

Load Calculation and Energy Simulation: The link between design and operation for building design

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Abstract

The current challenge for HVAC engineers is be able to provide a high level of thermal comfort in an energy efficient manner. It is argued that HVAC engineers must use the vitally important combination of right sizing *and* energy simulation to first predict, and then achieve, high performance outcomes in air-conditioned buildings.

This two-step process benefits from the use of the most accurate algorithms to compute HVAC system sizing, and the application of practical experience and knowledge in the use of energy simulation programs which can represent system components and overall system control strategies to represent HVAC systems.

The authors have developed and used this process for well over a decade, which has resulted in the successful delivery and continued operation of a number of high performance buildings, particularly office buildings, whose performance has been proven by monthly utility bills for 12 consecutive months.

Introduction

HVAC engineers have always been proficient at delivering thermal comfort within a conditioned space. However, the current challenge is be able to provide a high level of thermal comfort in an energy efficient manner, to assist buildings reduce their greenhouse gas emissions.

Improved load estimation (right sizing), by itself, is not sufficient to deliver energy efficiency, stable operation and tenant comfort in operation. A combination of right sizing and energy simulation is, in our view, vitally important to first predict, and then achieve, high performance outcomes in air-conditioned buildings.

It is important to state, at the outset, that optimising the building envelope (trading off between mass, glass, shading and orientation) is a critical first step to reducing cooling and heating loads (demand). This design activity should be the domain of the architect with input from an engineer or /building physicist, and should be carried out at concept design stage. A building project is

severely hampered in its ability to deliver energy efficiency and occupant thermal comfort if this first step is not implemented.

The HVAC engineer has traditionally used the traditional (and narrow) definition of comfort based around space temperature and relative humidity range. For the purpose of this paper we have used an arbitrary (and admittedly narrow) definition with zone mean average temperature range of 20C – 24C and relative humidity of 40% - 70%. More recently, we have worked with building designers to minimise radiation asymmetry, by providing advice to try and limit the difference between the zone mean radiant temperature (MRT) and zone mean temperature (DBT) to ± 1 3C. Unfortunately, this is not always implementable, as the design of the building envelope has largely been finalised before the HVAC engineer can provide significant input.

Ultimately, the meter “hangs” on the HVAC plant and systems, and correctly representing and simulating the performance of these loops is even more important than load estimation when trying to predict real energy consumption. Simulating HVAC plant and system loops should be the domain of the HVAC engineer, as they should be aware of the practical limitations of each component, the limitations of HVAC system type, and indeed the limitations of the energy simulation program being used.

This paper outlines a modern process for the design of high performance, conditioned buildings, based on the use of right sizing AND energy simulation. We hope it will encourage more HVAC design engineers to combine their design and sizing skills with energy simulation skills for performance prediction.

A Brief (and Relevant) History of Cooling Load Estimation Research

Cooling load estimation is the cornerstone for HVAC system sizing.

A review of the history of research literature on cooling load calculations reveals there were three major advances that are relevant to our discussion. Readers are

referred to the paper by Mao, Haberl and Balthazar (2013) which provides a comprehensive review of the subject, (with many references for the interested reader). However this resource lacks a detailed discussion of the importance of the Heat Balance method for modern engineering work as developed in this paper.

Before 1945, design guidance methods were available from various sources including Carrier's psychrometric chart (ASHVE 1922) and Trane's load estimate sheet (1938). These methods were "at best inconsistent....However the foundation was laid for today's modern methods which began with sol-air temperatures, decrement factors and the use of a thermal R/C network" (Mao et al 2013)

In the late 1960s Mitalas and Stephenson (1967) developed the thermal Response Factor Method (RFM), which was the basis of consideration of thermal mass in cooling load calculations. "The Transfer Function Method (TFM) is considered to be the first, wide spread computer oriented method for solving dynamic heat transfer problems in buildings"...(Mao et al 2013).

A generation of USDOE energy simulation programs were developed based around advances on the transient conduction function ideas of Mitalas and Stephenson, and these included TARP (Walton 1983), DOE-2 (Winkelmann 1993) and BLAST (1986). These energy simulation programs were used to develop simplified load calculation methods that were widely used by engineers. The most famous was probably the modification of the Cooling Load Temperature Difference/Cooling Load Factor method (CLTD/CLF) for which Prof Ed Sowell (Sowell, 1988a,b,c) ran 200,640 simulations using the DOE-2 energy simulation program! *Therefore the take away message here is that all the popular ASHRAE cooling load calculation methods are based on results correlated from energy simulation programs!*

The most recent method of load calculation and energy simulation published in the current ASHRAE Fundamentals (2013) is the Heat Balance Method (Peterson et al 1997). It explicitly formulates inside and outside surface and zone air heat balances and simultaneously solves the resulting equations. It is arguably the most fundamental (and accurate) of approaches as it seeks to model the underlying physical processes with the minimum of assumptions. As noted in the current Handbook of Fundamentals (ASHRAE 2013) - "HB calculations closely approximated measured cooling loads when provided with detailed data for the test rooms."

A *simplification* of the Heat Balance Method, namely the Radiant Time Series (RTS) method is also referred to in the Handbook.

The Critical Importance of the Heat Balance Method

There are two further pieces of the puzzle that now allow a HVAC design engineer to use the right sizing and

energy simulation analysis combination to predict and then achieve high performance outcomes in air-conditioned buildings. These are that:

1. The Heat Balance Method is the first ASHRAE method to rely completely on computer implementation, *and also marks the change from load calculations based on energy analysis methods to those based on design day cooling load calculations* (paraphrased from Rees et al 2000), and
2. The Heat Balance Method has been encoded into EnergyPlus, the latest generation of energy simulation calculation engine developed and maintained by USDOE (Crawley et al, 1999)

The implication of the two points noted above are that if an HVAC design engineer chooses to develop an EnergyPlus building model at an early stage of the design process, they now have the opportunity to first size HVAC plant and systems based on ASHRAE Design Day data and then predict the energy performance of this same system using a reference hourly weather data file, *in a single energy simulation run*, using the most accurate load calculation algorithms currently available.

A significant insight here is the understanding that the dynamic simulation calculations used to predict the energy consumption of building systems are predicated on a load calculation at each time step; using weather data from the reference weather file for that particular time step. That is, the basis of energy simulation is the same set of calculations using the Heat Balance Method as used for sizing HVAC plant and systems.

Design Day, Reference Weather Data, Sizing and Energy Efficiency

HVAC design engineers use Design Day data and a cooling load calculation procedure to estimate plant and system size for an air-conditioned building. These Design Day data are combinations of ambient dry bulb (DBT) temperature, and a coincident ambient wet bulb temperature (CWBT). In humid locations, engineers may use ambient wet bulb temperature (WBT) and a coincident ambient dry bulb temperature (CDBT) instead. The ASHRAE handbook also lists a daily temperature range. Solar radiation is also considered in the load calculation, but is not generally listed explicitly, it is usually programmed into the calculation software.

These Design Day data groups are listed for a series of confidence levels. The current confidence levels are 0.4%, 1% and 2% when a single design day is used for the year, or 0.4%, 2%, 5% and 10% when design day data is listed for each month of the year. These confidence levels represent the probability of occurrence of these extreme (Design Day) weather conditions *not being exceeded* for more than that percentage time in a year. Design day data is based on historical observations. The probability of extreme weather conditions not being exceeded is based on statistical

analysis of weather data going back many decades, where observations exist.

A Reference weather file created for use by energy simulation analysis performs a different function. It is a single year of periodic (usually hourly) data selected to represent an average or typical year for a location. It is intended to be a basis for comparing the predicted annual energy consumption of different building and HVAC system designs. There are a number of established formats, eg., TRY, TMY and their derivatives like IWEI, IWEI2 etc.

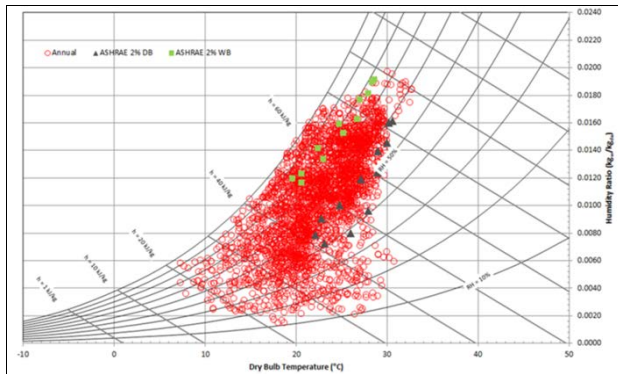


Figure 1 Monthly Design Day and Reference Weather data plotted on the psychrometric chart.

Figure 1 compares the ASHRAE monthly design Design Day at 2% confidence level with the 8,760 hourly temperature and humidity combinations for an IWEI reference weather data file (Brisbane, QLD, Australia) on the psychrometric chart (which represents temperature on the x-axis and humidity on the y-axis). Clearly the HVAC design engineer should be using the wet bulb priority combination for load calculations as the highest green rectangle point (WBT/MCDBT) has a higher enthalpy (total energy content) than the right most black triangle (DBT/CWBT).

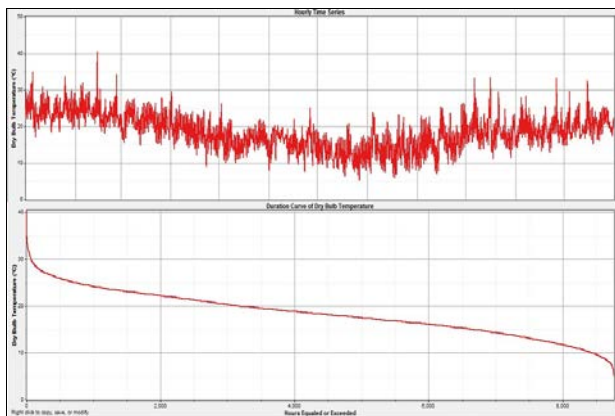


Figure 2(a) Hourly representation of ambient DBT, and (b) Duration curve for ambient DBT

The implication of the Design Day confidence level for HVAC system sizing is illustrated in Figure 2. The top graph is a plot of the hourly ambient dry bulb

temperature (DBT), while the bottom graph is ranked duration curve for the same data (Sydney, NSW, Australia). By definition, the Design Day DBT is not exceeded more than 2% of the year. That is, the HVAC system selected has more capacity than required for 98% of the year!

Therefore improving energy efficiency for an air-conditioned building is about selecting the appropriate HVAC system components and control strategies that will allow the system to “back off”, in an energy efficient manner, for 98% of run hours. This is particularly relevant for buildings located in composite (or variable) climates.

Similar thinking applies for heating systems, although our paper concentrates on cooling systems. Integrating the operations of cooling and heating systems to minimise conflicts is an important part of delivering an energy efficient building.

It is argued that reviewing specific results from load calculation and energy simulation runs can provide the HVAC engineer with the insights required to select and design a system that will deliver energy efficiency and thermal comfort in operation, and this is demonstrated in the following sections.

Sizing

Figure 3 is a representation of a three storey rectangular building, divided into five thermal zones, four perimeter and one internal zone, used to demonstrate how the Heat Balance Method coded in EnergyPlus is used at our consulting practise. The floor plate is 40m x 25m. The DesignBuilder GUI for EnergyPlus was used to develop these examples.

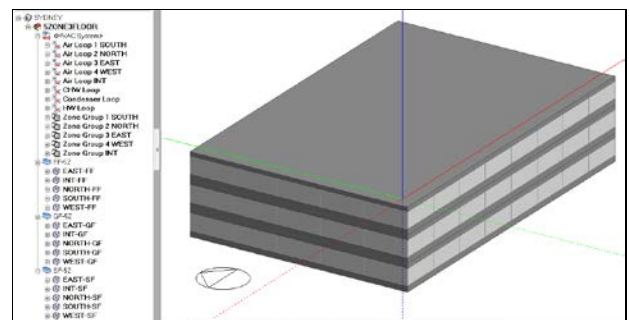


Figure 3 Rectangular three storey, five zone model with Ground Floor (GF-5Z), First Floor (FF-5Z) and Second Floor (SF-5Z) represented on the model tree (LHS bottom)

Other details (construction materials, internal loads, outside air rates, operational schedules, etc) are typical for Australia and are not reported here for brevity (and because these are less relevant for the discussion at hand). However, it noted (for the Northern Hemisphere audience) that summer months in Australia are Dec, Jan and Feb, and that Feb is generally the warmest month.

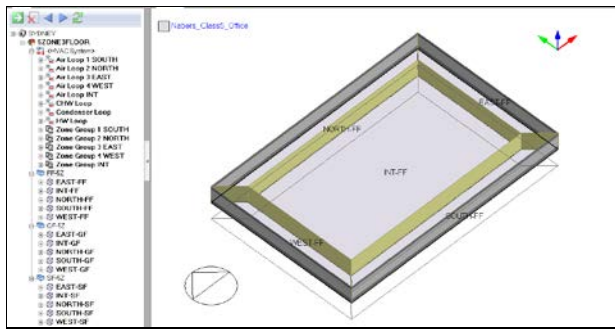


Figure 4 First Floor (FF-5Z) view showing the five zones (4 perimeter and 1 interior)

The 2% confidence level monthly Design Day with DBT priority was used to generate HVAC system sizing results, which are shown for the First Floor (Figure 4) representing a middle or typical floor, and also for the whole building (last line in Figure 5 and Figure 6).

Zone	Design Capacity (kW)	Design Flow Rate (m ³ /s)	Time of Max Cooling	Floor Area (m ²)	Flow/Floor Area (l/s-m ²)	Cooling Load Per Floor Area (W/m ²)	Bulb Temperature at Time of Peak Cooling Load (°C)
FF5Z:NORTHFF	12.62	0.773	Apr 13:00	151.7	5.1	83.2	34.6
FF5Z:EASTFF	11.38	0.699	Feb 09:00	95.8	7.29	118.8	29.8
FF5Z:INTFF	31.68	1.737	Feb 15:00	814.0	2.13	38.9	35.1
FF5Z:SOUTHFF	9.00	0.528	Feb 14:30	151.7	3.48	59.3	35.1
FF5Z:WESTFF	11.94	0.758	Feb 16:00	95.8	7.91	124.6	34.5
Totals	229.17	13.517	N/A	3926.8	3.44	58.4	N/A

Figure 5 Cooling load peaks for each thermal zone on First Floor (FF5Z). Check figures (l/s/m² and W/m²) and sum of the peaks (non-coincident load) for the building are indicated by the arrows

Results in Figure 5 illustrate the additional insight provided by using monthly Design Day data rather than a single day for the year. The cooling peak for the North (sun exposed façade in Australia) zone (FF5Z:NORTHFF) occurs in a “swing” month, when solar gains are predominant. Check figures in terms of l/s/m² for air supply and W/m² are informative. East and West zones peak as expected, in the morning and afternoon respectively. The South zone (least exposed to the sun in Australia) and the Internal zones peak at around the time of the highest ambient temperature (DBT). The Internal zone has the lowest loads, and the lowest required air flow rate as it has no interaction with the climate (except for outside air) via a façade, or even a roof or floor in this middle floor instance. The “sum-of-the-peaks” or the non-coincident cooling load for the building is listed to be about 229kW.

Zone	Design Capacity (kW)	Design Flow Rate (m ³ /s)	Time of Max Cooling	Floor Area (m ²)	Flow/Floor Area (l/s-m ²)	Cooling Load Per Floor Area (W/m ²)	Bulb Temperature at Time of Peak Cooling Load (°C)
FF5Z:NORTHFF	11.46	0.6969	Feb 15:00	151.7	4.60	75.6	35.1
FF5Z:EASTFF	8.83	0.5286	Feb 15:00	95.8	5.52	92.2	35.1
FF5Z:INTFF	31.68	1.7373	Feb 15:00	814.0	2.13	38.9	35.1
FF5Z:SOUTHFF	8.99	0.5274	Feb 15:00	151.7	3.48	59.3	35.1
FF5Z:WESTFF	10.84	0.6821	Feb 15:00	95.8	7.12	113.2	35.1
Totals	214.24	12.5073	Feb 15:00	3926.8	3.19	54.6	N/A

Figure 6 Cooling load peak for each thermal zone on First Floor (FF5Z) at the time of the building peak (coincident building total load indicated by LHS arrow).

Check figures (l/s/m² and W/m²) also indicated by the arrows

Figure 6 is a listing of the “coincident” load results for the same First Floor zones, and also lists the building peak. The results indicate that the whole building cooling load peak occurs in the afternoon of the hottest month, and that there is a 6.5% diversity between the sum-of-the-peaks and the building peak. The level of diversity depends on the unique combination of mass, glass, orientation and internal loads for each building. The building peak (about 214kW in this example) is the chiller block load for a central plant type HVAC design.

Building	Block	Zone	Design Capacity (kW)	Design Flow Rate (m ³ /s)	Time of Max Cooling	Floor Area (m ²)	Flow/Floor Area (l/s-m ²)	Cooling Load Per Floor Area (W/m ²)	Design Outside Dry-Bulb Temperature at Time of Peak Cooling
EAST-SYS	FF-SZ	FFSZ:EASTFF	11.38	0.6986	Feb 09:00	95.8	7.29	118.8	29.8
EAST-SYS	GF-SZ	GF5Z:EASTGF	7.43	0.4673	Feb 09:00	95.8	4.88	79.6	29.8
EAST-SYS	SF-SZ	SFSZ:EASTSF	12.35	0.7888	Feb 09:00	95.8	8.23	128.9	29.8
EAST-SYS	Totals		31.35	1.9547	Feb 09:00	287.4	6.8	109.1	N/A
WEST-SYS	FF-SZ	FFSZ:WESTFF	11.94	0.7581	Feb 16:00	95.8	7.91	124.6	34.5
WEST-SYS	GF-SZ	GF5Z:WESTGF	8.93	0.5519	Feb 16:00	95.8	5.76	93.3	34.5
WEST-SYS	SF-SZ	SFSZ:WESTSF	14.24	0.9162	Feb 16:00	95.8	9.56	148.6	34.5
WEST-SYS	Totals		35.11	2.2263	Feb 16:00	287.4	7.75	122.2	N/A

Figure 7 AHU sizing data when designing a “face zoned”, 5 central AHU system. Data for East and West AHU shown by arrows

The Design Day sizing results have been rearranged for a potential AHU arrangement in Figure 7. In this case a “face zone” design has been analysed, where one AHU is assigned to each orientation and caters to all floors in that orientation. Sizing data for the East and West AHUs is listed in Figure 7. A quick review of the numbers indicates that all is as expected, the Second Floor (SF) zones report the highest cooling loads due to impact of solar gains from the roof. Ground floor (GF) loads are lowest due to moderation of cooling loads from ground heat transfer (this is a separate discussion all by itself). Typical or First Floor (FF) zone loads are somewhere in between.

It is important to note that this level of detail, as provided in Figure 5 to Figure 7 is available using the simple/ideal HVAC system model in EnergyPlus, that is, there is a minimum level of effort required by the engineer to acquire these results. Sizing for other design alternatives could be test with relatively minimal time and effort. For example, the zones could be reassigned to test the sizing (and other implications like cost, loss of rental area, etc) implications of a floor-by-floor system, or a different arrangement of zones to AHU allocation.

Simulation of HVAC Systems

Representation of a full blown HVAC system is a challenge in any energy simulation program. The flexibility and detail afforded by EnergyPlus is a two edged sword. It will allow an experienced HVAC design engineer to model realistic building outcomes; but can be daunting and overwhelming for a new user.

The example results shown below are from different projects completed at our practise some years ago. These buildings have water cooled chilled water plant (with multiple chillers) supplying central AHUs with

VSD fan control. Further details cannot be provided due to the commercial-in-confidence nature of consulting, however the details provided are sufficient for the purpose of this paper while still allowing the building to remain anonymous. The completed projects easily meet the 5 star NABERS Energy (Base Building) requirements in Australia. That is, a Government trained assessor collected 12 months of utility bills, building survey drawings, carried out a site visit, and confirmed that the building landlord was responsible for less than 70 kg/m²/yr of GHG emissions.

(It useful for the reader to know that office buildings (in Australia) are required to rerate their buildings every 12 months. Therefore it is not sufficient for a building to perform efficiently in the first year, they need to continuously maintain, and indeed, improve upon their GHG emission performance).

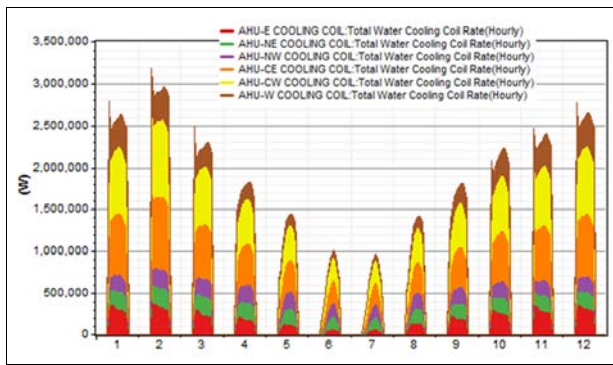


Figure 8 Chiller block load, represented as the sum of AHU loads for the Design Day of each month

Figure 8 is a graphical representation of the Design Day analysis carried out by EnergyPlus for the HVAC system described. Sizing is carried out at the start of each energy simulation run, provided EnergyPlus has been instructed to size Systems. A summation of the hourly cooling coil heat transfer rates for each monthly Design Day provides a clear picture of chiller capacity required for the peak day of each month. EnergyPlus then carries out the annual (or other time period) energy simulation run using these sizes.

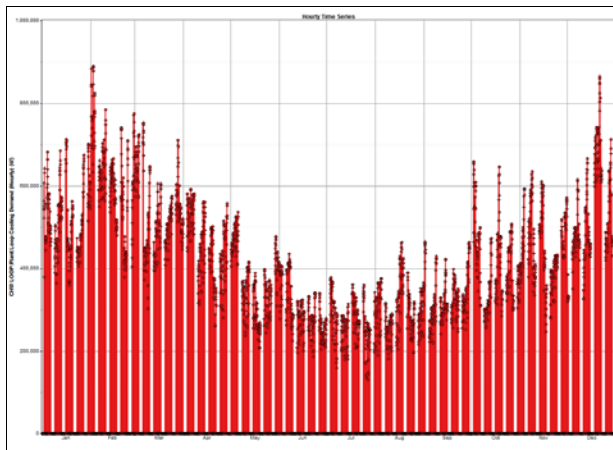


Figure 9 Hourly chilled water (CHW) loop cooling load

Figure 9 is the chilled water loop demand for each of 8,760 hours during which the HVAC is operational (the data shown in Figure 9 and Table 1 is from a different project to that shown in Figure 8).

The tabulated values shown in Table 1 are the data from Figure 9 that have been binned with reference the installed cooling plant capacity.

Taken together the data in Figure 8, Figure 9 and Table 1, when generated at design stage provide powerful insights for the HVAC design engineer.

Table 1: Bin analysis of hourly CHW loop load with respect to installed CHW capacity

Percentage of Installed Cooling Capacity	Estimated hours of operation	Percentage of total run hours
0 – 25%	750	27%
25-50%	750	27%
50-75%	1150	42%
75-100%	100	4%

For example, the data in Figure 8 predicts that this building will have a peak Design Day capacity of about 3,000kW. The early morning peaks which show up in the summer months (Jan, Feb, Mar, Oct, Nov and Dec) can be dealt with by starting plant operations an hour earlier. It also predicts that the maximum cooling loads in the winter months (Jun, Jul) are about a third of the maximum value at about 1,000kW.

The data in Figure 9 and Table 1 provide critical insights for energy efficient operation. These data are generated from analysing the thermal response of the building and it's systems to the periodic weather data contained in the reference weather data file.

The data in Figure 9 indicates that the chilled water plant, for this building, needs to be able to modulate efficiently down to 15% of installed cooling capacity. Furthermore, Table 1 informs the engineer that the correctly sized plant is only called to operate for 4% of operational hours above 75% of installed capacity.

The data also predicts that the “sweet spot” for the plant is in the capacity range between 50-75% of installed capacity, about 42% of operating hours. It also predicts that more than a quarter of the operating hours require the plant to work in the 0-25% capacity range.

Access to this type of design/performance information should lead to discussions on the risks to efficient performance due to HVAC plant and system oversizing, and insights into plant component selections, particularly for multiple chiller plant rooms. We note the difference between “oversizing” and “redundancy”. Engineers (and building owners) should strive to deliver flexible buildings with redundancy in systems; but should avoid oversized systems.

Used intelligently, an experienced mechanical designer can use information from right sizing and energy

simulation as demonstrated above, to design and deliver an HVAC system that will perform in an exemplary manner in the field.

Conclusions

It is our experience that in many building projects, the energy simulation analysis is carried out by an ESD team, separate from the HVAC design team. This paper argues the case for mechanical services engineers to leverage the opportunity of integrating these two functions to deliver exemplary design and performance outcomes.

This paper demonstrates how incorporation of the Heat Balance Method cooling load calculations into the EnergyPlus energy simulation program allows for the development of a modern approach for the design of high performance, conditioned buildings, based on the use of right sizing *AND* energy simulation. We hope it will encourage more HVAC design engineers to combine their design and sizing skills with energy simulation skills for performance prediction.

The authors have developed and used this design process for well over a decade. Combined with domain knowledge of HVAC systems, plant and control systems, it has resulted in the successful delivery and continued operation of a number of high performance buildings, particularly office buildings. An independent case study by the Office of Environment and Heritage (OEH 2016), NSW, Australia has documented a reduction of 46% annual electricity consumption for the Base Building (landlord's consumption) for an end-of-life HVAC plant upgrade in a 10,000m² office building carried out by the authors using this approach.

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