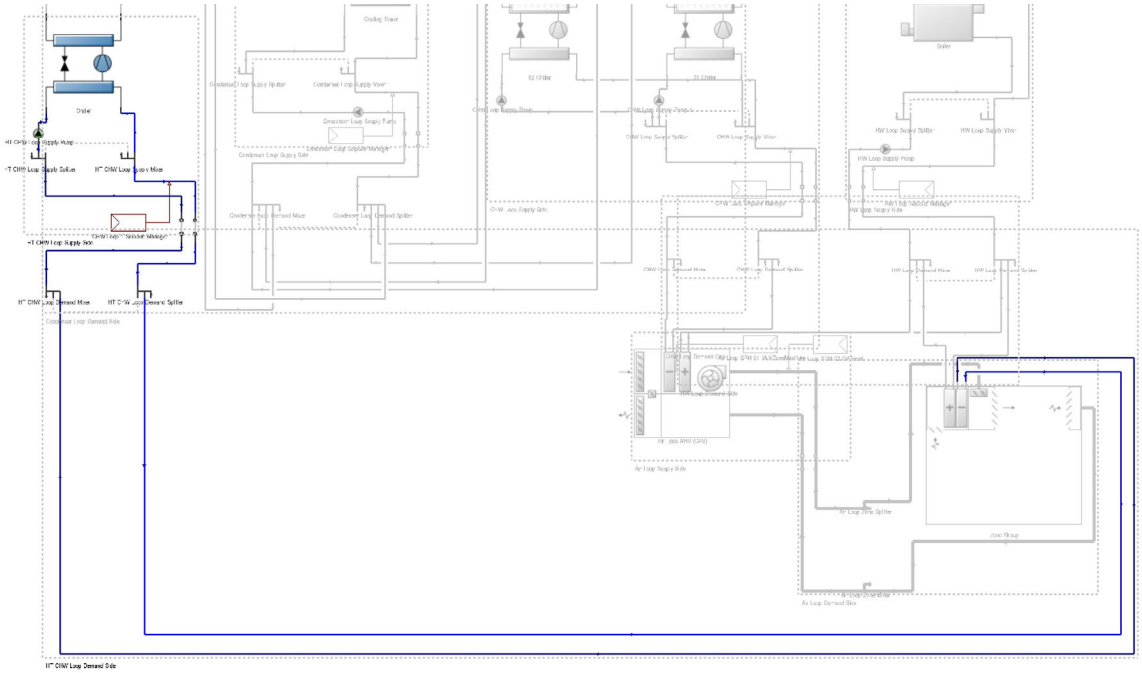

Figure 6: High Temperature Chiller (HTCH) supplying zone level ACBs with 14/17 C water

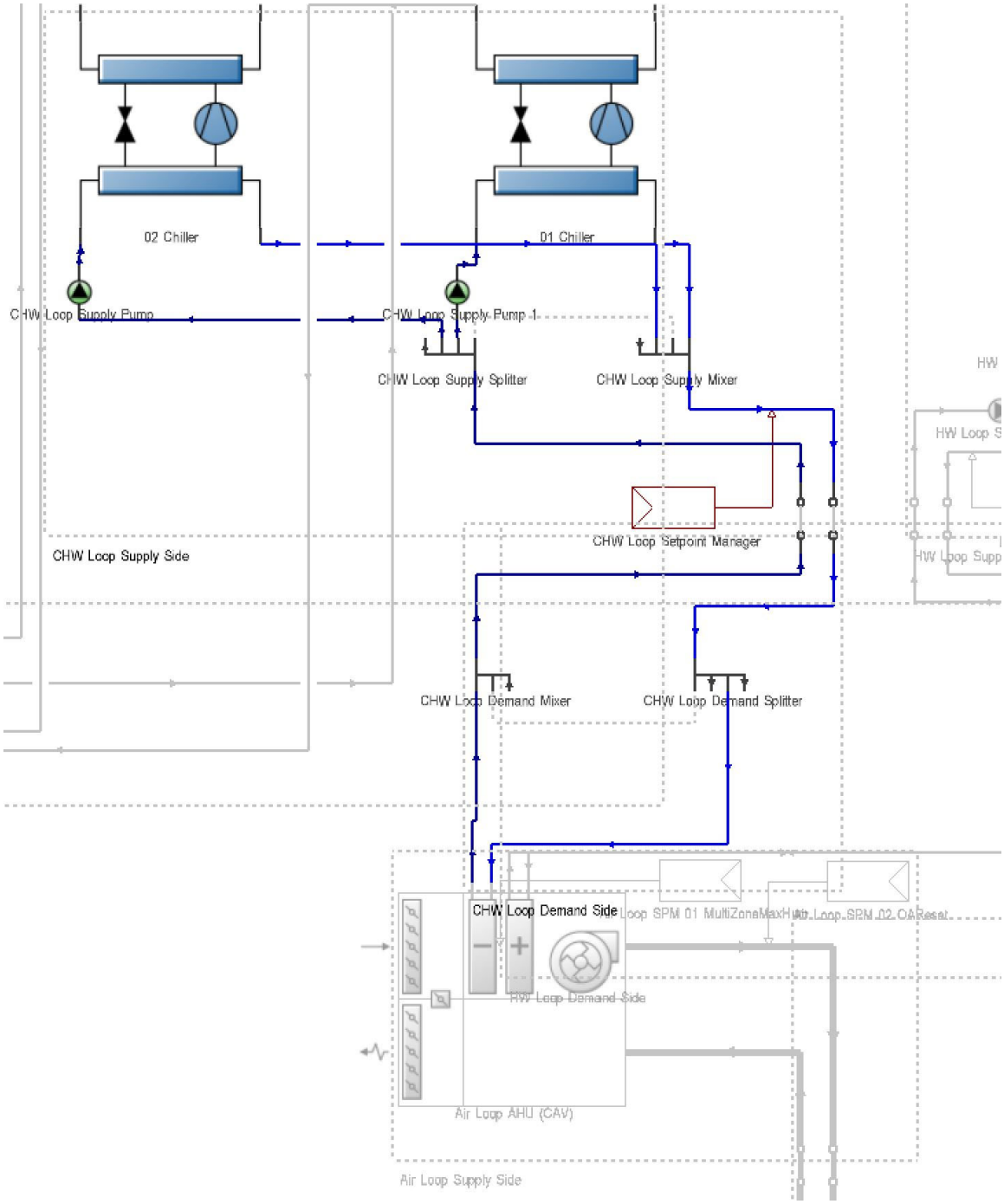

Figure 7: 2 X chillers supplying the AHU cooling coil with 5/13 C chilled water

3.3.2 HEAT REJECTION PLANT

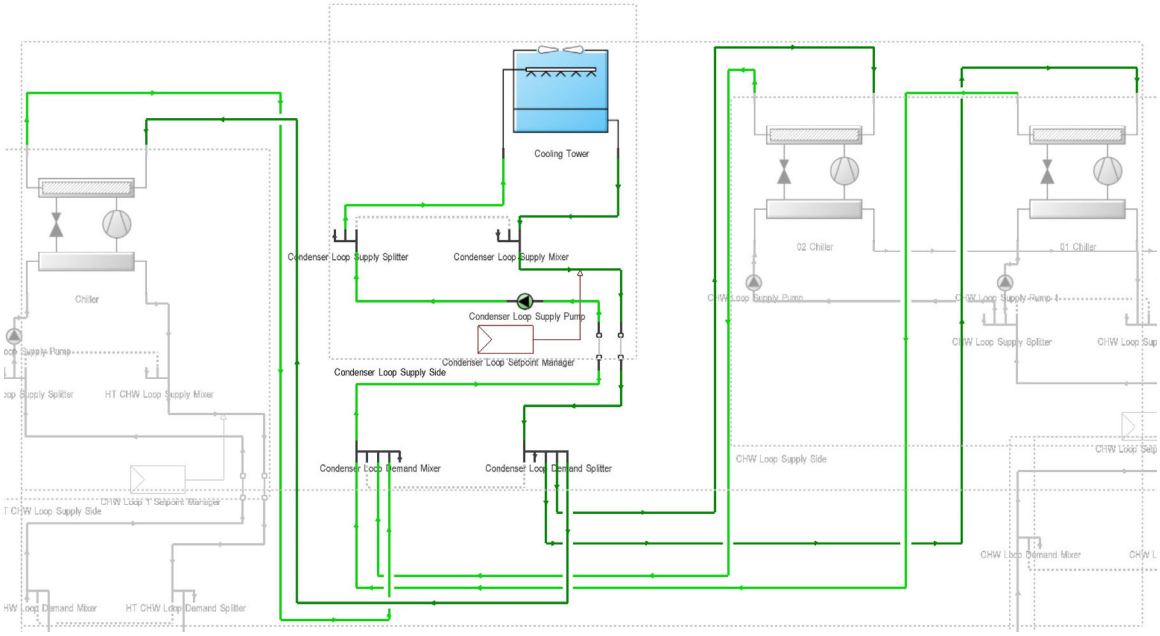

Figure 8: HVAC plant – heat rejection or condenser water (CW) loop

The heat rejection system for the HVAC plant has been modelled to be a single cooling tower, a simple single speed fan and cycling control operation. The cooling tower has it's own dedicated constant volume pump designed to meet a 200 kPa head. Cooling tower sizing is based on a 29C/34.5C loop split. The sump water temperature is controlled to follow ambient wet bulb temperature down to 20C with an approach of 3C.

3.3.3 HEATING HOT WATER PLANT

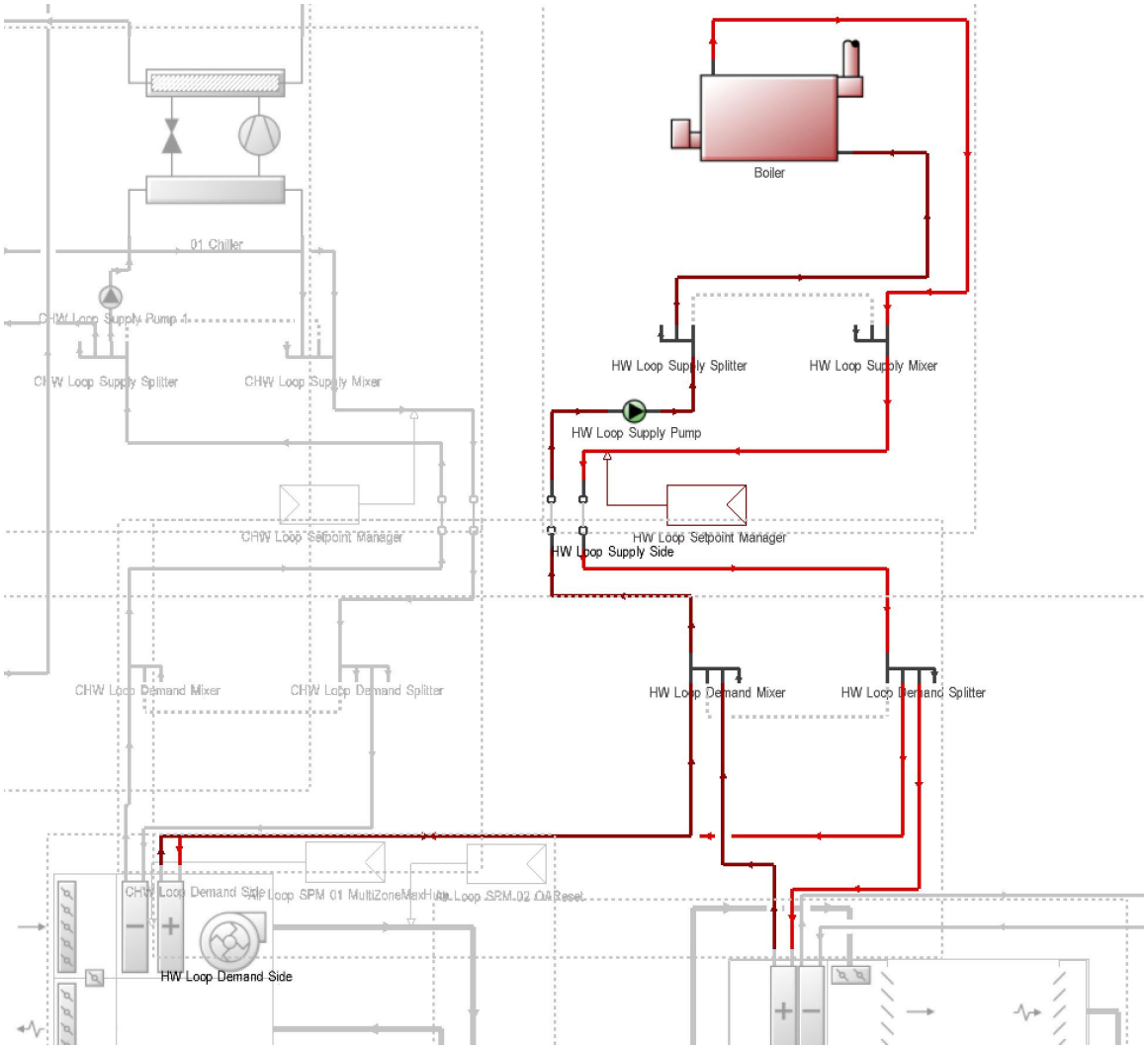

Figure 9: HVAC plant – heating hot water (HHW) loop

The heating hot water loop has been modelled to be a single natural gas fired boiler, running a 80C loop design temperature at 80% efficiency, with a 20C temperature differential. A variable speed pump circulates the hot water across the system and it is designed to meet a head of 200 kPa.

3.4 AIR HANDLING UNIT SYSTEM

The single Air Handling Unit (AHU), modelled for both HVAC system configurations, has a function similar to that of a Dedicated Outside Air System (DOAS). It delivers de-humidified and conditioned air to the ACBs at zone level. In keeping with recent design trends for such systems in Australia, the AHU is set to recirculate air and includes a carefully controlled economy cycle.

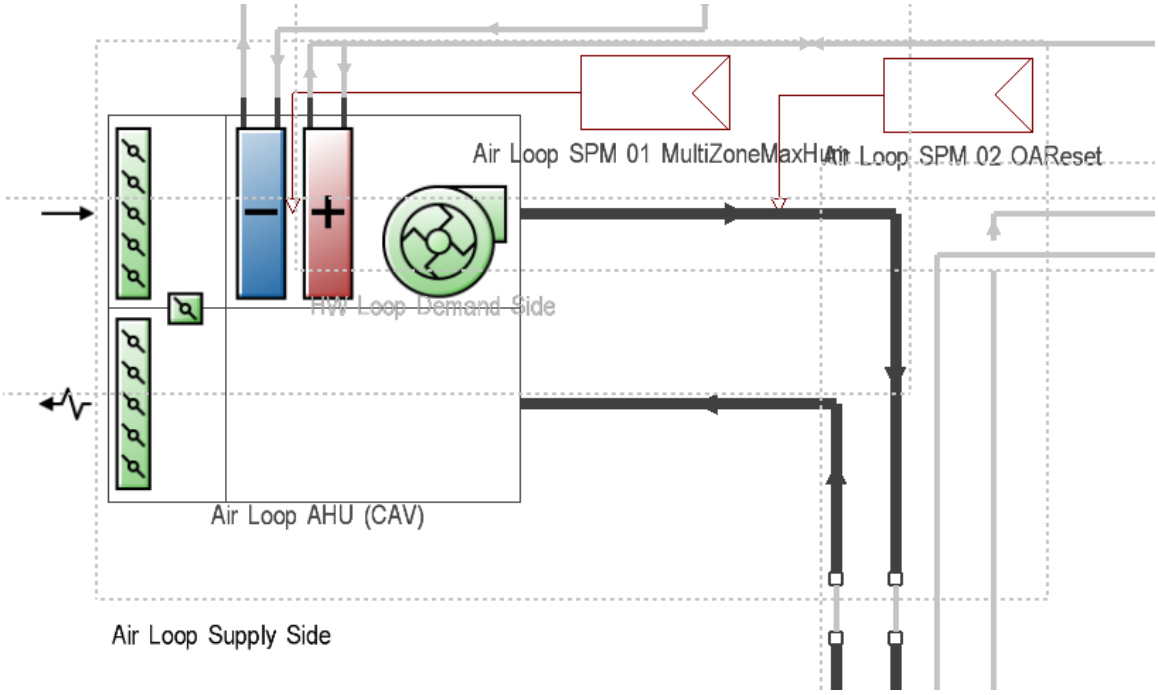

Figure 10: AHU supply control strategy

The supply air condition leaving the DOAS type AHU has two control conditions imposed on it (see Figure 10). The first condition is imposed by the cooling coil which imposes a de-humidification priority cooling algorithm that maintains a zone maximum absolute humidity of 8 gm of water vapour per kg of dry air. The 2nd control conditioned is imposed on the supply air condition downstream of the supply fan and is based on an outside air reset condition. When the outside air ambient dry bulb temperature is 15C or less, the AHU supplies air at 18C to the Active Chilled Beams (ACBs). When the outside air ambient dry bulb is 18C or higher, the AHU supplies air at 12C to the ACBs.

An economiser control strategy has also been applied. However, the economiser is locked out when there is a heating call on the AHU, is controlled to a dewpoint limit (12.5C) and a specified ambient dry bulb temperature range (13C to 21C). As noted earlier, the system is not a 100% outside air system, but works within the parameters above to recirculate some portion of the supply air as required. Both con

It is the authors view that the control strategy detailed above brings into control the most common disadvantage of a traditional Chilled Beam HVAC system, i.e., that of having to constantly monitor the dewpoint temperature in the space, and in fact, having to 'pull back' the cooling capacity of the beams at times when cooling may most be needed in more humid locations.

3.5 ACTIVE CHILLED BEAM

The zone level Active Chilled Beams (ACBs) have been represented by four pipe induction units, incorporating a heating coil and a cooling coil (see Figure 11). The unit receives treated air from the DOAS type AHU and induces room air past the coils with a three fold induction ratio. In practise, modern chilled beams are a single coil (2-pipe component) which can accept either heating hot water or high temperature chilled water via a multi-port control valve. Therefore two sets of neighbouring beams can have opposite duties, with one working in cooling mode and the other in a heating mode. This allows for a high degree of tenant fitout flexibility.

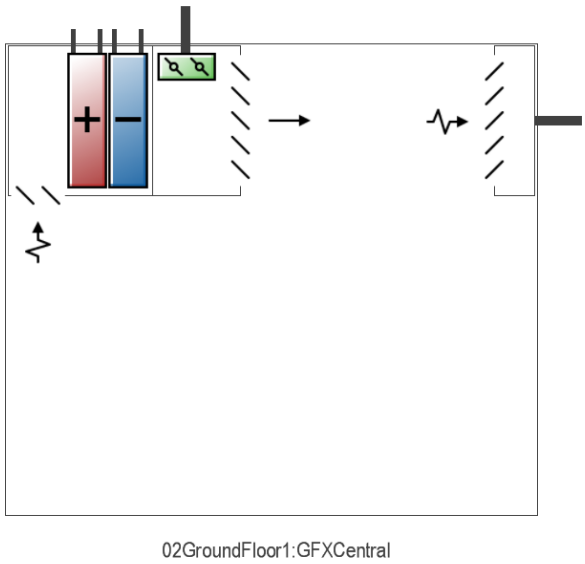

Figure 11: Active Chilled Beam representation at zone level

4 RESULTS

4.1 PREDICTED ENERGY (ELECTRICTY AND GAS) CONSUMPTION

Table 4: HVAC sub-system end use, and annual energy intensity for the Standard and HTCH plant configurations for the ACB systems modelled

	STD HX ACB		Dedicated HTCH ACB	
SYSTEM TYPE →	*STD HX ACB*		*Dedicated HTCH ACB*	
HVAC END USE ↓	*Electricity [kWh]*	*Natural Gas [kWh]*	*Electricity [kWh]*	*Natural Gas [kWh]*
Heating	2	68,168	2	57,056
Cooling	80,760	-	41,021	-
Fans	24,465	-	23,423	-
Pumps	65,472	-	79,679	-
Heat Rejection	13,551	-	11,198	-
Total	772,482.3		743,555	57,056
HVAC totals	184,250.8	68,168.1	155,323	57,056
Energy intensity, kWh/m2-yr	*28.0*		*23.6*	

The annual energy intensities, for the two variants of the Active Chilled Beam systems with the different Chilled Water Plant configurations modelled in an identical hypothetical building located in Sydney, are listed in Table 4 above. Predicted annual energy consumption for each HVAC sub-system (fans, pumps, etc) are also listed, and indicate the spread of energy use for these sub-systems for each HVAC system configuration.

The predicted results are logical. There are energy savings in the chiller energy consumption for the system with the Dedicated High Temperature Chiller (HTCH). Some of these savings are offset by additional pumping energy required to move larger quantities of high temperature chilled water around the system.

The hourly cooling loads for the three chillers for each configuration are plotted separately below. Figure 12 shows the STD configuration with HX, and Figure 13 shows these results for the HTCH configuration.

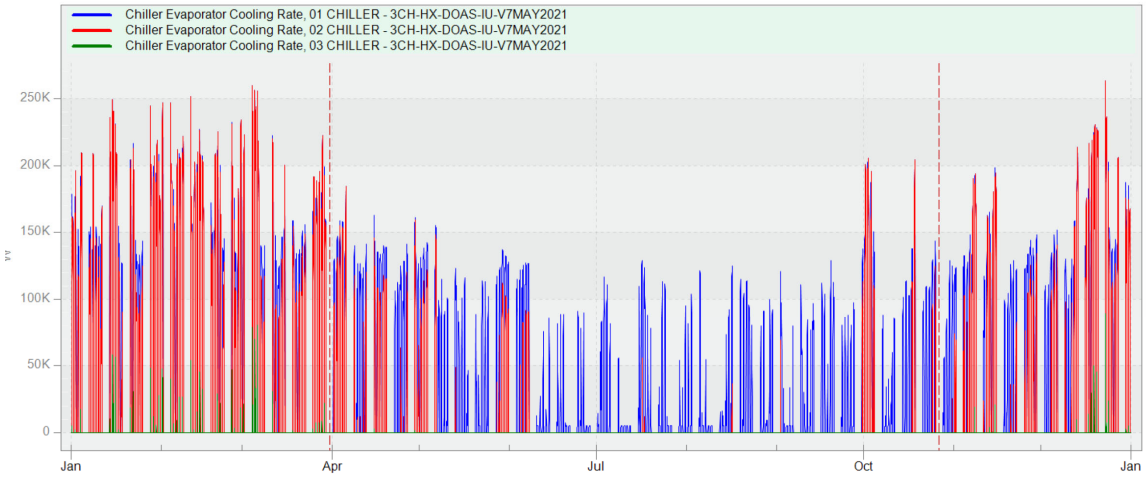

Figure 12: Predicted hourly cooling loads for the three chillers in parallel for the STD configuration with the ACBs being supplied via a Heat eXchanger (HX). Chillers 01 and 02 run for most of the year, with the 3rd chiller helping out in summer months

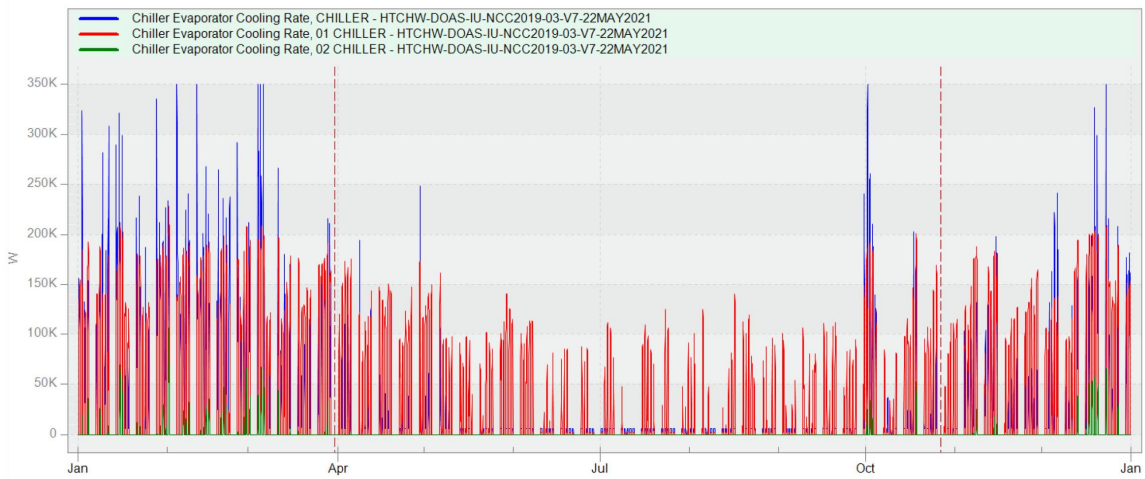

Figure 13: Predicted hourly cooling loads for the chillers in the Dedicated High Temperature Chiller HTCH option. Chillers 01 and 02 supply the DOAS type AHU and 'Chiller' (blue lines) represents cooling loads seen by the ACBs at zone level (note: these are NOT electricity consumption, these are thermal cooling loads)

Some insights from the modelling exercise, and indeed from our practical experience, are discussed in the next section. When reviewing these results (or those from other studies using models) it is good to remember George Box's famous saying – "all models are wrong, but some are useful[2]…"; the carefully modelled representations here are useful, and should be used appropriately.

[2] *Box, G. E. P. (1976), "Science and Statistics",* Journal of the American Statistical Association*, **71**: 791–799*

4.2 SYSTEM LEVEL INSIGHTS

We list below a series of system level insights from the modelling exercise, and from anecdotal observations made by experienced HVAC engineers that are consistent with the simulation study outcomes:

- the dedicated chiller supplying High Temperature Chilled Water (HTCHW) to the ACBs is very efficient in delivering the cooling duty; however, selection of this machine must be carried out carefully to ensure stable operation across all load ranges
- Chilled Beam systems will call for cooling all through the year in Sydney and similar climates; this is a result of dehumidification duty and limitations in accessing economiser mode
- Chilled Beam systems are less 'forgiving' and control strategies need to be commissioned carefully and monitored continuously. A control failure can result in significant energy and thermal comfort penalties, and the risk of condensation in the conditioned space
- Chilled Beam systems work best with an efficient façade; their response time is slower than that of all air systems (although that difference is mitigated with the Active Chilled Beam components modelled here)
- Since chilled water (and hot water) needs to be pumped around the building and in around occupied spaces, there is always the risk of leaks or hose connector failure with the tenant space. This must be managed by ensuring high quality components are specified and installed correctly

5 RESEARCH TEAM

This study has been carried out by:

PC Thomas, Director, Team Catalyst. PC has been using building energy simulation tools for more than 30 years, and provides training in the use of building performance simulation tools to students and colleagues in the industry in Australia and internationally. Among his other experiences PC helped found the ESD team at Arup, Sydney, in the early 2000's. He is a member of the International Education Committee with IBPSA (the International Building Performance Simulation Association), and is currently Adjunct Associate Prof at the University of Sydney.

GS Rao, Director, Team Catalyst. GS provided high level advice and review for modelling of each system configuration, with particular attention to the practicability, component performance limitations and application of control strategies. He has more than 30 years of HVAC systems knowledge and experience having worked variously with York, Carrier and Trane over the course of his career, and having designed and delivered major HVAC installations in a number of countries.

Ms Ayshvarya Venkatesan, Associate, Team Catalyst developed the building envelope model that formed the basis of the study. The model was developed by Aysh for other projects that Team Catalyst previously carried out for other research projects, including projects for the Australian Building Codes Board. Aysh has a background in Architecture and is passionate about delivering occupant comfort and reducing GHG emissions in the built environment.

Akshay Deokar, ESD/Architecture, has a post graduate degree in Arch Science and Architecture. Akshay worked with Aysh on updating the building model to NCC2019 requirements, and carried out the simulation runs under guidance from Aysh and PC.