Energy performance and water usage of aquatic centres

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

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Declaration

I certify that except where due acknowledgement has been made, the work is that of the author alone; the work has not been submitted previously, in whole or in part, to qualify for any other academic award; the content of the thesis is the result of work which has been carried out since the official commencement date of the approved research program; any editorial work, paid or unpaid, carried out by a third party is acknowledged; and, ethics procedures and guidelines have been followed.

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Publications

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List of Abbreviations

ABS	Australian Bureau of Statistics
ACC	autoclaved aerate concrete
ACH	air change by hour
ARV	Aquatics and Recreation Victoria
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BCA	Building Code of Australia
BMS	building management system
BREEAM	Building Research Establishment Environmental Assessment Method
CBD	central business districts
CERM PI	Centre for Environmental and Recreation Management Performance Indicators
CHP	combined heat and power
CIBSE	Chartered Institution of Building Services Engineers
CO_2	carbon dioxide
COP	coefficient of performance
CTF	conduction transfer function
CV	coefficient of variation
DCCEE	Department of Climate Change and Energy Efficiency
DE	delivery energy
DEA	data envelopment analyses
DOE	Department of Energy
EM	engineering modelling
EPS	expanded polystyrene

EPW	EnergyPlus Weather
ENECC	EnergyPlus normalised consumption coefficients
ERR	Energy Efficiency Ratio
EU	European Union
EUI	energy use intensity
FAEC	final annual energy consumption
FEMP	Federal Energy Management Program
GBEL	Green Building Energy Label
HVAC	heating, ventilation and air conditioning
IDF	intermediate data format
IPMVP	International Performance Measurements and Verification protocol
ISO	International Organization for Standardization
IQR	interquartile range
LED	light-emitting diode
LEED	Leadership in Energy and Environmental Design
MBE	mean bias error
NABERS	National Australian Built Environment Rating System
NCC	National Construction Code
OLS	ordinary least square
PE	primary energy
PIR	polyisocyanurate
PIS	performance indicator system
PUR	polyurethane
PV	photovoltaic
RERM	Roadmap to a Resource Efficient Europe
RMSE	root-mean-square error

RMY	Representative Meteorological Year
SHGC	solar heat gain coefficient
SVM	support vector machines
UK	United Kingdom
UNEP	United Nations Environment Programme
US	United States
UV	ultraviolet
VAWT	Vertical-axis wind turbine
W-SAHP	water–solar-assisted heat pump
WELS	Water Efficiency Labelling and Standards
WUI	water use intensity
Q1	first quartile
Q3	third quartile

Abstract

Aquatic centres are major community facilities that require large amounts of water and energy to operate. They are unlike any other type of building in terms of energy and water consumption, and can consume up to seven times more energy per floor area compared to an average commercial office building. To date, there have been insufficient studies examining the energy performance and water usage of aquatic centres worldwide, thus, causing a lack of information and research, and complicating understanding such energy and water usage markers. Therefore, the aim of this study is to investigate the energy performance and water usage of aquatic centres. The research objectives are listed below:

1. Develop a guideline for the definition of aquatic centres in Victoria, Australia for the purpose of energy and water benchmarking.
2. Benchmark the energy and water consumption of aquatic centres by analysing the data collected from existing aquatic centres.
3. To investigate operational and building design features that will improve the energy and water performance of a sample aquatic centre by using building performance simulation.

By reviewing previous studies on energy and water benchmarks for aquatic centres and using industry-obtained data, this study emphasises how the lack of a clear definition for 'aquatic centres' creates confusion when researching such consumption. The first section of this study proposes a definition of an aquatic centre by investigating those operating within Victoria through desktop research. Information from 110 aquatic centres was collected and used to establish various categories of these facilities based on the types and number of amenities they provide. This study next defined an aquatic centre as a community or public venue that provides at least an indoor swimming pool and three different types of amenities, including a gymnasium, sauna or spa, a cafe and a creche.

The second section establishes energy and water benchmarks for aquatic centres by analysing data collected from 22 aquatic centres using questionnaires and site visits. The main data used to perform this analysis included utility bills (e.g., gas, electricity and water) for at least 12 months, floor areas of the sample aquatic centres, types of amenities and occupancy data. Other architectural and electromechanical information such as heating, ventilation and air conditioning (HVAC) systems, lighting types, glazing types and construction materials were also collected. A statistical regression-based benchmarking method was then used to identify the relevant correlations and significance of several variables such as conditioned usable floor area, gross floor area, water surface area and number of visitors in relation to the energy and water use of aquatic centres. This analysis indicated that conditioned usable floor area and visitor numbers had the strongest correlation and significance to aquatic centre energy and water consumption, respectively; however, no strong correlation was found between energy and water use. In addition, the energy consumption of aquatic centres ranged between 648 kWh/m^2 and 2,283 kWh/m^2 (conditioned usable floor area), while water consumption ranged between 11 L/visitor and 110 L/visitor. However, this method has limitations in understanding the influence of different control strategies, design and occupancy variables on the energy and water use of aquatic centres. Indeed, building energy simulations have been identified as an alternative approach to address such enquiry.

The final section of this study was to simulate such consumption data using DesignBuilder and EnergyPlus (version 8.7). DesignBuilder was used to facilitate the construction of the three-dimensional aquatic centre model, while EnergyPlus 8.7 was used to perform the simulations in relation to the complex interaction (evaporation) between water and air within swimming pool halls. An existing aquatic centre within the sample was used as a case study, which was then calibrated against the measured

energy and water data (utility bills obtained from the aquatic centre) before undertaking a range of parametric studies concerning several energy- and water-efficient features, including solar heating for pool water using glazed collectors (15% reduction on the total energy of the aquatic centre), light-emitting diode (LED) lighting (3.5% energy reduction), pool-water and pool hall air temperature reduction by 1 °C (6.1% energy reduction), pool covers (3% energy reduction and 1.2% water reduction) and vacuum filters (20% water reduction). A respective 34% and 20% reduction in energy consumption and greenhouses gas emissions was achieved by combining several architectural and electromechanical features such as double glazing, insulation upgrades, air and water temperature reductions, pool covers, using high-density materials, glazed solar pool-water heating systems and LED lighting.

Overall, this study provides a significant contribution to the knowledge of energy and water usage in aquatic centres, as it is one of the first to propose a clear definition of an aquatic centre prior to performing further investigation. In addition, it also models the energy and water consumption of an aquatic centre using the indoor swimming pool module in EnergyPlus. A set of energy and water benchmarks for aquatic centres was also proposed, which can be subsequently applied for wider industry use. Together with the proposed definition, the proposed guidelines and the energy and water benchmarks, it is now easier for aquatic centres in Australia and worldwide to compare their energy and water use. Also, a step-by-step guide on how to simulate an aquatic centre using EnergyPlus is provided in this study. The results will be beneficial for not only future simulation of swimming pool facilities but for also to the aquatic industries.

Chapter 1: Introduction

1.1 Introduction

Many countries around the world are now in agreement that climate change is one of the greatest threats facing the planet. A rise in greenhouse gas emissions in the last 30 years is a major cause that governments and industries are constantly looking at ways of reducing. According to Lucon et al. (2014), greenhouse gas emissions from the building sector have more than doubled since 1970, reaching 9.18 $GtCO_2$ in 2010, while the United Nations Environment Programme (UNEP 2009) similarly found such production contributes up to 30% of global annual greenhouse gas emissions. Indeed, this sector alone accounts for approximately 32% of total global final energy, thus, making it one of the largest end-use sectors worldwide, which consumes a global average of 30% of the world's fresh water over an entire life cycle (IEA 2013; UNEP 2006). According to the Roadmap to a Resource Efficient Europe (RERM), better construction and uses of buildings could facilitate significant resource savings and reduce 42% of the world's final energy consumption, about 35% total greenhouse gas emissions and potentially save up to 30% water in some regions (ECORYS 2014).

Rapid growth in purchasing power in emerging economies and developing countries caused by a growing population means that energy demand in buildings could increase by 50% by 2050 (UNEP 2016). In the United Kingdom, the housing sector alone contributes to roughly 20–30% of a nation's greenhouse gas emissions (Gupta and Gregg 2012). Therefore, the building sector has the largest potential to significantly reduce greenhouse gas emissions compared to other sectors. For example, more than half the world's new buildings are constructed in Asia every year. China alone has 40 billion square metres of existing buildings and adds an additional 2 billion square metres of floor area each year; similarly in India, the built area more than doubled between 2000 and 2005 (ABC 2008). An increase in the construction of new buildings will also drive energy demand and buildings-related emissions, with the global floor area expected to double to more than 415 billion square metres by 2050 (UNEP 2016).

According to the International Organization for Standardization (ISO 2006) Standard 14064, greenhouse gas emissions from buildings are generally created by three sources: direct emissions sources—which are the greenhouse gas sources located physically in a building, mainly fossil-fuel consuming equipment such as gas boilers and gas stove cooking—indirect emissions sources from building electrical energy consumption by electrical equipment incorporated in buildings—including heating and cooling systems, electric lighting, elevators, pumps and household appliances—and a building's indirect emissions from other sources, which relate to the embedded emissions from building materials and the greenhouse gas emissions generated by urban planning decisions such as unnecessary travel or location-induced traffic.

Given the inefficiencies of existing and old buildings worldwide as well as a growth in construction to accommodate rising populations, greenhouse gas emissions will continue to increase if no action is taken. The industry's contribution to climate change and climbing emissions has resulted in a growing interest in the energy efficiency of buildings. With its unique potential to simultaneously contribute to long-term energy security, economic growth and even improved health and wellbeing—particularly to reduce greenhouse gas emissions (IEA 2014)—energy efficiency can help address the challenges of climate change. For example, a study by UNEP, the United Nations Foundation and the World Bank (2006) estimates both China and India could cut current energy consumption in the building sector by 25% through high-efficiency lighting, efficient air conditioners, boilers and waste heat recovery systems technologies, which are each widely available today.

Further, there is an increase in the use of environmental rating tools such as Green Star, Leadership in Energy and Environmental Design (LEED), the National Australian Built

Environment Rating System (NABERS) and the Building Research Establishment Environmental Assessment Method (BREEAM) to assess the energy component of buildings with the aim of making them more energy-efficient. As of October 2013, 19,416 projects received LEED certification globally, with 17,270 of those being based in the United States (US) and another 494 in China, which also became certified in August 2012 (Khanna et al. 2014) since the launch of the Green Building Energy Label (GBEL) in 2007. Additionally, as described by Williamson, Soebarto and Radford (2010), there has been an increase stringency in building regulations in Australia and worldwide aimed at reducing greenhouse gas emissions and achieving an efficient use of energy and water. For example, in Australia, energy-efficiency requirements for all classifications of buildings have been incorporated in the National Construction Code (NCC) to encourage the efficient use of energy and to reduce greenhouse gas emissions.

The focus of this study is directly related to the energy performance of a particular type of building: aquatic centres. Typically, an aquatic centre includes indoor swimming pools and other facilities, and, based on previous studies, also consume large amounts of energy and water. According to Rajagopalan (2014), aquatic centres can expend around seven times more energy for every square metre of building area compared to an average commercial office building; likewise, Sydney Water (2011) found aquatic centres in Sydney alone can use around 1,000 ML of water each year and an office building with a Net Lettable Area of 10,000 m^2 can consume approximately 15 ML of water each year (Bannister, Munzinger and Bloomfield 2005). Conversely, it can be argued that the number of aquatic centres around the world is significantly lower compared to other types of commercial buildings. However, based on Rajagopalan's (2014) estimation, a reduction of 10% in the energy consumption of Australian aquatic centres can avoid the production of at least 3.5 million tonnes of carbon dioxide (CO_2) emissions. Therefore, focusing on energy efficiency in aquatic centres can contribute towards reducing the greenhouse gas emissions of buildings.

1.2 Problem Statement

The many inconsistencies in defining buildings with swimming facilities nationally and internationally have created difficulties when researching and comparing data. One such issue within the aquatics and recreation industry is a lack of clarity regarding a definition for aquatic centres, including the types of amenities they provide. Further, such buildings are often not included in major research studies on energy performance, with several of the aforementioned environmental ratings systems (i.e., Green Star, LEED, NABERS and BREEAM) also lacking specific rating tools to assess aquatic centres. In 2012, the Department of Climate Change and Energy Efficiency (DCCEE 2012) investigated the baseline energy consumption and greenhouse gas emissions in Australian commercial buildings to identify the average energy intensity of different types of buildings, including office buildings, supermarkets, hotels, shopping centres, hospitals, schools and universities; however, aquatics centres and swimming pool facilities were not part of the study. Overall, it found supermarkets have the highest average energy intensity of around 940 kWh/m^2 (DCCE 2012), which is less than that of an aquatic centre.

Another issue regarding why aquatic centres are often overlooked in research concerns the complex interactive nature of this building type. Typically, such centres have specific ventilation requirements, high humidity levels, water evaporation, and water and space heating. Indoor swimming pools have very high evaporation rates and extreme humidity-control issues that must be considered both architecturally and mechanically, both to provide good thermal comfort and to protect structural integrity (West 2005). Around 70% of heat energy lost by pools is due to pool-water evaporation, while a further 27% of heat energy is lost through ventilation systems for indoor pools (Sydney Water 2011).

The discrepancies discovered in current literature have identified the main problem as a lack of information and performance standards for aquatic centres compared to other building types (such as office buildings, residential buildings and shopping centres).

Essentially, there has not been sufficient research to date that examines the energy performance and water usage of aquatic centres worldwide compared to other building types. Reliable performance requirements and indicators are one of the main '"building blocks" for a successful greenhouse gas mitigation and energy efficiency strategy for buildings' (UNEP 2009, p. 15). This lack of information and research have consequently made it difficult to obtain clear and verifiable indicators with which to measure, compare and understand the energy and water usage of aquatic centres. Currently, there are no general Australian energy and water performance standards for either public swimming pools or buildings housing public pools (Wilkenfeld & Associates 2009), and, upon reviewing current literature on benchmarking energy performance and water use in such buildings, there is neither consistency between researchers in the way these benchmarks were performed (different performance indicators were used). Indeed, as most will inevitably bear their own definitions and interpretations of what constitute an aquatic centre, such complications have assisted in identifying and establishing this study's aim, research objectives and questions.

1.2.1 Research Aim and Objectives

The aim of this research is to investigate the energy performance and water usage of aquatic centres. The objectives are to:

1. develop a guideline for the definition of aquatic centres in Victoria for the purpose of energy and water benchmarking
2. benchmark the energy and water consumption of aquatic centres by analysing the data collected from existing facilities in Victoria
3. To investigate operational and building design features that will improve the energy and water performance of a sample aquatic centre by using building performance simulation

1.2.2 Research Questions

This study aims to answer the following research questions:

1. How can aquatic centres be defined for the purpose of energy and water benchmarking?
2. What are the key performance indicators that can be used to benchmark the energy and water consumption of aquatic centres in Victoria?
3. What are the ranges of energy and water consumption of aquatic centres in Victoria?

4. How can the energy and water consumption of Victorian aquatic centres be benchmarked?
5. What are the main energy- and water-efficiency features that can influence the energy and water use of an aquatic centre?

1.3 Research Significance

The findings of the research will provide substantial information about the energy and water performance of aquatic centres in Australia and globally. This study will also provide a clear definition of an aquatic centre, thus, streamlining the distinction between aquatic centres and other buildings with swimming pool facilities. The aquatic industry will also be able to use the findings of this research to understand their own performance. For example, an aquatic centre can refer to the energy and water benchmarks provided in this study to decipher whether they are classified as a low-, medium- or high-energy or water user; this can then assist their decision-making when making any necessary adjustments to be more water and energy efficient, should they be classified as the latter. Likewise, researches and academics can use the techniques, processes and guidelines provided in this research to perform further studies on aquatic centres and swimming pool facilities. For example, one could simulate the energy performance of indoor swimming pools using the new EnergyPlus indoor swimming pool module.

Moreover, other organisations such as local councils, state government and building associations can use the findings to identify targets for energy, water or greenhouse gas reduction projects, measures or regulations. Overall, any structure with indoor swimming pool facilities can refer to this study to further understand how best to approach and investigate the complex interaction of air and water present in buildings with indoor swimming pools.

1.4 Thesis Outline

This chapter defined the link between energy use and the built environment. Buildings have been identified as a major consumer of energy and water worldwide, which are likewise responsible for producing significant greenhouse gases. A brief introduction of the type of building (i.e., aquatic centres) being investigated in this study has also been established, with the key issue begging further analysis being a lack of relevant information and research; in turn, this has complicated the process to source reliable performance standards and develop efficient and cost-effective strategies for reducing the energy and water use of aquatic centres. Indeed, it is understood that reducing energy consumption can result in lower greenhouse gas emissions.

Chapter 2 will demonstrate how defining the term aquatic centre has been complex and, thus, created a need to identify what it is and what types of amenities it typically includes. The increasing popularity of such buildings and indoor swimming pools, both nationwide and globally, is demonstrated, with the significance of the industry also shown. Past and recent studies on aquatic centres and indoor swimming pools are reviewed and compared to emphasise the often-confusing research process of energy and water usage. This judgement is undertaken by examining the existing benchmarks of aquatic centres worldwide and in Australia.

Chapter 3 next comprises three parts: the energy and water use of aquatic centres, and the relevant benchmarking methods. Elements such the heating, ventilation and air conditioning (HVAC) systems, pool-water heating, evaporation, humidity and heat loss and gain, which denote aquatic centres among the most energy-intensive buildings, are then discussed, with evaporation being defined as one of the most important factors when dealing with such structures. The second part of Chapter 3 explores the water use of aquatic centres, which, although equally important to energy use, bears only limited global research. Indeed, change in one sector can affect the other; however, in Australia, only a few comprehensive guidelines on the water use of aquatic centres and swimming pools have been published. Finally, Chapter 3 then explains how to investigate the energy and water use of aquatic centres. Although developing performance standards can help understand these elements, retrofitting and predicting the performance of new building projects is crucial. Consequently, this discussion leads to a focus on computational-based building simulations.

Chapter 4 discusses the study's research approaches and investigates the relevant methods used in past literature. As discovered, benchmarking has been identified as the best approach to undertake this assessment, with both statistical regression-based methods as well as building simulations facilitating assessments of energy performance and examination. Discussion on the types of efficiency indicators relevant to aquatic centres for energy and water use is also undertaken in this chapter, with a whole-building simulation method and its relevance to this study being likewise discussed. As discovered, several software tools are available; however, identifying the most suitable to model the interaction between air and water within swimming pool halls can be challenging.

Chapter 5 then defines the research approaches used to undertake this investigation, with particular emphasis on quantitative research approaches. It also provides details of the data collection methods adopted, including statistical regression-based benchmarking and performing energy simulations. Evidently, simulating an aquatic centre proved a complex exercise, with the various steps of which being subsequently discussed. Overall, this chapter provides all the necessary steps and procedures adopted to investigate the energy performance and water use of aquatic centres.

Chapter 6 offers a definition for the term aquatic centre based on data collected from 110 aquatic centres which provides a clear understanding of the type of building being investigated in this study. A guideline for identifying aquatic centres and how best to facilitate their energy and water benchmarking is also provided prior to discussing the proposed scales. The appropriate energy use intensity (EUI) and water use intensity (WUI) relevant to aquatic centres have too been established based on statistical analysis, with both correlation and multiple regression analyses also applied to identify the most relevant and significant variables pertinent to the energy and water usage of aquatic centres. Once a set of benchmarks is proposed, further analysis is undertaken to facilitate a deeper understanding of the features that deem aquatic centres more energy and water efficient.

Chapter 7 next examines an actual aquatic centre simulation, with a participating facility being used as a case study. The simulation software employed are DesignBuilder (which builds the three-dimensional model) and EnergyPlus (which includes the swimming pools in the model and performs the simulation runs). The steps in building the model and calibrating against the data obtained from the utility bills are described in detail, including the method used for verifying the evaporation rate. Once the model is successfully calibrated and validated, parametric studies are undertaken to investigate the effects of selected architectural and electromechanical interventions on both energy and water use.

Finally, Chapter 8 compiles the research findings and conclusions of this study. Essentially, it finds this investigation provides considerable information on and analyses of the energy performance and water use of aquatic centres. The significance of these findings to the research field, as well as the limitations of the study and recommendations for further research, are also discussed in this chapter.

Chapter 2: Aquatic Centres

2.1 Introduction

Having discussed the research problem and identified the aims and objectives in Chapter 1, this chapter next provides an extensive overview of the inconsistencies when defining an aquatic centre, the global importance and significance of the industry and a comparison of existing aquatic centre and indoor swimming pools studies. Difficulties reaching a proper definition of the term 'aquatic centre' is discussed in Section 2.2, followed by a discussion on associated industries. Subsequently, existing aquatic centre studies are reviewed, and a comparison between the existing energy and water benchmarks is next undertaken.

Sport is an important aspect of Australian lifestyle that plays a significant part in the lives of many. Participation in physical recreation offers many benefits, ranging from simple enjoyment to improved health, as well as opportunities for social interaction (ABS 2011). Recreational swimming is also one of Australia's most popular activities. According to the Australian Bureau of Statistics, swimming participation grew to 14–19% in 2010, with many parents wanting to ensure their children are safe around water (Pigs Will Fly 2010). Additionally, as rising obesity rates continue to challenge the nation, the fitness industry has also changed dramatically in the past decade. An increase in obesity and obesity-related diseases have triggered the need for more physical activity and exercise, and has likewise been a major factor influencing sports policy in recent decades, with governments and companies increasingly turning to sport to address this crisis (CSIRO 2013). Alarmingly, one in two Australians are overweight, the proportion of which is projected to rise a further 15% over the next 10 years (OECD 2010). Naturally, this trend has caused an increase in demand for recreational facilities such as aquatic centres, gyms and fitness centres. For example, a major share of pool users will travel for more than 15 minutes to use high-quality aquatic facilities (Holroyd City Council 2013), thus, partly confirming the increased demand for superior services nationwide. Currently, there are approximately 1,900 aquatic and recreation centres in Australia, which attract around 263 million visits each year (ABS 2011).

As mentioned in Chapter 1, the number of aquatic centres is much lower than that of office buildings—in fact, Australia's office sector accounted for over 23.8 million square metres of office space across various central business districts (CBDs) (over 16 million square metres) and non-CBDs (over 7.5 million square metres) in July 2011 (PCA 2011). Additionally, the majority of the nation's aquatic centres are ageing, despite an increase in their refurbishment within recent years. In the past five years, the development and renewal of aquatic leisure centres within greater metropolitan Melbourne have been both significant and in direct response to the changing needs of customers, including the increasing role these facilities play in the provision of health and leisure activities for individuals, groups and families alike (Moonee Valley City Council 2014). A few recent examples of completed and ongoing restoration in Victoria alone include the Noble Park Aquatic Centre, the Hawthorn Aquatic and Leisure Centre in 2014 (ARV 2015), the Collingwood Leisure Centre in 2012 (Yarra City Council 2015), Ivanhoe Aquatic Banyule Centre (Banyule City Council 2015), Aqualink Box Hill (Whitehorse City Council 2015), the Broadmeadows Aquatic and Leisure Centre (Hume City Council 2015), and the Eltham Leisure Centre (Nillumbik Shire Council 2015), to name a few. Indeed, these recent refurbishments provide evidence of a definite rise in aquatic centre interest nationwide, and underline a need to streamline energy and water efficiency in such buildings in the short term. In fact, several of these revamps have already focused on efficiency. Notably, Whitehorse City Council (2015) expressed their attempts to set a new benchmark for aquatic and leisure facilities with the redevelopment of Aqualink Box Hill, not only as a model facility for accessibility and quality but also for energy efficiency.

To understand how aquatic centres operate, it is then necessary to identify what an aquatic centre is and what amenities they typically include. However, based on a review of the available literature, this proves a difficult task. As shown in Section 2.2, several terms have been used to describe aquatic centres in the past.

2.2 Inconsistencies in Defining Aquatic Centres

As Tower, McDonald and Stewart (2014) note, a major issue in the aquatics and recreation industry concerns a lack of clarity regarding the definition of aquatic centres and the types of amenities they provide. They also acknowledge a difficulty to suggest a single term that accurately describes all aquatic and recreation facilities. There have been many inconsistencies in naming buildings with swimming facilities nationally and internationally, with many different terms and names being used in past studies to describe aquatic centres; some of which include aquatic leisure centres (Sydney Water 2011), public pools (Wilkenfeld & Associates 2009), public aquatic and recreational centres (Howat 2013), aquatic and recreational centres (Tower, McDonald & Stewart 2014), aquatic facilities (Rajagopalan 2014), indoor swimming pools and leisure centres (Hancock & Chem 2011), public swimming baths (Saari & Sekki 2008), natatoriums (USA Swimming 2010) and leisure pool facilities (Kampel, Aas & Bruland 2014). There is also conflict within ABS figures regarding the collection of data about the sport and recreation industry. Tower, McDonald and Stewart (2014) pointed out that in recent years there have been three changes in the statistical parameters of measurement for facilities that include aquatic and recreational centres. Aquatic centres were included under health and fitness centres and gyms in 2010, then were changed to structured facilities such as gyms, public pools or courts in 2011; to add confusion, in the analysis and naming of aquatic centres, the ABS divided this type of building into two separate sections: indoor and outdoor facilities. Therefore, based on ABS (2011) data, there is no clear indication under which category aquatic centres with both indoor and outdoor swimming pools fall.

In addition, several past studies fail to clearly describe the exact facilities included within aquatic centres. For example, Tower, McDonald and Stewart (2014) stated an aquatic and recreational centre is defined as a community venue that provides a pool and both fitness and active recreation facilities, but without specification of whether that pool is indoor or outdoor. Further, neither Sydney Water's (2011) 'Best Practice Guidelines for Water Management in Aquatic Leisure Centres' provides a definition of what constitutes an aquatic leisure centre, nor do the Centre for Environmental and Recreation Management Performance Indicators' (CERM PI 2013, 2014) 'Operational Management Benchmarks for Australian Public Sport, Leisure and Aquatic Centres' reports indicate their included facilities.

Figure 2.1 illustrates the layout of an aquatic centre with three indoor swimming pools, a spa, a gym, a creche and a cafe, while Figure 2.2 provides an internal photographic image of an aquatic centre. Indeed, it is vital to identify what an aquatic centre means or consists of to provide a clear understanding for this study's subsequent investigation (see Chapter 6 for a proposed definition). Just how substantial aquatic centres in both Australia and worldwide are will be demonstrated in Section 2.3.

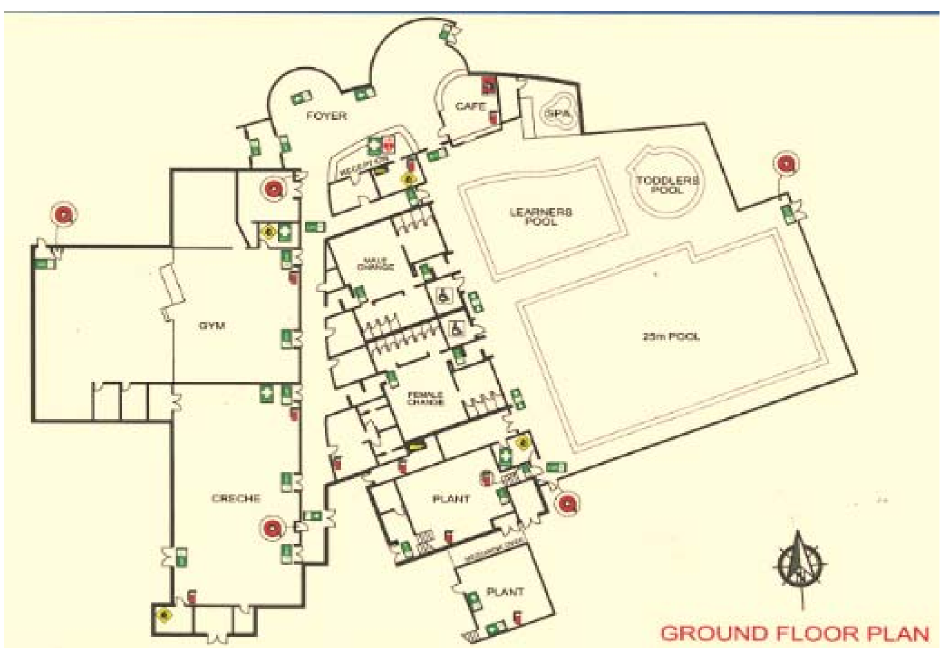


Figure 2.1. Example layout of an aquatic centre.

Figure 2.2. Internal photo of an aquatic centre.

2.3 Aquatic Centres and Associated Industries

The aquatic and recreational sector is a large global industry. In Europe, there are around 1.5 million sports facilities that include swimming pools, which represent 8% of the world's overall building stock (Step2Sport 2015). In 2014, the Step2Sport project was introduced by several European countries to support the refurbishment of existing sport buildings contributing to the European Union's (EU) energy objectives. This project focused on two types of sporting facilities—indoor swimming pools and indoor sport facilities such as multifunction sports centres, community centres and gymnasiums—and aimed to have a long-term effect on and involvement in Europe's strategic goals by contributing a minimum 20% reduction in CO_2 emissions by 2020. Indeed, Europe has a large number of sports centres with swimming pool facilities. That is, Norway has around 850 swimming pools ranging from small school pools to various amenities for therapeutic use, sports and leisure, as owned and operated by various municipalities (Kampel, Aas & Bruland 2014). There are also approximately 1,468 swimming pools in Belgium, 189 in Denmark, 750 in France, 3,168 in Germany, 29 in Greece, 89 in Ireland, 1,489 in Italy, 300 in the Netherlands, 116 in Portugal, 1,025 in Spain and 2,390 in the United Kingdom (UK) (Trianti-Stourna et al. 1998).

With over 10.4 million residential and 309,000 public swimming pools in the US (CDC 2016), it is unsurprising that swimming was the fourth most popular recreational activity in 2009 (US Census Bureau 2012). Additionally, there were approximately 301 million visits to swimming pools each year by persons over the age of six, with 36% of children aged 7–17 years old and 15% of adults swimming at least six times annually (US Census Bureau 2012). Similarly, research on the overcrowding of swimming pools in China found there are well over 6,000 swimming pool facilities registered in China's Health Ministry Report (Kaushik 2015). Despite this information, it is still relatively difficult to obtain or source existing data on global aquatic centres and swimming pools, especially for developing countries.

The aquatics and recreational industry in Australia is equally significant. With over 250 million visitors each year and 86,000 staff across Australia (Australian Water Safety Council 2007), this sector comprises a significant part of the nation's broader economy. According to Aquatics and Recreation Victoria (ARV 2014), there are around 1,900 aquatic centres in Australia, with 500 of which located in Victoria. Across the nation, there are 217 aquatic facilities in New South Wales (Swimming Australia 2015), with 84 council-owned aquatic centres and 57 public swimming pools in clubs in Sydney alone (Sydney Water 2011); there are approximately 120 aquatic centres in Western Australia, 82 registered aquatic centres in Queensland, 17 in South Australia, nine in the Australian Capital Territory, nine in Tasmania and three in the Northern Territory (Swimming Australia 2015).

Evidently, the aquatics and recreation industry is big, with over 100,000 swimming pool facilities located around the world as demonstrated above. Hence, focusing on the energy and water performance of these centres can provide benefits, not only in energy and water conservation, but also in the goal towards reducing global emissions. The size of this industry has been identified to demonstrate the relevance of this study beyond Australia, with the provided definition (Section 2.2) facilitating the distinction between aquatic centres and small indoor swimming pools (e.g., within a school)—hence, as the majority of the countries listed has classified all swimming pool facilities within the same category, regardless of their size, it is, therefore, illogical to compare an aquatic centre with a small indoor swimming pool.

Accordingly, Section 2.4 will provide a brief review of several relevant past studies undertaken on aquatic centres and indoor swimming pools to provide a general understanding of the main areas of focus within such research. However, a more in-depth review will also be awarded within the following chapters when specific factors relevant to this study are investigated.

2.4 Past Aquatic Centres and Indoor Swimming Pools Studies

In previous decades, and with further acknowledgement of global warming, there has been increased interest in energy efficiency, thus, spurring substantial changes in the design and development of swimming and aquatic facilities. Prior to the 1980s, most swimming pools were outdoors, whereas many current indoor pools serve different types of communities and various population sizes (Holroyd City Council 2013). Although conventional outdoor pools are great assets during summer, they are less cost-effective than their indoor counterparts. The lack of shallow and heated water, exposure to weather and the short season (especially in the cooler regions) limit the range and flexibility of programming at traditional facilities. Conversely, indoor heated pools have the potential to break even financially, as they are occupied year round. According to the IECU (1994), indoor pools receive around 300,000 visits each year compared to the annual 53,000 visits for outdoor pools.

The complex nature of this building type has limited the studies on aquatic centres and indoor–outdoor swimming pools compared to other buildings. The majority of those studies investigated different aspects or areas of such buildings; that is, some analysed swimming pool halls only, others studied an entire aquatic centre (which can include several amenities including a gym, sauna or indoor sports hall) and several instead focussed on HVAC and pool-heating systems. Kampel, Aas and Bruland (2013, 2014) audited several aquatic centres in Norway and produced one of the most recent studies on the characteristics of energy-efficient swimming facilities. Additionally, Rajagopalan (2014) recently performed a study on the energy performance of aquatic facilities in Victoria; however, only six aquatic centres were analysed. Trianti-Stourna et al. (1998) also performed a number of energy audits and analyses to improve indoor conditions and optimise energy usage as such, while Isaac, Hayes and Akers (2010) studied one aquatic facility to understand its energy and water expenditure.

Importantly, none of these studies provides detailed energy-use data on swimming facilities, excluding Saari and Sekki (2008), who used a computational research method to perform in-depth energy and water analyses on one selected public swimming bath located in Greater Helsinki. They also investigated the sensitivity of environmental effects on swimming pools' operational energy consumption in relation to a design solution (i.e., insulation and ventilation) and to the mode of use (i.e., increasing and decreasing temperature, and attendance). Further, Mousia and Dimoudi (2015) recently published papers on the energy performance of swimming pools in Greece, albeit focusing solely on outdoor swimming pools. Another study performed in Greece by Marinopoulos and Katsifarakis (2017) discussed ways of improving the sustainability of swimming pools by reducing energy and water consumption. Using an open swimming pool in Thessaloniki in Greece as a case study, they investigated how best to improve energy and water use; however, they focused more on heating energy opportunities and how more savings could be achieved, instead of water optimisation. The installation of solar thermal collectors, geothermal heat pumps, solar photovoltaic (PV) panels and the construction of a light roof were also analysed. Marinopoulos and Katsifarakis (2017) concluded it was possible to achieve an energy saving of up to 80–90% with solar panels.

Several research papers have also analysed HVAC systems used in indoor swimming pools, including heat pumps (Sun et al. 2011), different heat-recovery systems for indoor swimming pools (Johansson & Westerlund 2001; Lazzarin & Longo 1996) and energy savings using solar energy for water heating (Tagliafico et al. 2012). Some papers have also investigated water evaporation in swimming pools, which constitutes a major factor influencing energy consumption. For example, Shah (2012) examined several methods for calculating evaporation rates, while Asdrubali (2008) evaluated water evaporation in indoor swimming pools using a scale model. Meanwhile, others researched the quality of indoor environments and the thermal comfort of swimming pool halls (Sun et al. 2011; Yuce et al. 2014), while Rajagopalan and Luther (2013) examined the thermal and ventilation performance of a naturally ventilated sports hall within an aquatic centre. Jelinek, Krupicova and Petricek (2014) presented research papers on the optimisation of a swimming pool hall's envelope with respect to thermal and moisture design, and Mancic et al. (2014) looked at the mathematical modelling and simulation of thermal performance, while investigating the effect of solar-heating systems for pool-water heating. Additionally, Koper, Lipska and Michnol (2010) explored thermal comfort within indoor swimming pools using numerical computational fluid dynamic analysis for their assessment. Some recent papers used artificial neural networking to predict energy consumption and evaporation rates for indoor swimming pools. Notably, Yuce et al. (2014) utilised this technique to predict energy consumption and thermal comfort levels as such, while Lu, Lu and Viljanen (2014) similarly predicted water evaporation rates for an indoor swimming pool hall in their study.

Evidently, most of these papers deal with specific aspects related to energy consumption, with few focusing on the overall energy use and performance of aquatic centres. However, there is a lack of published material on the water usage of aquatic centres and indoor swimming pools compared to energy. Perhaps the most notable include Isaac, Hayes and Akers (2010), who investigated the water use of one aquatic facility in Wales using an audit. Their study looked at the operation of filters, backwashing procedures and frequencies, and the evaporation of pool water. Similarly, Kampel, Aas and Bruland (2014) briefly mentioned the water consumption and water quality of several aquatic centres in Norway in a research paper that otherwise focused on energy efficiency. Hence, a lack of research papers on the water consumption of aquatic centres in European countries is clear, and this is possibly due to the continent's general lack of issues with water supply compared to Australia. Correspondingly, Sydney Water (2011) and the ARV (2009) have performed comprehensive studies focusing on the nation's water use in aquatic centres. Both organisations have produced several guidelines on water usage and savings, each of which include detailed information on water management systems in aquatic centres, saving water from treatment, filtration, make-up, and evaporation, sustainability opportunities and alternative water sources.

Nonetheless, one key difference between aquatic centres and other building types remains their effect of both water and energy consumption. That is, an increase or decrease in the consumption of one can directly affect the other. When investigating aquatic centres, both water and energy use must be considered, particularly as very little studies have concurrently examined both. As such, this study endeavours to fill this gap, beginning with Section 2.5, which discusses the confusion that arises when comparing aquatic centres studies that is perhaps linked to this lack of descriptive clarity in the field. Since the main focuses of this study are both energy and water use in aquatic centres, a review and comparison of an existing benchmark will be undertaken.

2.5 Current Benchmarks of Aquatic Centres

Aquatic centres are often overlooked or omitted in major efficiency studies, including that of the DCCEE's (2012) regarding baseline energy consumption and greenhouse gas emissions in Australian commercial buildings. This investigation assessed the average energy intensity of several types of buildings including office buildings, supermarkets, hotels, shopping centres, hospitals, schools and universities, but not aquatic centres or any building containing public swimming pool facilities. In addition, many existing environmental rating tools such as Green Star, LEED, NABERS and BREEAM do not specifically rate aquatic centres for energy efficiency.

According to British Swimming (2008), no specific BREEAM tool exists for sport and recreation buildings; however, a bespoke assessment can be made based upon the components that comprise such a structure. For example, an office within an aquatic centre can be accessed under the BREEAM ‘Office’ category, a cafe or gym under the ‘Retail’ category and a stadium under the ‘Other Buildings’ category. Some of the main BREEAM credits that can also find relevance to aquatic centres are energy and water. Conversely, NABERS measures the energy efficiency, water usage, waste management and indoor environment quality of a building or tenancy, including its environmental effects. It does this by using measured and verified performance information (such as utility bills) and converting them into a comprehensible star-rating scale ranging from one to six (NABERS 2016). Essentially, this tool assesses multiple building types, including offices, shopping centres, hotels and data centres. A NABERS rating could then be obtained for the office area of an aquatic centre, but only if it were metered separately, which is rarely the case. Additionally, the NABERS hotel category, in particular, does allow for the energy consumed by indoor swimming pools within its internal calculation, but this category can only be used to assess hotels specifically. Meanwhile, LEED and Green Star rating tools are similar to BREEAM in relation to their custom-made assessments, which can be deciphered based upon the different areas of an aquatic centre. Both LEED and Green Star also have similar credits (notably ‘Energy’, ‘Water’ and ‘Indoor Environment Quality’) that can find relevance to such facilities. For example, within Green Star’s ‘Energy’ category, there is an energy consumption and greenhouse emissions calculator in which the energy consumption arising from an indoor swimming pool obtained from hand calculations or building energy simulations can be included. Nonetheless, neither of these frameworks specifically assess sport and recreational buildings with indoor swimming pools or aquatic centres.

Conversely, benchmarking is a common method used in several studies. As demonstrated in Tables 2.1 and 2.2, which offers a comparison between the energy and water use of aquatic centres, benchmarking is a common method to measure, compare and promote the efficient use of energy and water in buildings. Additionally, it also describes the process of either accounting for and comparing a metered building's current energy and water consumption with an energy or water baseline, or comparing a metered building's energy and water use with that of a similar type of building (DOE 2010). Typically, these models are constructed in a simple benchmark table (percentile table) of energy use, which is normalised with indicators such as floor area, temperature and occupancy (Chung, Hui & Lam 2006). Additionally, several methods can be used to compare the energy and water efficiency of buildings, the most common of which include statistical regression-based benchmarking, computational or simulation model-based benchmarking and points-based rating systems. More details and reviews on benchmarking will be provided further within this study, as this method has been previously proven useful for investigating energy and water consumption. Reviewing past aquatic centre benchmark studies in Sections 2.5.1 and 2.5.2 subsequently helps highlight the difficulty in comparing studies and identifying which should be applied as such.

2.5.1 Energy Benchmarks for Aquatic Centres

Benchmarking the energy and water use of an aquatic centre is a complex task due to its unique building-specific patterns. It is equally difficult to find two aquatic centres with similar layouts. Further, only a few research papers that have benchmarked the energy performance and water use of aquatic centres have been published in recent years. Most notably, Trianti-Stourna et al. (1998) and Kampel, Aas and Bruland (2013) collected data from several aquatic centres to find their average energy intensity in Greece and Norway, respectively. Additionally, Kampel, Aas and Bruland (2014) performed an in-depth analysis of Norwegian swimming facilities, with data collected from 41 aquatic facilities using questionnaires to determine methods to lower energy consumption. Several organisations such as the Chartered Institution of Building Services Engineers (CIBSE), Carbon Trust, Step2Sport and British Swimming have also benchmarked the energy performance of aquatic centres. Meanwhile in Australia, insufficient studies have been completed to provide a reliable benchmark for the energy and the water use of the nation's aquatic centres, bar two studies: Rajagopalan's (2014) study on the energy use of aquatic facilities in Victoria, and CERM PI's (2013, 2014) aforementioned reports. Table 2.1 summarises several energy benchmarks for aquatic centres and indoor swimming pools from current literature.

Table 2.1:
Energy Benchmark Comparison of Aquatic Centres

Energy use intensity (kWh/m^2)			Unit	Source	Comments
Low	Typical/average	High	ua or ws		
< 510	510–745	> 745	ua	CIBSE (1997)	Sport centre with pool
725	1,573		ua	British Swimming (2008)	Swimming pool building only
	1,375		ua	CIBSE (2008)	Swimming pool hall, changing and ancillaries
737	1,579		ua	Carbon Trust's (2005) Good Practice Guide	Centre with leisure pool
287		451	ua	Step2Sport (2015)	Sports complexes with indoor pools and gymnasiums and/or sports halls (by gross floor area)
437		544	ua	Step2Sport (2015)	Sports complexes with indoor pools and gymnasiums and/or sports halls (by conditioned floor area)
632		2,247	ua	Rajagopalan (2014)	Swimming pools with other facilities
	4,300		ws	Trianti-Stourna et al. (1998)	Swimming pools only (Mediterranean region)
	5,200		ws	Trianti-Stourna et al. (1998)	Swimming pools only (European region)
2,002		4,419	ws	Kampel, Aas and Bruland (2013)	Swimming facilities only
0.47		2.93	ws/hour	Kampel, Aas and Bruland (2014)	Swimming facilities only
141		318	ua	CERM PI (2014)	Aquatic centre; electricity usage only
129		332	ua	CERM PI (2013)	Aquatic centre; electricity usage only

The first three columns in Table 2.1 contain EUIs from several sources and authors ranging from low to high. The fourth column lists the units used, with ‘ua’ denoting usable area (which is often interpreted as floor area) and ‘ws’ indicating water surface area (which is the total surface area of all swimming facilities, such as lap swimming pools, diving pools, hydrotherapy pools, family and toddler pools, and wave pools). The ‘Comments’ column identifies how swimming pools and aquatic centres have been categorised and how the authors or organisations have defined the benchmarked building. The description or definition of aquatic or swimming pool facilities (under the ‘Comments’ column) are noticeably different to each other. That is, some focus solely on swimming pools, while others emphasise swimming facilities. Indeed, the types of amenities included in the benchmarking is neither clear, nor is their consistency in the methods researchers used to select or define the chosen buildings.

It would be difficult for an aquatic centre (e.g., an aquatic centre with indoor pools, gymnasiums, cafes or creches) to compare its EUI against these Table 2.1 benchmarks, particularly as different energy performance indicators and units have been used (i.e., kWh/m^2 ua (usable area) and kWh/m^2 ws (water surface)). Using water surface as a performance indicator will make energy comparisons between aquatic centres and other types of buildings (e.g., residential buildings, retail buildings or office buildings) rather difficult. Instead, a water surface performance indicator might be appropriate if a research were focused solely on an indoor swimming hall. However, as most aquatic centres contain several amenities including dry areas (e.g., gyms, sports halls and cafes), using water surface as a performance indicator or unit might actually produce unreliable benchmarks. As the CIBSE (2008) found, a common unit for energy benchmarks is measuring the kilowatt hours (kWh) of energy used for each unit of floor area (kWh/m^2) measured over one year. Additionally, they highlighted the importance of developing a benchmark based on energy consumption for each unit of floor area, as this enables direct comparisons with other buildings (CIBSE 2008).

Indeed, several studies have used usable area (floor area) as an energy performance indicator for benchmarking. However, many do not clearly describe what is meant by the term. A question that can arise from this discrepancy regards whether the usable area chosen includes both conditioned and unconditioned areas. For example, there may be some confusion when deciding whether a naturally ventilated stadium or an unconditioned indoor sports hall within an aquatic centre should be included in an analysis. Step2Sport (2015) is the only recent study that clearly presented the energy performance indicators used in its report, specifically energy consumption by gross floor area, energy consumption by net floor area, energy consumption by conditioned floor area, and energy consumption by conditioned volume. Although definitions for these energy performance indicators were provided, Step2Sport (2015) failed to clarify what amenities had been included in their analysis.

Omitting clear definitions and details on the areas included in energy benchmarks can lead to confusion, particularly if used in future projects—of which the CIBSE (2008), British Swimming (2018) and Carbon Trust's (2005) Good Practice Guide benchmark figures are comparable. However, as shown in Table 2.1, both Step2Sport's (2015) annual energy consumption by gross floor area (unconditioned floor areas are also included) and annual energy consumption by conditioned floor area are significantly lower compared to other studies. For example, its 544 kWh/m^2 estimation is the highest annual energy consumption recorded among the audited sport complexes. Yet, when compared to the other EUIs listed in Table 2.1, it is among the lowest. Another concern regards Step2Sport's (2015) 287 kWh/m^2 estimation, which is considerably low for an aquatic centre when compared to other centres. Conversely, Rajagopalan's (2014) and CERM PI's (2013, 2014) figures are the most current EUIs of aquatic centres in Australia. However, the sample used by Rajagopalan (2014) was small, and CERM's reports only benchmarked electricity usage, despite bearing sufficient samples. Additionally, gas is instead the major source of energy to heat pool water in aquatic centres, but was not considered in either report.

2.5.2 Water Benchmarks for Aquatic Centres

Evidently, Table 2.2 summarises the water benchmarks for aquatic centres and indoor swimming pools. It exhibits that several water performance indicators have been used, and this can prove both complex and misleading when drawing comparisons. It is also unclear what performance indicators ‘kL per person’ and ‘kL per visit’ mean, thus, raising potential questions regarding whether such persons are using a swimming pool or another facility, such as a gymnasium. The ARV’s (2014) and CERM PI’s (2013, 2014) ‘high’ categories of water usage by centre benchmarks are within close range (26,000 kL to 30,000 kL); however, their ‘low’ categories of water usage by centre benchmarks are different, ranging from 875 kL to 8,400 kL. CERM PI also used ‘kL by m^2’ as a performance indicator, but their reports do not indicate the specific areas used for analysis. Again, this creates inconsistencies in how researchers and organisations subsequently benchmark the water use of aquatic centres and swimming pools. That is, using different units produces significant differences in WUI variables.

Conversely, the majority of the water benchmark studies listed in Table 2.2 were completed in Australia (i.e., by the ARV, Sydney Water and CERM PI). Internationally, little studies have investigated this same phenomenon.

Table 2.2:
Water Benchmark Comparison of Aquatic Centres

Water use intensity (kL)			Unit	Source	Comments
Low	Typical/average	High			
875		27,899	Per centre	ARV (2009)	Aquatic centre including facilities
3,533		48,418	Per centre	Kampel, Aas and Bruland (2014)	Swimming facilities only
<0.02	0.02–0.04	>0.06	Per bather	Sydney Water (2011)	Aquatic centres including facilities
0.065		0.154	Per person	Kampel, Aas and Bruland (2014)	Swimming facilities only
8,397		30,266	Per centre	CERM PI (2014)	Aquatic centre
2.2		7.4	Per m^2	CERM PI (2014)	Aquatic centre
0.026		0.117	Per visit	CERM PI (2014)	Aquatic centre
7,837		26,778	Per centre	CERM PI (2013)	Aquatic centre
2.4		7.7	Per m^2	CERM PI (2013)	Aquatic centre
0.025		0.144	Per visit	CERM PI (2013)	Aquatic centre

Reviewing the existing energy and water benchmark of aquatic centres has revealed a clear need to define such buildings (including those with indoor swimming pool facilities), as well as their enclosed amenities. Inconsistencies in how researchers for these definitions (as identified in Tables 2.1 and 2.2) further problematise any instances of comparison between the already available energy and water benchmarks. For example, as Madani and Khatami (2015) discussed, there are several metrics for measuring the effects of water on energy production, including water consumption, water withdrawal and water use, among others. The energy metrics used such as delivery energy (DE), primary energy (PE) and final annual energy consumption (FAEC) (Kampel 2015) are also poorly defined in the majority of the studies listed in Table 2.1, while an inconsistent definition of water and energy use has likewise complicated comparisons between existing benchmarks of aquatic centres. A further lack of research that thoroughly investigates the link between the water and energy use in aquatic centres, as well as how each element is firmly interconnected and interdependent, certainly add to the confusion (Madani & Khatami 2015). Thus, proposing a definition for an aquatic centre and identifying the difficulty in comparing such energy and water use may suggest that a universal guideline should be created to facilitate both the identification of aquatic centres and future comparisons between such studies.

2.6 Conclusion

This chapter has demonstrated that the global aquatic and recreational industries are significantly large. Therefore, increasing their energy and water efficiency can contribute towards the reduction of greenhouse gas emissions worldwide. This chapter also highlighted the major inconsistencies in how researchers and organisations have defined buildings with swimming pool facilities. As such, no study or research performed by any academics or organisations have clearly defined what an aquatic centre is and what types of amenities they comprise. In addition, the current literature on benchmarking energy performance and water use has also revealed a lack of consistency between the methods researchers typically use (evidently, different performance indicators are routinely used), with each bearing their own unique definitions and interpretations of what constitute an aquatic centre. Hence, establishing a clear definition of the subject being benchmarked or analysed is a vital step. Conversely, ambiguity only breeds uncertainty and unreliable results or outcomes, as was proven in Tables 2.1 and 2.2. Consequently, this has raised concerns regarding whether these benchmarks are both reliable and useful for aquatic centres to compare their own energy and water performance.

Evidently, providing a clear definition of a study's subject is an important step to ensure its reliability. Therefore, an investigation is required to identify a clear and universal description of an aquatic centre. Chapter 3 will provide more details on aquatic centres in terms of energy and water use, as well as how they differ to other types of buildings.

Chapter 3: Energy and Water Use of Aquatic Centres

3.1 Introduction

Chapter 2 attempted to define the term aquatic centre to clarify the type of building this research is investigating because, as proven, there exists many inconsistencies when interpreting a building with indoor swimming pool facilities. Hence, this chapter will demonstrate how aquatic centres consume energy and water to operate, with Section 3.2 considering the factors that affect both energy and water consumption.

Aquatic centres are unlike any other type of building in terms of energy and water use. They are usually large spaces where high air and water temperatures must be maintained and a high volume of air needs to be ventilated to regulate evaporation and humidity within swimming pool halls. In addition, large volumes of water are both continuously heated to maintain conformable conditions for bathers, and filtered or treated to remove impurities. HVAC systems, pool-water heating and evaporation are the main factors that require particular attention when determining the energy efficiency in aquatic centres. Indeed, pool-water heating in particular is one major energy consumer, which must be maintained at a specific temperature to provide comfort and reduce evaporation. Thus, this chapter will examine how electromechanical systems such as HVAC systems are used in such buildings, as well as the key factors that can minimise energy use. Essentially, this is affected by two variables that are usually not encountered in other buildings: evaporation and high moisture or humidity. As this chapter will prove, these important variables must be controlled efficiently to protect the fabric of an aquatic centre and to reduce both energy use and water loss.

3.2 Factors Affecting the Energy Use of Aquatic Centres

Swimming pool halls within an aquatic centre usually constitute the majority of a whole building's energy consumption, and this is typically intensified when inefficiencies occur. Attempts to draw comparisons reveal a difficulty to find any two swimming pool halls with identical or similar energy usage for a variety of reasons, including differences in building design, the use of the facility, its age, how it is operated and its standard of maintenance. Indeed, even if two buildings share the same design, are built concurrently and have the same standards of construction, they may still consume different magnitudes of energy as a result of their location and different climatic conditions, opening hours and levels of use (British Swimming 2008). Recent baseline studies by the DCCEE (2012) on commercial buildings conducted in Australia looked at the average energy intensity of several building types—from office buildings, supermarkets, hotels, shopping centres, hospitals, schools and universities—excluding aquatic centres. Supermarkets had the highest average energy intensity of around 940 kWh/m^2 (DCCE 2012), which is still significantly less than that of aquatic centres (see Rajagopalan 2014).

Basically, energy consumption in aquatic centres is comprised of thermal (space heating and pool-water heating) and electrical energy (cooling, ventilation, lighting and mechanical or electrical equipment), while for swimming pool facilities it constitutes 45% for ventilation (including heating and cooling), 33% for pool-water heating, 10% for heating and ventilating the remainder of a building, 9% to power equipment and lighting, and 3% for hot-water services (Trianti-Stourna et al. 1998). Therefore, the main energy usage and areas of focus for an aquatic centre are space and pool-water heating, as well as ventilating a swimming pool hall.

According to the Carbon Trust (2006), there are a number of ways that aquatic centres use energy unlike other building types. The following factors are essential when dealing with energy use in relation to an indoor swimming pool:

1. High pool hall air temperatures are required (28–30 ºC) to maintain the comfort of pool users and to reduce the risk of condensation both from humid air and from heating large volumes of water, which should be maintained at 1–2 ºC below pool air temperature to limit evaporation from a pool's surface.
2. High extraction and ventilation levels are required. Typically, an air change rate each hour of around 4–10 is required to remove excess humidity from pool evaporation. High ventilation rates also require high levels of fresh

make-up air to replace extracted air, while all incoming fresh air is usually heated.
3. Pool water must be continuously pumped through filters.

In Australia, aquatic centres use both electricity for utilities such as lighting, motors, pumps and fans (particularly for water treatment and ventilation systems), and gas for water and space heating. Collectively, each is responsible for more than 25% of the energy costs in swimming pools (Carbon Trust 2008). Rajagopalan (2014) stated that the average proportion of gas and electricity used in aquatic facilities is around 75% and 25%, respectively. However, Australia's electricity is still produced mainly from traditional fossil fuels such as black coal, brown coal and gas, which, according to the ABS (2012), sits at around 88%, with 65.3% from coal and 22.8% from natural gas. With electricity generation remaining one of the major causes of greenhouse gas emissions in Australia, targeting the energy performance of one of the most energy-intensive types of buildings (aquatic centres) can contribute towards reducing these harmful emissions.

3.2.1 HVAC Systems

One of the most important and energy-intensive pieces of equipment in an aquatic centre or swimming pool hall is its HVAC system. Designing an HVAC system for such a facility is difficult and complex because, compared to other building types, evaporation and humidity are important factors that require additional consideration. As mentioned in CIBSE's (1997) Good Practice Guide, maintaining the appropriate levels for temperature, humidity and air quality within a pool hall for bathers, spectators and staff is a complex task for designers and operators. The control of evaporation from water is a phenomenon not normally encountered by standard HVAC systems and can, therefore, be misunderstood by both parties (Carbon Trust 2008).

The main aims of an HVAC system in an aquatic centre are:

1. controlling a swimming pool's air temperature (heating and cooling), humidity and air quality to minimise pool-water evaporation and prevent condensation (i.e., excessive condensation can corrosion damage)
2. maintaining comfortable environmental conditions for bathers

3. removing chlorine and other contaminants from the air.

Based on CIBSE's (1997) Good Practice Guide, HVAC systems should maintain a pool hall's air temperature at 27–30 ºC and relative humidity at 50–70%, while the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE 2007) suggests air temperature should be 24–29 ºC for public, school and competition pools, with relative humidity at 50–60%. Conversely, the ventilation of an aquatic centre, especially a swimming pool hall, needs more consideration compared to other building types due to factors of evaporation and other air pollutants or odours, such as chlorine. Accordingly, these facilities are required by the Swimming and Spa Pools Code of Practice in Australia to use chemicals to disinfect pool water in all public indoor swimming pools. However, these chemicals have adverse effects on the indoor air quality when they off-gas from pool water, thus, potentially causing eye irritation or even asthma. Therefore, when designing a ventilation system for a swimming pool hall, a significant amount of outdoor air is required to control any potential odour problems. In fact, ASHRAE (2007) increased the amount of outdoor air required for indoor swimming pools in comparison to standard office buildings, with Standard 62.1 Table 6-1 suggesting 2.4 L/s for each square metre of a swimming pool and wet deck area, and an additional 8 L/s for each person by spectator area.

Effective, well-distributed and mechanically controlled supply and extraction are also required to maintain appropriate conditions in aquatic centres. Conditions in pools vary constantly, thus, complicating a prescriptive design to suit all possible situations (CIBSE 1997). A simple HVAC system for a swimming pool will have a separate supply and exhaust air system, which will work simultaneously, supplying the necessary amount of fresh outdoor air and then exhausting from a swimming pool to provide the required temperature, volume flow and relative humidity level (Kalinina 2011). These systems are similar to air conditioners used in residential buildings, with the main difference regarding the control system, which is not only based on temperature but also on relative humidity. However, most aquatic centres' or swimming pool halls' HVAC systems will typically include a dehumidifier to control the considerable moisture in the air caused by the evaporation of pool water. Indeed, there are more complex HVAC systems including heat-recovery systems, mechanical heat pumps and energy-recovery dehumidifiers.

Several studies have been conducted on HVAC systems in aquatic centres and indoor swimming pool halls. Notably, Johansson and Westerlund (2001) investigated energy savings in indoor swimming pools by comparing different heat-recovery systems. They looked at mechanical heat pumps and open-absorption systems, with both presenting energy demand reductions of 14% and 20%, respectively. Lazzarin and Longo (1996) also compared heat-recovery systems in public indoor swimming pools; however, theirs concerned a heating system with simple ventilation, one with heat recovery, one with an electric heat pump and an internal combustion engine-driven heat pump. In addition, Tagliafico et al. (2012) examined the energy assessment of solar-assisted heat pumps for pool-water heating and space heating. They simulated a water–solar-assisted heat pump (W-SAHP) comprised of a commercial water-to-water heat pump coupled with unglazed flat plate solar collectors directly installed over the copper roof of a swimming pool building. Essentially, this demonstrated that such systems could achieve a PE saving over 20%, depending on location.

Further, Ribeiro, Jorge and Quintela (2011) presented research on the control strategies that can be implemented in the building automation system and HVAC system of an existing indoor swimming pool complex to minimise energy consumption. Lentz (2011) also compared the performance of two different approaches to swimming pool HVACs within the same facility. In this study, the old system was a pool dehumidification unit that used the heat rejected from a refrigeration system to heat pool water and, thus, provide hot gas reheat for the ventilation unit; however, this began to fail after 12 years. The new system was a direct-fired, variable volume 100% outdoor air unit equipped with an indirect evaporative precooler used to provide sensible energy recovery during both heating and cooling seasons.

3.2.2 Pool-water Heating

Pool-water heating also consumes large amounts of energy. According to Sydney Water's (2011) energy use breakdown of a typical aquatic centre, pool heating accounts for around 64% of total energy use. Pool water temperature must also be within 26–30 ºC, which is approximately 1–2 ºC below pool air temperature, to maintain the comfort of pool users and to reduce the risk of condensation from the humidity of pool surface evaporation. Reducing the temperature to a point in which pool water must be heated needs careful consideration, as lower temperatures can be uncomfortable for users and may infringe upon particular public swimming pool guidelines and regulations. Apart from using an energy-efficient water-heating system, the only way to save energy from pool-water heating is to reduce the rate at which heat is lost (Isaac, Hayes & Akers 2010). Although pool-water temperature is controlled automatically, temperature sensors require frequent checking, as even a 0.5 ºC rise will result in a substantial waste of energy.

Several papers have been published on pool-water heating, with the majority investigating the use of solar panels and heat-recovery systems to warm pool water. Mancic et al. (2014) performed mathematical modelling and simulation to surmise the annual hot-water demand of an indoor pool and then size an appropriate solar system. They discovered that the maximum solar collection area needed was approximately 26% of a pool's water surface. Similarly, Ruiz and Martinez (2010) investigated pool-water solar-heating systems, but instead performed the analysis on an open-air swimming pool, while Sun et al. (2011) examined heat pump energy supply systems for indoor swimming pools and concluded that the latent heat recovered by the evaporator of heat pump dehumidifiers operating in heat-recovery mode could meet the total demand of pool-water heating on typical summer days. Aboushi and Raed (2015) then examined the use of solar energy with evacuated collectors to heat an indoor swimming pool, thus, finding an installed solar system resulted in an energy reduction of about 75%. Kincay, Utlu and Akbulut (2012) also utilised solar energy to heat swimming pool water and discovered that solar energy could compensate between 30–47% of total heat losses arising in indoor swimming pools. Evidently, most of these papers provide little to no information on the total amount of energy use for heating an indoor swimming pool water, albeit Saari and Sekki's (2008) work, which calculated and analysed the energy consumption of a Finnish public swimming bath. Essentially, they estimated that the annual energy consumption for heating the studied swimming bath was 396 kWh/gross-floor-m^2, while the annual electric energy consumption was 240 kWh.

Generally, a number of different appliances and systems are used to heat aquatic facilities. A combined heat and power (CHP) system uses a relatively low-cost fuel to generate both heat for a pool and electricity for lighting and pool pumps. Heat pumps are also used to transfer heat from a low-grade temperature source to upgrade it to a higher and more useful temperature (to heat a pool) by using the principle of a refrigeration system to transfer heat. There are also several types of heat pumps available that can use both electricity and gas as fuel. However, hot-water boilers are the most common type of heating system for swimming pools, which employ the basic concept of transferring heat from an energy source to water. Indeed, different types of boilers such as gas-fired hot-water boilers, oil-fired hot-water boilers, electric hot-water boilers and gas-fired condensing boilers exist. According to CIBSE (1998), modular boilers, high-efficiency condensing boilers and CHP systems can improve efficiency for pool heating and provide good energy saving. Even solar systems are described in several papers as effectual mechanisms to heat pool water. However, there too exists some rarely used alternatives that can utilise renewable energy sources, such as geothermal water or ground heat sources, to provide heat energy for air and water heating in aquatic centres. For example, Fahmy, Farghally and Ahmed (2014) used MATLAB/Simulink to identify whether geothermal energy could be used to supply the heat gain required to keep swimming pool water at a desired temperature in Egypt; basically, they claimed the proposed swimming pool temperature of 26 °C was easily achievable through this method. Hence, it is now crucial to consider the three important variables that rival the electromechanical systems used in aquatic centres: evaporation, humidity and heat loss or gain.

3.2.3 Evaporation, Humidity and Heat Loss or Gain

Indoor swimming pools have very high evaporation rates and extreme humidity-control issues that must be considered during the early design stages of an aquatic both, and at both architectural and mechanical levels, to ensure good thermal comfort and to protect structural integrity. According to West (2005), if humidity is not controlled in an indoor swimming pool hall, pool water will evaporate and the space dew point will rise high enough to cause potentially catastrophic condensation. Indeed, pool evaporation is also a major concern for indoor pools, accounting for around 70% of heat energy loss, with a further 27% of loss occurring through the sensible heat of a ventilation system (Sydney Water 2011). In fact, water evaporation requires the supply of latent heat of vaporisation. When the energy in water vapour is lost through ventilation, this expenditure can significantly exceed the heat losses occurring through conduction (building envelope), including ventilation itself (Hancock & Chem 2011).

However, as Australia experiences both cold and hot climates, there is an added need to reconsider heat gain. As Wilkenfeld and Associates (2009) explained, heat loss through ventilation may be necessary to cool a pool enclosure, thus, designating high air change rates a potential advantage rather than a liability, especially during summer periods. Exhaust air may still be cooler than outside air, which means a building's heat exchanger will have to work in reverse (i.e., to cool rather than heat incoming air). Therefore, despite the importance of heat loss through evaporation and ventilation, heat gain should not be neglected, particularly in an Australian climate.

Water evaporation from indoor swimming pools is a major aspect in the design of both HVAC systems and water-heating plants in indoor swimming pools. Essentially, this is because water evaporation concerns several parameters such as air temperature, water temperature, relative humidity, air velocity and the activity level of its occupants (Asdrubali 2009). In fact, Asdrubali (2009) emphasised that high thermal loads are due to water evaporation, which, therefore, represent an entire plant's main source of energy consumption. In addition, the evaporation from swimming pools must be accurately calculated to ensure both energy consumption as well as HVAC sizing are properly estimated (Shah 2012). Underestimating the water evaporation of an indoor swimming pool can lead to the improper selection of an undersized HVAC system. This may cause excessive humidity, which begets discomfort for users and damages the building envelope due to fungus, rot and wet insulation, thus, undermining the facility's performance. Conversely, overestimation can lead to an oversized HVAC system with excessive energy consumption, high costs and operating problems due to excess cycling (Shah 2003). Evidently, calculating the water evaporation from free surfaces (including outdoor and indoor swimming pools) is complex.

While several studies in the last 15 years detailed methods for evaluating evaporation from water basins, only few are specifically related to indoor swimming pools. Of note, Asdrubali (2009) used a scale model to evaluate water evaporation from indoor swimming pools, while Smith, Lof and Jones (1999) estimated evaporation rates by observing a pool water's energy balance. Sartori (2000) presented a critical review of equations to calculate the evaporation rate from a free water surface, and Shah (2003) investigated how to predict evaporation from occupied indoor swimming pools. Subsequently, he investigated an improved method for calculating the evaporation from indoor water pools, which dually considered their occupancy (Shah 2012). Shah (2013) then performed further research to develop a new correlation for predicting evaporation from occupied swimming pools. Hence, despite the availability of several evaporation calculation formulas, the most common are, arguably, his and the ASHRAE method. Other methods of calculating evaporation do exist—most notably from Carrier (1918), Smith, Lof and Jones (1999) and Hens (2009)—but those intended for swimming pools are mostly not well verified. Each method also has its advantages and disadvantages. For example, according to Shah (2012), the ASHRAE method does not properly account for evaporation from natural convection—in fact, theirs was actually derived from Carrier's method, which includes a multiplication factor termed an activity factor. Similarly, Moghiman et al. (2007) derived a formula that considers both natural and forced convection, but it has only been verified in a small test chamber. Hanssen and Mathisen (1990) also pondered natural and forced convection, but only received verification with their own data sourced from a commercial swimming pool. Indeed, calculating evaporation rates from indoor swimming pools is crucial when sizing HVAC equipment and performing accurate energy consumption calculations. Yet, each of the methods described are unique, so extra care is required when performing evaporation estimates.

Energy Star (2009) is perhaps the most common industry standard available. It uses in-depth engineered calculation when computing energy-performance ratings for swimming pools compared to other guidelines, such as CIBSE's (1997) Good Practice Guide for Energy Efficiency in Swimming Pools, among others. Energy Star's technical methodology employs an engineered pool model based on the fundamental rules of physics involved in heated pools and their interaction with the surrounding space. The documents also provide for the calculation of both indoor and outdoor pools using ASHRAE's evaporation formula.

3.3 Factors Affecting the Water Use of Aquatic Centres

Aquatic centres require huge amounts of water to operate. According to Sydney Water (2011), council-owned aquatic centres in Sydney use around 1,000 ML of water each year. As such, understanding the link between energy performance and water consumption in aquatic centres is imperative, as any changes in either factor will directly affect the other. For example, an increase in water consumption will be related to an increase in energy consumption, as more energy must be used to heat make-up water to the required temperature. A typical water-use breakdown of aquatic centres in Sydney sees 36% of water used in pool make-up (including backwash), 22% for leaks, 20% for showers and the remainder for toilets, basins and other facilities (Sydney Water 2011). Indeed, pool make-up water also includes water loss from evaporation. An indoor 25 m pool with eight lanes can lose around 550 kL of water each year through evaporation alone (Sydney Water 2011). Hence, a significant amount of water can be lost to evaporation if its rates are not appropriately controlled.

Several research studies on swimming pools have provided only brief information on water use, most of which do not specifically investigate factors that affect that of aquatic centres. Of particular note is Isaac, Hayes and Akers (2010), which investigated the water and energy use at the Wales National Pool. They provided a water-use breakdown that demonstrates 47% of water use occurred through evaporation, 23% through backwashing, 20% through showers and 10% for other utilities. Evidently, evaporation from the centre's pool was by far the largest consumer of total water. Yet, despite this water audit of the Wales National Pool, Isaac, Hayes and Akers (2010) concluded there was little scope for reducing its water use, despite an evident lack of information on the total volume for the centre's water use. Conversely, Kampel, Aas and Bruland (2014) provided an overview of the collected data for all swimming facilities, including water consumption both in absolute terms and by person for each aquatic facility category; however, their studies were mainly focused on energy use and energy efficiency. Trianti-Stourna et al. (1998) also discussed pool-water quality in their study and suggested 30 L of fresh make-up water daily for each bather was necessary to maintain satisfactory water quality; they also mentioned the annual water consumption at a typical pool was approximately 3,100 kL. Nonetheless, no details were provided in their study to indicate how these figures were calculated. Similarly, Maglionico and Stojkov (2015) performed a case study on the water consumption of a public swimming pool in Bologna, Italy to determine that the average total water consumption for each person by day was approximately 96.1 L.

Despite a lack of research, some studies have investigated factors that can influence the water use in aquatic centres. For example, the ARV (2009) performed water audits and surveys on several aquatic centres in Victoria in 2009, detailing the average water use of several aquatic centres, which they split into three categories: large, medium and small. Upon distributing surveys on water use to 193 public pools, only 50 responded. With 52% also unable to provide data on their annual water usage, the ARV (2009) consequently received the water usage information of 25 aquatic centres. Likewise, Sydney Water (2011) completed a survey of 42 aquatic centres in Sydney regarding water use. The data gained not only helped clarify the water use trends and practices of the state's aquatic centres, but also laid the grounds for two key performance indicators using bathers' and patron numbers; subsequently, these were used to classify aquatic centres from poor to best practice.

3.3.1 Backwashing

An aquatic centre's water usage interests several factors. Backwashing is perhaps largely responsible for high water consumption rates, accounting for up to 40% of total water use in any given aquatic centre (ARV 2009). For example, the Finglas swimming pool in Ireland used approximately 30 kL each week to backwash its pool-water filters (Sustainable Energy Ireland 2006). However, this does not have to be the case, as, according to the ARV (2009), a comprehensive reclaim system through treating can lead to potential savings, which can average around 125 kL/week; additionally, up to 60–70% of backwash water can also be re-used as make-up water for such swimming pools.

Filter backwashing is a very important aspect of pool-water treatment. Contaminants such as organic matter, dirt, small particles and sediments are typically caught in pool filters during the continuous circulation of pool water, for which backwashing helps to unclog by reversing the flow of water through the filters and discharging the backwash water to the wastewater system. Importantly, the frequency, duration and types (volume of water used) of backwashing will affect the amount of water consumed by swimming pools, while backwashing is usually being performed when necessary—that is, when the pressure drop across filters exceeds the manufacturer's recommended limit. There are also several backwashing-recycling systems available that allow aquatic centres to treat and re-use backwash water for replenishment, irrigation and toilet flushing. Basically, harvesting backwash refers to the capturing and treating of swimming pool backwash water for re-use within a centre, instead of being directed to a sewer.

As the ARV (2009) described, there are three treatment options for pool backwash water: low, medium and high. Low treatment involves the settling of water to remove large suspended matter, followed by filtration, disinfection and then transferral to storage tanks. Low-treated backwash water is primarily used for irrigation and can achieve only low annual water saving, which is around 25% of total backwash water volume. Medium treatment involves the settling of water for removal, which concerns suspended matter, filtration and two levels of disinfection before being transferred to storage tanks. Medium-treated backwash water is suitable for toilet flushing and urinals, and could increase a pool's backwash harvesting to over 80%. Finally, high treatment consists of several levels such as settling to remove large suspended matter, filtration, dechlorination, softening and reverse osmosis with appropriate disinfection. This type of treatment means that all harvested water can be used as make-up water year round. Additionally, it returns warm instead of cold water to pools, thus, conserving energy that would have otherwise been used for heating purposes (ARV 2009). Indeed, as Section 3.3.2 explores, backwashing cycles also depend on the types of filter used, filter media and a filter's general methods of operation.

3.3.2 Pool Filters

Significant amounts of water can be saved depending on the type of filter a pool uses. Several exist, the most common of which in Australian aquatic centres being gravity filters, pressure filters, pre-coat filters and vacuum filters (Sydney Water 2011). Gravity filters are slow-rate filters that rely on gravity to push water through the filter media (e.g., typically sand). As they are typically large and require significant amounts of backwash to clean impurities (such as sand), these are mostly found on older 50 m outdoor Olympic pools. Pressure filters are perhaps the most common filters for commercial pools that are operated at medium- and high-rate pressures. They involve two to four filter vessels in parallel, each about two thirds filled with filtration media in layers of different particle sizes ranging from 0.5 mm to 1 mm. Basically, water is forced through the filter bed and exits through the laterals (the perforated pipes located at the base), with the most common media used being sand. Similarly, pre-coat filters provide a very high level of filtration that creates water of low turbidity and high clarity. Diatomaceous earth is the most common pre-coat filter media, but perlite and cellulose fibre are also used. The filter media also comes as a fine powder, which is mixed with water to form a slurry used to coat a filter's sock or filaments. At the end of the filter cycle, the filter media is 'bumped' off the filter filaments and then discarded. Finally, vacuum filters are a low-rate, open-tank filter in which water is pumped into one end of a filter tank and drawn through by pool-water return pumps. The tank has a bank of removable filter elements coated with filtration media, which is commonly dry cellulose fibre. The element coating is automatically replenished through a dosing hopper that is manually filled with the filtration media. Vacuum filters require much less water than backwashing gravity and pressure filters due to the size of their holding tank (7–10 kL) (which is used for cleaning), the low amount of water used to hose down the filter elements (1–2 kL) and the reduced frequency cycle for backwashing (Sydney Water 2011).

Based on a 50 m pool, gravity filters use around 50–100 kL of water each cycle, medium- and high-pressure filters use between 30–50 kL, pre-coat filters use approximately 15–20 kL and vacuum filters use only 10–15 kL of water (Sydney Water 2011). Notably, a Sydney Water (2011) case study on the Waves Leisure Centre in Kingston, Victoria replaced its medium-pressure sand filters with vacuum media filtration. Their retrofit increased the filter cycle from one week to 10–12 weeks, and produced a saving of approximately 26 kL of water a day. According to Hazell, Nimmo and Leaversuch (2006), the installation of ultra-fine filtration systems can also reduce water consumption and maximise water re-use by allowing centres to backwash their swimming pools more efficiently. This is achieved by reducing the time taken to backwash a pool, and through less regular backwashing and high water quality.

3.3.3 Pool Treatment and Other Factors

Pool-water treatment is an important aspect to consider when operating an aquatic centre. During this process, there is always a need to add free make-up water to maintain water quality, with chlorination being perhaps the main treatment method to disinfect pool water. Achieved by adding sodium or calcium hypochlorite to water, many aquatic centres will pair this with ultraviolet (UV) light irradiation or ozone treatments (Sydney Water 2011). Of note, magnesium salt is now also employed in aquatic centres as an alternative chemical treatment. Others factors may also affect an aquatic centre's water use and water quality, including make-up water control (which relates to water losses caused by evaporation, splash, leaks and backwash), filter backwashing schedules (the majority of which are now automated) and the duration for backwashing.

Water-efficient amenities and fittings directly affect the total water use of an aquatic centre. According to the ARV (2009), the best water-saving measures can be achieved through shower systems, urinals, basin systems and toilets. As pool users regularly use showers, replacing them with water-saving shower heads that flow at 8 L/min is perhaps one of the simplest methods of reducing up to 50% water usage (ARV 2009). Other water-efficient fittings such as taps, toilets and urinals can also help reduce water consumption. In Australia, water fixtures and fittings with higher government-imposed Water Efficiency Labelling and Standards (WELS) stars are the most efficient products that regulate water consumption. WELS measurements are based on the volume of water used by that product during a single or standard 'operation'. For example, the water efficiency for taps and showers is based on the volume of water (in litres) emitted from an outlet each minute (L/min) (WELS

2017). Based on Maglionico and Stojkov's (2015) study on the water consumption of a public swimming pool, a reduction of 22.3 L/day for each person was achieved by upgrading to low-consumption water fixtures.

Leaks are another important cause of water loss in aquatic centres. According to Sydney Water (2011), 22% of water waste occurs through leaks, particularly as they can be difficult to detect unless an aquatic centre has efficient metering and monitoring systems. Leaks can stem from pool structures, cracks or faulty plumbing components, from hot-water sources (showers, basins and kitchen) and even taps. Indeed, the locations of which can be detected through thermal imaging.

3.4 Conclusion

Evidently, aquatic centres use both energy and water differently to other types of buildings. There, energy is used mainly for heating, cooling and ventilating swimming pool halls, heating and pumping pool water through filters, and facilitating both lighting and water-treatment equipment, among other utilities. As discovered, high air and water temperatures within swimming pool halls can also cause excessive energy usage in aquatic centres, as compared to that of other buildings. These structures also experience high rates of water consumption due to swimming pool make-up water, backwashing and high domestic hot-water use, such as hot water for visitors' showering.

Evidently, several important factors affect the energy and water use of aquatic centres. Most notably, pool-water evaporation is a critical factor in this equation, mostly because it is not typically encountered in other buildings. Excessive evaporation within a swimming pool hall can likewise result in excess heat and water loss. Accordingly, HVAC systems must be carefully designed to adhere to these side effects, with specific temperatures between pool air and pool water requiring added maintenance and monitoring. High evaporation rates can increase humidity and condensation levels, and, thus, can cause structural damage such as corrosion; it can also increase the amount of make-up water required to replenish the water lost from evaporation. In fact, this could constitute as much as 47% of an aquatic centre's total water use (Isaac, Hayes & Akers 2010). Unfortunately, evaporation rates can be difficult to estimate, as many factors must be considered; these include the activity levels of a swimming pool and pool hall, a centre's occupancy rate, the amount of splashing that typically occurs, and a centre's required air and water temperatures. Several formulas have been discussed throughout this chapter regarding how best to calculate such rates, but without the consensus of researchers. Nonetheless, ASHRAE's evaporation rate formula is largely recommended in most research and guidelines.

In addition to evaporation, several other factors also affect the total water use of an aquatic centre. Notably, up to 40% of water consumption can be linked to backwashing, with the types of filters used then determining the amount of water expended. Additionally, several other factors such as water-efficient fittings, leaks and pool treatment were also recognised as causing increased wastage.

Having now identified the difficulty in defining what an aquatic centre is in the previous chapter, this chapter built upon the factors that commonly affect its energy and water use. Hence, it is now necessary to engage the methods used to investigate, compare and study these elements in greater depth.

Chapter 4: Methods of Assessing the Energy and Water Use of Aquatic Centres

4.1 Introduction

To understand the energy and water use of aquatic centres, appropriate methods for assessing each factor should be carefully selected. While Chapter 3 discussed how aquatic centres consume energy and water, and further specified several factors that influence these elements (the majority of which are not usually present in other types of building), this chapter will identify the methodologies, approaches, processes and techniques used in past studies to investigate such consumption, but in relation to aquatic centres. Benchmarking methods are discussed, specifically statistical regression-based benchmarking and computational model-based benchmarking (whole-building simulation)—both of which require the often-challenging collection of information on existing aquatics centres. Indeed, many are old and are not properly metered, thus, leading to unreliable data. For example, Kampel, Aas and Bruland (2014) found that more than one third of the answers in a questionnaire could not be used due to inaccuracy, missing data or a lack of energy-measuring devices at the facilities used for investigation.

As such, Section 4.2 reviews various benchmarking methods, including efficiency indicators applicable to aquatic centres. This is followed by a discussion on building simulations and their importance, as well as techniques for subsequent calibration.

4.2 Benchmarking Methods

Benchmarking is a common method used to measure and promote the efficient use of energy and water in buildings. According to Chung, Hui and Lam (2006), such models are mostly constructed in a simple benchmark table (percentile table) of energy or water use, which is then normalised with floor area, temperature or occupancy. Importantly, the benchmarking process accounts for and compares a metered building's current energy performance or water consumption with an energy or water baseline, or, conversely, compares a metered building's energy performance and water consumption with the energy performance and water consumption of similar types of buildings (DOE 2010). Li, Han and Xu (2014) emphasised that energy benchmarking is a necessary step when assessing the energy performance of a building, while Djuric and Novakovic (2009) defined energy benchmarking as a macro-scopic level of performance assessment, using metrics to measure its performance relative to other building or its previous performance. According to Sartor, Piette and Tschudi (2000), benchmarking the energy performance of buildings is instrumental to determine its current energy-efficiency status, establish targets for improving energy performance, increase the accuracy of property value assessments and gain recognition for excellent energy-efficiency achievements.

Several methods are also used for benchmarking; the most common of which involve averages, medians, normalised ranking and simple ranking (Sharp 1996). According to Karaguzel and Lam (2011), statistical regression-based benchmarking relies on an existing dataset (utility data and onsite measurements) to discover the possible relationship between a dependent variable (e.g., utility bill) and other independent variables, such as weather data and occupancy. However, they also indicated that computational model-based benchmarking can be used for energy performance benchmarks. This method of benchmarking can help investigate the prioritisation of choices for replacing building components and systems yielding optimal energy performance for a given budget, which might otherwise be lacking if standard regression-based benchmarking is employed. Additionally, Li, Han and Xu (2014) examined several methods for benchmarking building energy consumption against its past or intended performance. Essentially, the main methods were the Black Box method (i.e., multiple linear regression, artificial neural networking, the bin method and support vector regressions (SVM)), Grey Box testing (i.e., the Bayesian network and the resister–circuit network for air conditioning load) and White Box testing (i.e., normative methods, idealised model-based methods, modified bin methods and detailed energy simulation methods). However, as Li, Han and Xu (2014) suggested, the most popular of the three identified for energy benchmarking is the Black Box method. In terms of detail, the multiple linear regression relates a predicted variable to multiple variables, while the bin method groups historical loads into a bin if their associated variables (such as hour of week, temperature and humidity) are close and, thus, fall into the same categories. The average value of the bin is then used to predict load with similar variables (Li, Han & Xu 2014). Conversely, an SVM regression is a data-driven Black Box method that relates a variable 'X' with another variable 'Y' in an equation, while artificial neural networks are composed of multiple layers of neurons and functions, which are trained using an appropriate number of datasets to predict output (Li, Han & Xu 2014).

Mozes (2006) listed four methods of benchmarking in their study: statistical regression-based benchmarking, simulation model-based benchmarking, point-based rating systems, and hierarchal and end-use metrics. The first method utilises statistical models that are developed by using existing data to discover a correlation between several variables such building floor area, building age, occupancy density and window-to-wall ratio. The second calculates benchmarks based on simulation models of building performance, while the third is mainly a rating system rather than a benchmarking method for buildings; this system does not compare buildings but rather rates a specific building against 'Best Practice' standards. As discussed in Chapter 1, examples of this include Green Star, LEED, NABERS, BREEAM and Energy Star, the first of which is a rating tool that provides buildings with an overall score or credit ranging from a four- (classified as Best Practice) to six-star rating (classified as World Leadership). Both LEED and BREAM are similar to a Green Star rating, as each can assess both new and existing buildings. Conversely, a NABERS certification can only be performed on existing buildings with at least 12 months of operation (12 months of utility bills are required); although, its Energy Commitment Agreement can be performed on new buildings using whole-building energy simulations to estimate a possible NABERS rating with which to work towards a full NABERS certification after the given 12 months. Lastly, Energy Star is a US-based rating system that compares a building's energy performance to similar buildings and scales them from 0–100 points (Energy Star 2010). The final benchmarking methods are hierarchal and end-use metrics, which remove from the average benchmarking features that are unique to certain building types; the normalisation of climatic and functional data are then used to more accurately establish a base case with narrower categories (Kinney & Piette 2002).

Numerous research papers have investigated the energy benchmarking of buildings throughout the last 10 years. Xing et al. (2014) performed comparative analyses to determine the energy-consumption benchmark for public buildings using mean values, regression analysis, and both fixed horizontal and technical calculation. Similarly, Chung, Hui and Lam (2006) employed multiple regression analysis to assess the relationship between EUIs and other factors (e.g., operating hours, temperature and occupancy), and subsequently developed a benchmarking system that could be used in policy analyses. Similarly, Nikolaou, Kolokotsa and Stavrakakis (2011) investigated and presented research work, tools and programs focused on energy-benchmarking methods, energy-rating procedures and classification schemes for the building sector. Shabunko et al. (2014) also used three bottom-up benchmarking methods for residential buildings in an energy-rich economy: ordinary least square (OLS), SVMs and engineering modelling (EM). Conversely, Singh, Mittal and Upadhyay (2014) performed water benchmarking and investigated two widely used techniques: performance indicator systems (PIS) and data envelopment analyses (DEA). Bannister, Munzinger and Bloomfield (2005) gathered data on the water consumption of 132 office buildings and 18 public buildings around Australia to establish a simple benchmark by unit floor area; as such, the average performance benchmark for public buildings was 3.34 kL/m^2 annually, while the best practice benchmark was 3.34 kL/m^2.

Based on a review of the literature, it appears several papers have used the statistical regression-based benchmarking method to investigate the energy and water usage of buildings. Therefore, it appears most logical to employ this same method to form a benchmark for this study.

4.2.1 Statistical Regression-based Benchmarking

The statistical regression-based benchmarking method uses statistical models developed with existing data to discover a correlation between several variables. Karaguzel and Lam (2011) used this technique to conclude that the characterisation of dominant factors or significant determinants of energy consumption through sensitivity analysis is also possible. For example, Dong, Lee and Sapar (2005) developed a baseline model for benchmarking commercial buildings' energy consumption in Singapore using a multiple linear regression analysis of utility bills and weather data. They discovered several correlations between energy use and climate parameters (e.g., dry-bulb temperature, relative humidity and solar radiation), and ultimately concluded that there was a strong correspondence between outdoor dry-bulb temperature and energy consumption. Similarly, Signor, Westphal and Lamberts (2001) used the statistical regression-based benchmarking method to develop multivariable regression equations to calculate the annual electricity consumption of office buildings in Brazil. Their regression equations focused on building envelope parameters such as window-to-wall ratios, shading coefficients, thermal transmittance, heat-transfer coefficients and the solar absorbance of roofs. The effects of these same parameters were likewise explored by Lam, Hui and Chan (1997), who examined these in relation to the energy consumption of commercial buildings in Hong Kong. Meanwhile, Kampel et al. (2016) used multiple regression analysis to propose appropriate energy performance indicators and provide a reliable benchmark for swimming pool facilities. Theirs is the most current investigation on indoor swimming pools, which also directly relates to this study; however, they included in their analysis all types of swimming pool facilities, from small school pools to leisure pool facilities. Comparing the energy performance of a small school pool to an aquatic centre is not logical, as there is a significant difference in terms of the size of wet and dry areas and their occupancies in a building. Additionally, they neither explained how they separated the small school pools' energy consumption from the whole school's energy consumption, nor included the whole school's energy consumption.

Conversely, Chung, Hui and Lam (2006) produced a statistical model using a linear regression analysis of the EUIs of supermarkets in Hong Kong. They found correlations between the climate-adjusted EUIs and several building variables such as their occupancy patterns, building age, HVAC systems, and their lighting equipment and controls. Rajagopalan (2014) also used a simple statistical analysis to compare the energy performance of aquatic centres in Victoria. Building datasets including utility bills and building area measurements from six aquatic centres, her study investigated the interrelation between several variables that contributed to the energy consumption of these facilities, with their EUIs next established by dividing the total energy used by their gross floor area. Indeed, this method has been used by several researchers to analyse the performance of buildings, the majority of which also employed regression analyses as a benchmark (see Carlo & Lamberts 2008; Olofsson, Andersson & Sjögren 2009; Rajagopalan, Wu & Lee 2009). However, this method may be problematic when applied to aquatic centres, as it is generally difficult to gather reasonable sample sizes. For example, Rajagopalan (2014) used a sample of only six aquatic centres, Sydney Water (2011) conducted detailed water and energy audits on 10 aquatic centres in the Sydney metropolitan area and Mozes (2006) performed benchmarking for the US state of Colorado's recreational facilities, with data available from only six facilities. Similarly, Step2Sport (2015) had only a sample of five sport complexes to perform their benchmarking analysis, while Kampel et al. (2016) collected data from 43 Norwegian swimming pools, which represented only 5% of the 848 swimming facilities operating nationwide.

Efficiency indicators are often used in statistical analysis to indicate, for example, the energy consumption performance level of an energy-consuming system. As Chung, Hui and Lam (2006) described, energy-efficiency indicators are developed first before conducting the benchmarking process. With EUIs being among the most common energy-efficiency indicators used for buildings (Nikolaou, Kolokotsa & Stavrakakis 2011), they will form the basis upon which this study will examine and compare the energy and water use of aquatic centres.

4.2.2 Efficiency Indicators

Efficiency indicators are essential when examining both the energy or water consumption performance levels or systems of a building (Patterson 1996). Indeed, as Nikolaou, Kolokotsa and Stavrakakis (2011) found, these indicators play an equally significant role in building energy benchmarking methods, with EUIs being the most common performance metric for whole-building energy consumption. Perez-Lombard et al. (2009) investigated the use of EUIs for different cases and determined that they are both the starting point in energy audit procedures, and the marker for which to assess energy-saving scenarios by comparing this indicator with existing references of average, above-average and best-practice cases. A commonly used EUI is the annual energy use normalised to the floor area. For example, Filippin (2000) utilised energy-consumption samples and floor areas to determine the EUI for school buildings in Central Argentina; these calculated EUIs were then ranked as a benchmark table. Lovell-Smith and Baldwin (1998) studied and presented another measure of building inefficiency by comparing the difference between actual EUIs and predicted EUIs, while Zmeureanu and Fazio (1992) established normalised EUIs that consider the energy for heating, a building’s size and operation schedule, as well as its internal temperature and wind exposure.

Based on a review of the literature, using EUIs to investigate the energy performance of aquatic centres will be appropriate. However, these types of facilities require added consideration to their water usage; hence, working similarly as EUIs, WUIs can be used as an indicator to investigate the water consumption performance of aquatic centres. Energy Star (2018) nominates two types of water-efficiency indicators that can be used for water benchmarking:

1. WUI (all water source) divides all water sources by a building's floor area (not including parking or irrigated area); water intensity is not adjusted for any of the property use details, such as the number of workers and weekly hours.
2. Indoor WUI (all indoor water sources) divides all indoor water meters by a building in square metres, not including parking or irrigated area.

Irrigated area is not included in building floor area for WUI calculations to create consistent metrics that can be used across different building types and different resources (e.g., energy, water and waste). If the irrigated area were included, the denominator for the WUI would be fundamentally different than for the EUI, even for the same building. Thus, a WUI should be not confused with water-use efficiency, which is a generic label that encompasses an array of performance indicators used to describe water use within a cropping system in Australia (Montgomery, Tennakoon & Wigginton 2013). Some notable studies include the Water Corporation's (2017), which provides water-efficiency benchmark guidance to the owners and operators of commercial office buildings in Perth, Western Australia using the water intensity water by net lettable area (kL/m^2/annum), as well as Greenovate Boston's (2015), which also investigated the water use of several building types such as universities, hospitals, hotels, laboratories, offices and residence dorms in Boston using water use to floor area normalisation (gal/ft^2) as its WUI marker. Similarly, Bint (2007) performed a pilot study examining the water use in Wellington office buildings, thus, creating benchmarks for local and international comparison. The author nominated a benchmarking measure that normalised water use with both the size and the use of a given building, which then allowed for comparative measure with other similar buildings. Basically, a normalised consumption model is a measure of water consumption against a driver, with the most statistically and pragmatically appropriate of which being the net lettable area. This means the benchmark figure can be provided in cubic metres of water by square metres of annual net lettable area (Bint 2007).

Having identified the importance of performance indicators for the analysis of both energy performance and water usage, selecting the appropriate EUIs and WUIs for benchmarking aquatic centres is the next important step. Sharp (1996) discussed the limitations of using a simple normalised EUI for buildings, and expressed concern regarding its inadequacy to provide a credible energy-consumption performance rating. As such, Section 4.2.3 offers another method of analysing the energy performance and water use of aquatic centres.

4.2.3 Computational Model-based Benchmarking and Whole-building Simulation Method

The computational model-based benchmarking method, also known as simulation model-based benchmarking, establishes benchmark values based on building performance simulation models. One such advantage is it does not require a large sample size to work. However, detailed information about the construction and operation of a building is essential as input to develop detailed simulation models. According to Nikolaou, Kolokotsa and Stavrakakis (2011), computational model-based benchmarking sets up a mathematical model to calculate theoretical energy consumption and make a comparison between theoretical energy consumption and observed energy consumption to evaluate a building's performance energy consumption. They also stated that these simulation models have the benefit to consider a wide range of factors and parameters to estimate performance and, thus, determine targets and compare retrofit scenarios. Olgyay and Seruto (2010) added that the use of whole-building modelling forms the basis of computational model-based energy benchmarking, which offers unique advantages such as generating hourly energy data through dynamic simulations; basically, this makes it possible to predict the dynamic behaviour of a building's systems under changing internal and external conditions. Such an approach works well for assessing individual building components and providing the possibility of analysing and optimising integrated and coordinated energy savings deduced from interactions of multiple building systems, including envelope improvement, alternative HVAC layouts and other passive or active load-reduction measures (Olgyay & Seruto 2010).

There are several studies that have used simulation to investigate the energy performance of buildings. Notably, Chimack, Walker and Franconi (2001) created a baseline energy model of a 107-year-old science museum using the DOE-2.1E simulation program. Essentially, this was used to estimate its current performance levels and to conduct parametric variations on the same model to assess various retrofit scenarios on HVAC system configurations. In addition, Pan, Huang and Wu (2007) also used DOE-2.1E to simulate a high-rise commercial building in Shanghai after collecting necessary building data such as built drawings, system components, operational schedules and a minimum of 12 months' worth of historical utility and weather data. Similarly, Bannister (2005) studied the energy consumption of 215 office buildings in capital cities in Australia and carried out extensive modelling with the aim of creating a corresponding benchmark by comparing the simulated efficiency of buildings to actual buildings. Additionally, Wang (2013) performed a study for the US Department of Energy (DOE) focusing on the development of an online toolkit to measure the energy-efficiency performance of commercial buildings; basically, she evaluated building EUIs based on both utility bills and energy simulations. Fumo, Mago and Luck (2010) used DOE's EnergyPlus benchmark models to develop a series of EnergyPlus normalised consumption coefficients (ENECC) that can be used to estimate hourly building energy consumption from utility bill information; they argued that having predetermined coefficients (derived from actual data and energy simulation models of typical US buildings) could relieve users from the burden of performing a detailed dynamic simulation in the first place. Meanwhile, Kalay (1999) pointed out that whole-building energy modelling techniques could promote the concept of performance-based design where there exists a context-based relationship between form and function, instead of causality-based connections. The author describes that this can lead to understanding that different forms can successfully achieve similar functions. Likewise, different functions can also be offered by similar forms, which paves the way to deviate from prescriptive methods of code compliance listing comprehensive requirements of individual building components, such as maximum U-factors for envelopes, U-factors and solar heat gain coefficient (SHGC) values for windows, efficiency factors for water heating and HVAC components to alternative performance-based compliance paths. Such alternate methods rely on the development of a whole-building energy model as a comparative baseline for a proposed design model, which must then reach a certain level of performance for energy rating end certification. Importantly, too, such a method will provide valuable information on the energy and water use of aquatic centres. For example, an end-use energy breakdown consisting of space heating, pool heating and lighting is possible when using simulation methods in contrast to statistical regression-based benchmarking. According to Karaguzel and Lam (2011), the current literature on benchmarking energy performance for retrofit projects reveals that both statistical regression-based and simulation-based models require the historical energy-use data (either collected from utility bills or onsite measurements) of various resolutions to be both functional and reliable.

4.3 Simulations of Aquatic Centres

If performance standards for aquatic centres were to be developed in Australia, it would be necessary to also create methods of predicting performance so that compliance could be established. For example, in Australia there is an energy performance method (JV3 simulation) that provides a protocol or guide on how to correctly perform whole-building simulation, as listed in the Building Code of Australia (BCA) for various building classes.

This method compares a proposed building's annual energy consumption against a reference building's energy consumption. The NABERS Commitment Agreement (base- and whole-building simulation) is another example that demonstrates how simulation is used to predict the energy consumption of a proposed building. Essentially, this helps estimate NABERS ratings and make subsequent adjustments as necessary to the design or proposed services to achieve that require rating.

Most aquatic centres are old or in the process of being retrofitted. Furthermore, there is now an increase in the use of computational performance models for retrofit projects, perhaps because statistical regression-based benchmarking does not investigate the advantages or disadvantages of the building components and systems being replaced. Fortunately, building simulations can address this quandary, with several benchmarking studies having now too included simulation to better understand how changing several variables can affect performance. Notably, Trianti-Stourna et al. (1998) not only performed audits to benchmark the energy used in aquatic centres, but also simulated three different swimming pool facilities to test different architectural and electromechanical interventions. Basically, energy-simulation programs use three main groups of variables and set of parameters to estimate a building's energy performance: design variables (i.e., geometry, material properties and HVAC systems), climatic variables (i.e., temperature, humidity, solar radiation, and both wind speed and direction) and occupancy variables (i.e., occupancy schedules, internal thermal loads and equipment gains). There are two major uses of simulation: one is to simulate a new building to predict future performance (investigate as well as optimize relevant parameters to improve the performance), and the other is to diagnose existing performance in an existing building in order to propose improvement strategies. In this study, simulation has been used for the second purpose. The results are then analysed in detail before performing parametric studies.

A building energy simulation program can next be used to simulate aquatic centres, but there exist few building energy-modelling programs that can fully model a swimming pool. The main requirement is to model water evaporation interaction with mechanical equipment; yet, the current tools in most energy-modelling software cannot be combined and controlled to emulate some of the more specialised pool mechanical systems. Costa et al. (2011) noted that simulating a swimming pool environment is a challenging task due to the interrelations between water, air temperature and relative humidity in a pool hall, which affect water evaporation rates and, therefore, the latent load in that zone. They also stated that few simulation tools for swimming pools exist and, in many cases, also bear limitations. Heat loss from evaporation is one of the main energy losses when modelling a swimming pool and is difficult to simulate. This heat loss is also the latent heat gain to the volume of space in a swimming pool hall. Therefore, when simulating such a space, both sensible and latent heat gain must be considered.

There are two known energy-simulation packages: TRNSYS and EnergyPlus 8.3, which has an indoor swimming pool simulation module. The TRNSYS Type 344 module can perform calculations of heat flow rate by evaporation, convection and long-wave radiation, and even calculate the heat loss of a covered pool (Auer 1996). Conversely, EnergyPlus is a whole-building energy simulation program that engineers, architects and researchers use to model both energy consumption—for heating, cooling, ventilation, lighting, and plug and process loads—and water use in buildings; an indoor swimming pool module was later added in version 8.3. Modelling this structure is integrated into this iteration's surface heat-balance procedures, with special modifications added to monitor the radiation between the pool-water surface and the surrounding space, the convection to the surrounding air, the evaporation of water, the conduction to a pool's bottom, the solar radiation absorbed in pool water, the pool-heating system and the presence of a cover. Conversely, several researchers have likewise used TRNSYS to simulate indoor and outdoor swimming pools. Ruiz and Martinez (2010) used the software to model the entire system for an open-air swimming pool (including the use of a solar-heating system), while Hahne and Kuebler (1994) also utilised TRNSYS to monitor and simulate the thermal performance of solar-heated outdoor swimming pools; basically, they reported that the use of unglazed solar collectors could reduce natural gas consumption for heating by around 40%. Further, Alkhamis and Sherif (1997) used TRNSYS to perform a feasibility study of solar-assisted heating and cooling systems for aquatic centres in hot and humid climates, and Mancic et al. (2014) created a multizone building model to determine a pool hall's energy demand and losses while concurrently simulating the effect of solar heating. Their simulation showed that pool heating accounts for around 22% of the total pool hall heat demand, whereas heating and ventilation constituted around 60%; it was also demonstrated that up to 87% of the water-heating demand could be met by a solar thermal system (Mancic et al. 2014). However, as each of these studies neither include a comparison between the simulated energy use and the actual energy use of aquatic centres, nor place additional emphasis on the energy savings obtained from solar heating, theirs lack a sense of validation.

There are several building energy simulations such as ESP-r, IESVE, DesignBuilder, MATLAB/Simulink and DOE-2.1E that have been or could be used to simulate aquatic centres, but fail to include a specific module on swimming pools. As such, evaporation must instead be calculated separately and included as latent heat loss and gain inputs into such software. Of particular note is the work of Ribeiro, Jorge and Quintela (2011), in which ESP-r was used as an integrated modelling tool to simulate the thermal, visual and acoustic performance of buildings, and to assess the energy use and gaseous emissions associated with the environmental control systems and constructional materials to, thus, simulate the HVAC system energy optimisation in indoor swimming pools. They manually calculated heat losses and gains from pool-water evaporation, which were then added as sensible and latent heat within the software. The authors concluded that there were obvious benefits to using pool covers at night (even with normal control in HVAC), with a reduction of approximately 85 toe/year. Conversely, Trianti-Stourna et al. (1998) used DOE-2.1E to simulate the energy consumption of indoor swimming pools. However, they provided no indication in their research on how they actually calculated heat loss and gain arising from evaporation. Instead, they clarify the heating, cooling, electrical and total annual energy consumption for the base-case simulated swimming pools.

Meanwhile, Dongellini et al. (2015) examined a dynamic model of a ‘passive’ solar-heating system composed of horizontal solar flat collectors to heat an outdoor swimming pool using the MATLAB/Simulink environment; essentially, this is an interactive tool for modelling, simulating and analysing dynamic systems that enables designers to build graphical block diagrams for simulation. Simulink is then integrated with MATLAB to provide immediate access to an extensive range of analysis and design tools (Dongellini et al. 2015). Different systems can also be studied (including linear, non-linear, continuous time, discrete time, multi-rate, conditionally executed and hybrid systems), with a hierarchical methodology (top-down or bottom-up) that facilitates the intuitive analysis of a model and the interactions between its system’s components.

Conversely, Costa et al. (2011) utilised EnergyPlus to simulate a sports facility with a gross floor area of approximately 8,000 m^2 distributed over two stories; this space included several functional areas such as a swimming pool, sports halls, gyms, multiple studios and several courts. However, the version of EnergyPlus they used did not have an indoor swimming pool module (unlike version 8.3), and the sensible and latent loads from the heat exchange between the water in the pool and the air in the pool hall had to be manually calculated and added to the model. Nonetheless, Costa et al. (2011) demonstrated the effectiveness of the proposed methodology in integrating building energy simulations (to test the energy and comfort effects of different operation strategies) and artificial neural networks (to optimise HVAC systems). They also managed to propose a procedure to simulate swimming pool in EnergyPlus. As described above, energy simulation is used in this study to diagnose the existing performance in an existing building in order to propose improvement strategies. The breakdown of energy use and loads or components/parameters (ventilation, building envelope heat losses and gain, infiltration heat loss, evaporative heat loss, pool water heating loads and lighting electricity loads) that influence the simulation results, will be examined first before proposing and testing any changes.

Evidently, it appears that some have investigated the energy use of swimming pools using building energy simulations. However, this is not the case for predicting the water consumption of aquatic centres, which otherwise bears no research papers detailing how to predict or simulate such measures. In fact, there neither exists a program that can be used to simulate total water consumption for such buildings that use large volumes of water; in turn, this creates a need for a tool or procedure to accurately estimate these figures. Indeed, many variables are important when dealing with the water consumption of aquatic centres, particularly water loss to evaporation, filter backwashing, splashing, pool-water circulation and leaks, the use of water-efficient fittings, water recycling and even rainwater harvesting. Estimating water consumption from regular domestic water use in buildings may be possible, but perhaps not sufficient for aquatic centres, which otherwise require added consideration to calculate water loss to evaporation and make-up water for subsequent replenishment.

4.3.1 Calibration of Simulation Model

Several studies have discussed how computer simulations can provide misleading results. Claridge (2011) and Dall et al. (2012) both highlighted great discrepancies between simulated building energy performance and measured performance, while Bannister (2005) cautioned that computer simulation results can provide unreliable data and differ significantly from actual building data. To this, he specified several factors that can contribute to this trend:

1. Building designs are not fully represented in simulations. The system controls and the construction details are generally poorly represented and variables like infiltration are difficult to estimate.

2. A range of construction quality and detail, commissioning and operational issues usually affect the performance efficiency of real buildings, which are beyond the control of building operators.
3. Simulations have difficulties representing complex systems.

Therefore, it is necessary to validate or calibrate simulation results to achieve a reasonable and reliable baseline close to the actual performance of real buildings. Calibration is usually an iterative and empirical process of adjusting model parameters and comparing the results to measured data. Indeed, Lam et al. (2014) define such energy model calibration as an approach to modify and adapt a design case model (which is based on measured data) to generate an updated building energy model that accurately reflects an actual building's operational performance. Basically, significant discrepancies between simulation results and measured data from buildings should be eliminated to add value to the building energy models and extend their use.

Further, Fabrizio and Monetti (2015) stated in their study that the calibration of building simulation models is of growing interest. They presented several methodologies for calibrating building energy models, including manual calibration methods based on an iterative approach, graphical-based calibration methods, calibration based on special testing, and automated techniques for calibration based on analytical and mathematical or statistical methods. First, manual calibration is based on users' experiences and judgements. It includes 'trial and error' approaches and is grounded on an iterative manual tuning of the model input parameters. Input data are altered based on users' experience, the knowledge about the building and real-world data (Pedrini, Westphal & Lamberts 2002). Graphical-based calibration methods instead use manual calibration methodologies but in addition to graphical representations and comparative displays of results, with time series and scatter plots included (Fontanella et al. 2012). Conversely, calibration based on special tests and analysis procedures use analytical and test procedures that require short- or long-term monitoring periods. This method can be distinguished from automated methodologies, as it does not employ mathematical or statistical procedures for the calibration process. Among the special tests that

can be used for calibrating building models, measurement tests such as blower door tests or wall thermal transmittance measures are considered (Fabrizio & Monetti 2015).
Finally, automated techniques for calibration based on analytical and mathematical approaches include those that cannot be considered user driven and are built on automated procedures based on mathematical procedures such as Bayesian calibration, which is a statistical method that employs probability theory to compute a distribution for unknown parameters (θ) given the observed data (y) (Coakley, Raftery & Keane 2014; Heo 2011).

Another common method that has been used in several research studies to calibrate building simulation models is to compare the simulated energy data and the measured energy data (utility bills). In particular, Pan, Huang and Wu (2007) collected the necessary building data (e.g., drawings, systems components, operational schedules and 12 months of utility bills and weather data) to develop an energy model of a high-rise commercial building in Shanghai. They calibrated their model against actual building data and concluded that simulation models could be functional in identifying interactions between conservation measures with other building systems. Further, Christantoni et al. (2015) presented a paper describing the calibration process of an EnergyPlus simulation model for a multipurpose commercial building. They collected power, gas and air temperature data collected in 15-minute intervals as part of the calibration process; as such, their results indicated a mean bias error of –1.6% for the annual electricity consumption. Royapoor and Roskilly (2015) next conducted energy calibrations using an EnergyPlus model before examining the match between simulated and actual air temperatures. A set of two calibrated environmental sensors was together deployed with a weather station in a five-storey office building to examine the accuracy of an EnergyPlus virtual building mode. Tamburrini, Palmer and Macdonald (2003) also presented a case study in which calibration occurred in several steps of data description. They argued there are several considerable barriers to be transposed in building simulation, as changing only few inputs by small amounts can provide considerable variation. Further, Chimack, Walker and Franconi (2001), Mozes (2006) and Soebarto (1997) calibrated their simulation models against utility data to ensure their model predictions agreed with actual building performance. For example, the two main areas that were adjusted to calibrate the simulation models were fan efficiency and temperature set point. Hand calculation was also performed to verify the simulation results and to estimate both the swimming pool and domestic hot-water heating loads; these were then calibrated to the simulated electricity energy use and fuel use for space heating.

Evidently, simulating a whole building can be complex, as large numbers of input data and information are required. According to Claridge (2011), when modelling a building within a simulation program, accuracy especially relies on the ability of a user to input the parameters (input data) and establish a good model of an actual building's energy use. Indeed, making assumptions when building these complex energy models will directly affect the simulation results. However, there also exists several additional issues described by both Fabrizio and Monetti (2015) and Coakley, Raftery and Keane (2014) that can further influence the calibration process. They are outline below:

4.3.1.1 Model Complexity

The number of input will depend on the type of energy model created and its subsequent complexity. Normative quasi-steady models are simpler than transient energy models, and are created within energy simulation programs such as EnergyPlus, TRNSYS and DesignBuilder. The more complex the simulation model is, the larger the amount of input data required.

4.3.1.2 Standardisation

Statistical criteria are used for assessing whether a building model can be considered calibrated These assessments and simulations are usually carried out based on users' judgements and experience.

4.3.1.3 Building Model Uncertainty

Not all input data affect the investigated energy consumption equally. Hence, it is important to identify which parameters will influence a building model most and subsequently define their level of uncertainty.

4.3.1.4 Model Input Data

Although large quantities of input data are always involved in the modelling process, the exact amount may vary depending on the level of detail pursued in the model definition, the specific aspects of the system and on data availability and quality. Measured data are sometimes used for providing a model with further information, including building occupancy, actual HVAC coefficients of performance (COP) and temperature set points during the validation stage of a calibrated model, as based on statistical indices.

4.3.1.5 Discrepancies

Identifying discrepancies between the simulated consumption and the measured consumption is often encountered during calibrated simulation. Experienced users may be able to detect the underlying causes of a mismatch due to their building simulation skills and knowledge.

4.3.1.6 User Experience

A user's experience is also an important issue to consider. With Reddy's (2006) claims that calibration is highly dependent on the personal judgment of the analyst doing the calibration and that it is clear that one's proficiency can indeed affect this process at the early stages of a simulation. Usually, a more than basic knowledge of a building simulation is required when applying the procedure.

Once an appropriate calibration method has been selected, there are statistical indices criteria that can evaluate whether a simulation model is considered fully calibrated. These indices demonstrate how well the simulated energy consumption matches the measured utility data at the selected time interval. There are several statistical indices that have become the international reference criteria for the validation of calibrated models and are recommended by three main international bodies: ASHRAE's (2002) Guidelines 14, International Performance Measurements and Verification protocol (IPMVP 2002) and the M&V Guidelines for Federal Energy Management Program (FEMP 2008).

Further, the two most common statistical indices to evaluate the accuracy of calibration are the mean bias error (MBE) and the coefficient of variation (CV) of the root-mean-square error (RMSE). Basically, the MBE measures how closely the simulated data is to the monitored data. Equation (1) shows the total sum of the difference between simulated and measured energy consumption at the calculation time interval (i.e., hourly or monthly) divided by the sum of the measured energy consumption:

$$\textbf{MBE (\%)} = \frac{\sum period (\text{S}-\text{M})\text{interval}}{\sum period\ \text{M interval}}\ x\ 100\% \qquad (1)$$

Here, M is the measured energy date during the time interval and S is the simulation energy data point during the same time interval.

The RMSE is a measure of the sample deviation of the differences between the measured values and the values predicted by the model. The CV of RMSE (or CV(RMSE)) is calculated as the RMSE normalised to the mean of the observed values. CV(RMSE) is either a normalised measure of the variability between the measured and simulated data or a measure of the model's goodness-of-fit, which specifies the overall uncertainty in the predicted building energy consumption, which reflects the error size and amount of scatter. Basically, lower CV(RMSE) values provide better calibration. Equations 2, 3 and 4 calculate the CV(RMSE):

$$\textbf{A}_{\textbf{period}} = \frac{\sum period\text{M interval}}{\text{N interval}} \qquad (2)$$

$$\textbf{RMSE}_{\textbf{period}} = \sqrt{\frac{\sum (S-M)^{2}\text{interval}}{\text{N interval}}} \qquad (3)$$

$$\text{CV}(\text{RMSE}_{\text{period}}) = = \frac{\textbf{RMSE period}}{\textbf{A period}}\ x\ 100\% \qquad (4)$$

Here, $N_{interval}$ is the number of time intervals considered for the monitored period.

Table 4.1 displays the threshold limit of the MBE and the CV(RMSE) that must be respected to consider a simulation model calibrated.

Table 4.1.
Threshold Limits of Statistical Criteria for Calibration

Statistical indices	Monthly calibration		
	ASHRAE Guideline 14	IPMVP	FEMP
MBE	+–5%	+–20%	+–5%
CV(RMSE)	15%		15%

4.4 Conclusion

This chapter highlighted different ways of assessing the energy performance and water use of aquatic centres, with benchmarking emerging as the most common method to examine the former. Basically, this process can facilitate the analysis and comparison either of a building's current energy or water consumption to an energy- or water-use baseline, or to the energy performance and water consumption of similar types of buildings. Indeed, there are several methods of benchmarking that can be used for this study. However, the relevant literature emphasised two leading approaches of worthy consideration: statistical regression-based methods and simulation model-based methods.

These two benchmarking methods are appropriate for collecting the types of data specific to aquatic centres. Both statistical regression-based models and calibrated simulation-based models require historical energy and water use data, either collected from utility bills or from onsite measurements. Many of the previous aquatic centres' benchmarking studies have used statistical regression methods to assess their energy or water performance, with EUIs and WUIs being among the most important performance indicators that are imperative to such techniques. A review of both in Chapter 2 helped gauge the confusion associated when comparing existing energy and water benchmarks for aquatic centres.

Although statistical regression-based models can provide such valuable information, such benchmarking will not offer detailed information on the effect of specific building components and systems, such as HVAC systems, alternative building envelopes or alternative pool-water heating systems. Conversely, simulation-based methods can provide breakdowns on energy usage, and can also evaluate how changing particular variables (such as type of glazing) can affect performance. Hence, a combination of the two also proves valuable.

One key disadvantage of computer simulations is they can produce unreliable results that differ significantly from actual building data. A way of overcoming this issue is to calibrate a model. Calibration is the process of fine-tuning simulation inputs to ensure the observed energy and water consumptions closely matched the simulated energy and water results. Several calibration models were nominated in Section 4.3.1, but manual calibration methods based on an iterative approach will be most appropriate for this study. Once the simulation models have been calibrated, the MBE and CV(RMSE) can be used to evaluate the accuracy of a calibrated simulation.

Additionally, there are only little software that can simulate an entire aquatic centre. Two programs identified upon reviewing the literature were EnergyPlus (version 8.3) and TRNSYS. Several researchers have used the latter to simulate swimming pools, but there remains no evidence that EnergyPlus can do the same—possibly because its indoor swimming pool module is still new, having only been introduced in 2015. Indeed, simulating energy use is also common but no study was identified in relation to aquatic-centre-specific water simulation.

Overall, this chapter recognised several methods and techniques that are used to investigate the energy performance and water use of aquatic centres. In it, several concerns were also explored, including those pertinent to data accuracy and to the limited choice of simulation software currently available. A number of past studies were also reviewed (see also Chapters 2 and 3), which since provided sufficient information to subsequently undertake a new study. As such, Chapter 5 will discuss the research methods that have been chosen to investigate the energy performance and water use of aquatic centres.

Chapter 5: Research Approach

5.1 Introduction

Thus far, this thesis has identified several methodologies, approaches and techniques required to undertake the research study. Methodologies and techniques have been chosen based on their abilities to best address five research questions:

1. How can an aquatic centre be defined for the purpose of energy and water benchmarking?
2. What are the key performance indicators that can be used to benchmark the energy and water consumption of Victoria's aquatic centres?
3. What are ranges of energy and water consumption for the state's aquatic centres?
4. How can the energy and water consumption of Victoria's aquatic centres be benchmarked?
5. What are the main energy- and water-efficiency features that can influence the energy and water use of an aquatic centre?

Each of these research questions can be investigated using quantitative research methodologies. Many previous studies on aquatic centres have too been performed using this same technique, as quantitative methods accentuate measurements and the statistical, mathematical or numerical analysis of data collected through polls, questionnaires and surveys. Basically, quantitative research focuses on gathering numerical data and generalising it across groups of subjects to explain a particular phenomenon (Muijs 2010). In the context of this research, this approach will be used to analyse numerical data such as energy and water consumption figures from utility bills. This method has been chosen to examine the correlations between several variables to yield quantitative information on aquatic centres, which can then be summarised through statistical analyses.

Essentially, this chapter will provide details on how data were collected and analysed in an attempt to respond to the research questions. The chapter contains all the approaches, processes and techniques used to undertake this research study, many of which were also created specifically for this study based on the information obtained through a literature review. Several types of research approaches were utilised—from collecting energy-consumption data, observations, statistical analysis and building simulations—to obtain the required outcomes.

5.2 Data Collection

Data collection was undertaken in two parts. The first part collected sufficient information using internet sources to define what constitutes an aquatic centre. Defining this building type is directly related to the first research question and is an imperative first part of this study. Aquatic centres are usually available to the general public, with the majority also advertising their amenities or services online, either through a website or a social networking platform such as Facebook. Based on this notion, the internet was used to search for aquatic centres within Victoria. Specific websites such as Swimming Australia and YMCA Australia were visited to quickly and easily identify every current aquatic centre and public swimming pool available in each state. However, to distinguish aquatic centres from other types of public swimming pools (such as outdoor pools), both facility-type's websites were thoroughly investigated to determine each of the available amenities. Subsequently, data were collected from approximately 110 aquatic centres to categorise aquatic centres based on the amenities included.

The second part of data collection required Ethics approval from RMIT University College of Human Ethics Advisory Network which was obtained before proceeding with the data collection. This part of data collection was the most time-consuming portion of this study, as it proved difficult to obtain information from this industry sector. In addition to the internet-based research, a questionnaire (see Appendix 1) was also sent to several aquatic centres. Emails and telephone calls were the main means of communication, and most of the questions were open-ended. The questionnaire listed three types of information: operational, electromechanical and architectural data. Examples of the operational data requested include utility data (i.e., gas, electricity and water) accounting for 12 months, occupancy data for 12 months, internal temperatures (i.e., air and water), relative humidity and operating hours. The architectural data next concerned building envelope materials (i.e., external walls, roofs and types of glazing), information regarding a centre's functional areas and the number of swimming pools, while electromechanical data concerned a centre's HVAC, lighting and pool-water heating systems, its pumps, water fixtures, and both its renewable energy and water-treatment systems. The questionnaire was sent by email and followed up with a phone call to ensure it had been received by the appropriate staff (ideally management). Once the completed questionnaires were received, a site visit was organised with the participating centres. The purpose of this visit was to gain a visual perspective of the building, and dually verify the data received on the questionnaire or gather missing information (e.g., the floor area of functional areas).

A total of 50 aquatic centres were contacted and sent questionnaires over a six-month period. However, the response rate over that time was only 16%. Receiving a completed questionnaire proved complex, but, nonetheless, understandable, as aquatic centres are large buildings to manage and, therefore, allocating time to respond might be trying. The utility bills accounting for at least 12 months of operation were also hard to obtain because, usually, this information is managed either by a different department separate from the centre or by a different organisation, such as a local government.

First, YMCA Victoria—which manages the majority of the aquatic centres in Victoria—was contacted to explain the purpose and aim of this study, to which they agreed to facilitate their participation. However, the final response rate was approximately 46%; that is, data from 23 aquatic centres were collected in total. Quality control was applied by checking all reported values, and site visits were undertaken both to verify the arrangement of the centres and to measure their floor areas. It is noted that such spatial information (i.e., floor plans and floor areas) was difficult to obtain. When the floor plans were not available, the floor areas including the water surface areas of swimming pools were measured during the site visits using a laser-measuring tool. Occupancy data, such as the number of visits made, were also obtained from the questionnaire. The majority of the aquatic centres were made to record the number of people using their amenities using either an electronic scanning system or a manual system. The air temperatures within the swimming pool halls, the pool-water temperatures, the relative humidity levels within the swimming pool halls and thermal images of the centres were also recorded during the site visits. Overall, the sample collected represents 20% of all aquatic centres (110) in Victoria. Basically, every aquatic centre within the sample has at least one indoor pool and three amenities, as yielding to the classification. Only one centre was excluded from the list because it did not contain an indoor swimming pool (three outdoor pools, including one pool opened year round), despite bearing several amenities.

5.2.1 Data Sorting and Accuracy

Each questionnaire received was thoroughly examined to check the accuracy of the information provided. Many responses featured several questions relating to unanswered details about electromechanical systems and envelopes. It is understood that many of the aquatic centres' staff would have limited knowledge about such buildings and their mechanical systems. In addition, some of the aquatic centres are old and accessing information, such as their floor plans, was either unavailable or missing. Nonetheless, the main information required to perform the analysis for this study were 12-month spanning utility bills, floor plans or information on the location's area, a centre's amenities and its occupancy rates. Each of these data had to be thoroughly checked to ensure total accuracy because, as encountered, there were instances in which utility bills were not provided or the information entered in the questionnaire was not correct (e.g., the incorrect electricity 'kWh' values). These issues were corrected by either contacting staff by email, requesting a copy of the utility bills or by visiting the site itself.

Other missing information from the questionnaire was recorded during these same visits. However, some material—such as that regarding HVAC systems, lighting details and insulation details—was not easily obtained. Nonetheless, once all the necessary data were collected, an Excel datasheet was created for summary. Section 5.2.2 provides some details on how the site visits were performed.

5.2.2 Site Visits

Once the completed questionnaires were received, an email was sent in request of the possibility to arrange a site visit within the following weeks. These trips were important to establish a general understanding of each centre's operations, and to gain some insight on their general layout. Organising a site visit was challenging, as managers had to allocate times with designated staff members to accompany the researcher and provide access to restricted areas, such as the plant rooms. Many of these visits were then organised through YMCA Victoria, with the average duration of each being between three to six hours, depending on the size of the aquatic centre.

During the trips, onsite spot measurements of air temperature, water temperature, relative humidity and air velocity were recorded on the day. Depending on the area of the swimming pool hall, at least eight spot measurements were recorded throughout the hall at a height of one meter above ground. Thermal imaging the buildings was also captured when possible using an infra-red camera to identify major areas of heat loss; however, taking thermal photos within the pool hall was not allowed in several aquatic centres due to privacy issues. One important observation gained during site visits was that most of the stadiums within the aquatic centres were not conditioned, with some using natural ventilation while others used fans for ventilation, which were only occasionally operated. On average, stadium areas within the sample accounted for around 20% of the total area of an aquatic centre.

These measurements were undertaken in an attempt to identify whether there exist significant differences in air temperature, water temperature and humidity between aquatic centres. Area measurements were also undertaken, as several aquatic centres did not have any dimensioned floor plans or information regarding their internal areas. Indeed, the spaces in which different amenities were enclosed within aquatic centres are equally important to consider within this analysis. Overall, these trips (which were performed at the majority of the 22 total aquatic centres) allowed the researcher to verify the credibility of the information sent through the questionnaires.

5.3 Statistical Regression-based Benchmarking

Statistical regression-based benchmarking has been identified as the preferred method to investigate the energy performance and water use of aquatic centres in Victoria. Statistical models were created using existing data collected in both the questionnaire and during site visits to discover a possible correlation between several variables. Of the 110 aquatic centres identified in Victoria, information was collected from 22, thus, establishing a sample size that constitutes 20% of the state's total. This sample also contains a reasonable range of aquatic centres in terms of floor area.

One of the first steps was to identify a range of variables to normalise the energy and water use of aquatic centres. Several of which, such as water surface area relevant to aquatic centres, were chosen based on the information collected during the benchmark comparison performed in Chapter 2. A guideline is proposed in Chapter 6 to explain different area selections and specify ways of organising and choosing data to perform the benchmarking. Some of its area definitions used to perform the analysis are defined as:

1. gross floor area (m^2), or the total floor area contained within the building measured to the outer face of the external walls
2. gross internal area (m^2), or the floor area contained within the building measured to the inner face of the external walls—the purpose of including this area expiates a discovery that many of the aquatic centres did not have dimensioned floor plans, and, thus, required their measuring during the site visits, particularly as it proved more practical to measure internal spaces
3. unconditioned areas (m^2), as all floor areas are not conditioned for comfort (e.g., stairs, escalators, lifts, storerooms, air locks, plant rooms and service rooms)
4. indoor water surface areas (m^2), or the surface areas of all indoor pools within a pool hall

5. indoor and outdoor water surface areas (m^2), or the surface areas of all indoor and outdoor pools (if present)
6. conditioned usable floor area (m^2), which is defined as the gross internal area, less unconditioned areas and stadium areas (if present).

However, stadium areas have also been deducted from the gross internal area, even though they are classified as a usable space; this is because the site visits actually confirmed that the majority of these spaces are typically not conditioned for comfort. Hence, including unconditioned stadium areas can produce misleading results in the study.

Once the relevant areas have been selected or excluded, some adjustments to the energy and water consumed by unconditioned areas (especially the stadia) are required. Indeed, a stadium will have some energy use due to lighting. Since these spaces are not included in the analysis, it is logical that any energy consumed within that space should be deducted (if possible) from the total energy use of the aquatic centre. However, the energy use from ventilation fans installed in some stadia has not been deducted from the total energy use because, as noted during the site visits, their fans were mainly used during the summer season or only when required.

As mentioned in Section 5.2.2, site visits were performed for the majority but not all of the centres, as this proved difficult to determine the exact electricity usage for stadium lighting. It was easy to count the number of light fittings but locating the exact wattage of each fixture was almost impossible because there were no such available records; in fact, some lightings were controlled by sensors, which meant no details were logged regarding the span of their use, and staff rarely possessed knowledge on the types of lightings in use. For these reasons, it was concluded that in Australia, and as based on NCC guidelines and information obtained from site visits and interviews from some building operators, a maximum lighting density of 10 W/m^2 for a stadium is used for at least eight hours each day. Therefore, the following formula (Equation 5) was used to estimate the total electricity usage of lighting:

$$Stadium\ annual\ lighting\ electricity\ use(Wh) = 10\ W * 8\ hrs * floor\ area\ of\ stadium * 365\ days \qquad (5)$$

Once the areas, energy and water data have been organised for analysis, statistical regression-based benchmarking is used to determine the correlation and importance of several variables in relation to the energy use and water use of aquatic centres. According to Chung, Hui and Lam (2006), the simplest statistical approach is the OLS method, which is also known as a linear regression-based statistical technique. OLS is a fast way to estimate EUIs. The factors contributing to both the EUI and WUI are also assumed to be linearly related, with OLS determining the best fit of each across multiple variables. Essentially, a linear regression analysis is first applied to determine the correlation between all the variables used for energy and water benchmarking.

Multiple regression analysis is then used to provide further justification for why some variables are more important than others when predicting energy and water use, and for clarifying which variables should be used for benchmarking. Hence, once these benchmarks were created, they were then compared with existing benchmarks. The researcher also attempted to identify the factors that helped classify why some aquatic centres are more energy- and water-efficient than others. This was performed by summarising all the data collected from the questionnaires and the site visits, some of which detailed the building envelopes, the use of double or single glazing and backwash recycling. However, there was a risk of encountering insufficient data to successfully distinguish features that elevate one aquatic centre's energy and water efficiency above another's. Therefore, it was necessary to apply a simulation method to properly investigate the main features affecting both energy and water use in aquatic centres.

5.3.1 Statistical Analysis

Analysis of variance (ANOVA) was used to perform statistical analysis in Microsoft Excel, as it provides a great variety of tools. Essentially, ANOVA is a statistical method that tests the general rather than specific differences between two or more means. It also assesses the significance of one or more factors by comparing the response variable means at different factor levels. Performing ANOVA in this study will help emphasise whether any difference exists between the groups on some variables. The tool chosen depends on the number of factors and the number of samples tested. Thus, three tools will be used to perform the required analysis.

5.3.1.1 Correlation Analysis

The correlation tool uses both the Correl and Pearson theory. These work sheets function to calculate the correlation coefficient between two measurement variables when measurements on each variable are observed for each N subject. The correlation analysis tool is particularly useful when there are more than two measurement variables for each N subject, as it provides an output table as well as a correlation matrix that shows the value of Correl (or Pearson) applied to each possible pair of measurement variables.

Like the covariance, the correlation coefficient is a measure of the extent to which two measurement variables vary together. Unlike the covariance, the correlation coefficient is scaled so that its value is independent of the units in which the two measurement variables are expressed. Hence, the value of any correlation coefficient must be between –1 and +1 inclusive.

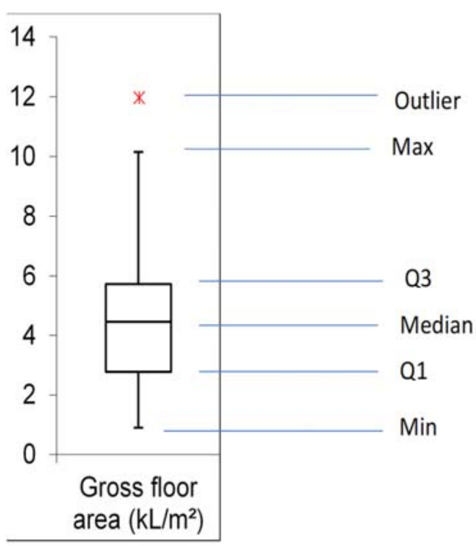
Further, the correlation analysis tool is used to examine each pair of measurement variables to determine whether the two measurement variables tend to move together—that is, whether large values of one variable tend to be associated with large values of the other (positive correlation), whether small values of one variable tend to be associated with large values of the other (negative correlation) or whether values of both variables tend to be unrelated (correlation near zero).

5.3.1.2 Regression Analysis

The regression analysis tool performs linear regression and multiple regression analysis by using the least squares method to fit a line through a set of observations. A single dependent variable can be analysed to discover whether it is affected by the values of one or more independent variables. For example, a building's energy performance is affected by such factors as area, occupancy and weather. Shares can be apportioned in the performance measure to each of these three factors (based on a set of performance data) and then used to predict the performance of another. As such, the regression tool uses the work sheet function 'Linest', with an ANOVA table created to show the sources of variation.

5.3.1.3 Box and Whisker Plots

A box and whisker plot is a graphical method of displaying the variation in a set of data. Essentially, it shows variation in the samples noting the statistical population for the aquatic centres. Box and whisker plots can display more information than a histogram and can even display multiple sets of data on the same graph; they also demonstrate the median, interquartile range (IQR), range and outliers for each variable. An example of this model is provided in Figure 5.1.



Labels	Gross floor area
Min	0.9
Q1	2.75
Median	4.45
Q3	5.75
Max	12
IQR	2.95
Upper Outliers	1
Lower Outliers	0

Figure 5.1. Example of a box and whisker plot.

Here, the median is represented by a line in the box (and is a common measure of the centre of data), the IQR box represents the middle 50% of the data, the whiskers extend from either side of the box and represent the ranges for the bottom 25% and the top 25% of the data values (excluding outliers), while the outliers are the data values that are far away from other data values that can affect the results—the outliers are identified by the asterisks (*).

This graphical method can be used to visually examine and compare the distribution of the energy and water consumption in aquatic centres for different benchmark categories. It will also identify any data (outliers) that can affect their overall range.

5.4 Building Simulation

A review of the literature revealed that only little studies have simulated entire aquatic centres and that little software can internally consider the interaction between air and water heat balance. The two most common software are TRNSYS and EnergyPlus version 8.3, as they can both simulate indoor swimming pools. Since the researcher has more expertise in the latter, the latest version (8.7) of EnergyPlus was chosen to perform the simulation. Additionally, that program can also be linked to other software, which, thus, facilitates the construction of three-dimensional modelling.

However, simulating an entire aquatic centre is a complex exercise for several reasons:

1. Aquatic centres can have many amenities or zones (a common term used in building energy simulation).
2. Evaporation is an important factor that will affect the heat balance within a pool hall.
3. The EnergyPlus indoor swimming pool module is new to the software and there are no studies identified in the literature that have used this version to perform this simulation.
4. Detailed information about the architecture, electromechanical systems and operational data of aquatic centres is also required.

DesignBuilder was then used to facilitate the construction of the three-dimensional aquatic centre models. This program provides a user-friendly modelling environment for simulating virtual building models, as well as a range of environmental performance data such as annual energy consumption, maximum summertime temperatures and performance data for

HVAC component sizes. Some typical uses include calculating building energy consumption, evaluating façade options for overheating and visual appearance, thermal simulation of naturally ventilated buildings, daylighting models lighting control systems, calculating savings in electric lighting, visualising site layouts and solar shading, and calculating both heating and cooling equipment sizes. DesignBuilder uses the EnergyPlus dynamic simulation engine to generate performance data, as it can produce EnergyPlus intermediate data format (IDF) files and transfer these to the EnergyPlus system to access functionality, which is not otherwise provided by DesignBuilder. EnergyPlus also has several options for users to create input files. The aforementioned IDF files are used to input information for simulation for which an IDF editor (provided by EnergyPlus) can then create and revise. DesignBuilder is then used to input components such as the HVAC systems used, lighting, domestic hot water, equipment, occupancy and lighting schedules, heating and cooling set points and schedules, envelope materials and insulation. Essentially, the maximum inputs possible will be entered in DesignBuilder before creating an IDF so that less input is required once the EnergyPlus IDF editor is used; again, this is because DesignBuilder does not have all the required functionality (such as indoor swimming pool input) to simulate an aquatic centre. Section 5.4.1 describes the indoor swimming pool module used in EnergyPlus in greater detail.

5.4.1 EnergyPlus Indoor Swimming Pool Module

The indoor swimming pool module is part of the heat gain section within IDF files. The subsequent modelling itself is then integrated into the surface heat balance procedures already in EnergyPlus, but with special modifications for radiation between the pool-water surface and the surrounding space, convection to the surrounding air, evaporation of water, conduction to the pool bottom, solar radiation absorbed in the pool water, the pool-heating system and the presence of a cover. Effectively, the pool-water mass is ‘added’ to or lumped into the inside face of the surface to which the pool is ‘linked’. Conduction through the floor uses the standard conduction transfer function (CTF) formulation; however, the heat balance is modified to include other terms specific to the pool water.

There are some assumptions of the model that require clarification before diving into the details of its individual components:

1. The pool water is lumped together at the inside face of a surface and follows the standard EnergyPlus heat balance methodology—some modifications based on the pool model details are later described in this section.
2. The pool itself must reference a surface that is specifically defined as a floor, which covers the entire floor to which it is linked.
3. The pool cannot be part of a low temperature radiant system (meaning that the construction of the floor cannot have any embedded pipes for heating or cooling). In addition, the floor or pool cannot be defined with any movable insulation or as a ventilated slab.
4. The pool or floor surface must use the standard CTF solution algorithm.
5. The pool may be covered, with the fraction defined by user input; this value may vary from 0.0 to 1.0.
6. The pool cover affects evaporation, convection, short wavelength radiation and long wavelength radiation. Each of these has a separate user input that reduces the heat-transfer parameter from the maximum achieved with a cover. While the cover percentage is allowed to vary by a user's schedule input, each individual parameter for these four heat-transfer modes is a fixed constant. For evaporation and convection, the factors simply reduce the amount of heat transfer proportionally. For the radiation terms, the factors reduce the amount of short and long wavelength radiation, which affects the surface (pool) directly. The remaining radiation is assumed to be convected off the pool cover to the zone air.
7. Pool-water heating is achieved by defining the pool as a component on the demand side of a plant loop.
8. Make-up water replaces any evaporation of water from the pool surface, with its temperature then within the control of users.
9. The pool is controlled to a particular temperature defined by user input.
10. Evaporation of water from the pool is added to the zone moisture balance and affects the zone humidity ratio.
11. The pool depth is small in comparison to its surface area. Thus, heat transfer through the pool walls is neglected. This is in keeping with the standard assumption of one-dimensional heat transfer through surfaces in EnergyPlus.

5.4.1.1 Energy Balance of Indoor Swimming Pool

Heat losses from indoor swimming pools occur by a variety of mechanisms, including sensible heat transfer by convection, latent heat loss associated with evaporation and net radiative heat exchange with the surroundings occurring at the pool surface. Conductive heat losses also occur through the bottom of a pool, while other heat gains or losses are associated with a pool-water heating system and the replacement of evaporated water with make-up water. The energy balance of an indoor swimming pool estimates heat gains or losses occurring due to several factors, including:

1. convection from the pool-water surface
2. evaporation from the pool-water surface
3. radiation from the pool-water surface
4. conduction to the bottom of a pool
5. fresh pool-water supply
6. pool-water heating by a plant
7. changes in pool-water temperature.

Detailed methods for estimating the heat losses and gains of indoor swimming pools are described in Sections 5.4.1.2–5.4.1.13.

5.4.1.2 Convection from the Pool-water Surface

The convection between the pool water and the zone are defined using Equations 6 and 7:

$$Q_{conv} = h \cdot A \cdot (T_p - T_a) \quad (6)$$

$$h = 0.22 \cdot (T_p - T_a)\ 1/3 \quad (7)$$

where

Q_{conv} = Convective heat-transfer rate (W/m^2)

h = Convection heat-transfer coefficient (W/(m^{2}K))

Tp = Pool-water temperature (°C)

Ta = Air temperature over pool (°C)

When a cover is present, the cover and the cover convection factor reduce the heat-transfer coefficient proportionally. For example, if a pool is half covered and a pool cover reduces convection by 50%, the convective heat-transfer coefficient is reduced by 25% from the value calculated using Equations 6 and 7.

5.4.1.3 Evaporation from the Pool-water Surface

There are five main variables used to calculate (Equation 8) the evaporation rate, including:

1. pool-water surface area
2. pool-water temperature
3. room air temperature
4. room air relative humidity
5. pool-water agitation and an activity factor.

$$m_{evap} = 0.1 \cdot A \cdot AF \cdot (P_w - P_{dp}) \quad (8)$$

where

$\dot{m}_{evap}$ = Evaporation rate of pool water (L/h)

A = Surface area of pool water (m²)

AF = Activity factor (which is chosen from values suggested by EnergyPlus according to the pool type and activity; see Table 5.1)

P_w = Saturation vapour pressure at surface of pool water (inHg)

P_{dp} = Partial vapour pressure at room air dew point (inHg)

Table 5.1:
EnergyPlus Activity Factor

Type of pool	Activity factor
Recreational	0.6
Physical therapy	0.65
Competition	0.65
Diving	0.65
Elderly swimmers	0.5
Hotel	1
Whirlpool, spa	0.65
Condominium	0.65
Fitness club	1
Wave pool, water slides	1.5–2

5.4.1.4 Radiation Exchange with the Pool-water Surface

Radiation exchange with the pool-water surface uses the EnergyPlus internal short and long wavelength radiation balances already in place. When a cover is present, it acts to reduce the amount of radiation that arrives at the pool-water surface in comparison to the no-cover case. Any reduction in either type of radiation is accounted for by adding a convective gain or loss to the zone air. In effect, the cover absorbs some radiation and then convects it to the zone air.

5.4.1.5 Conduction Through the Bottom of the Pool

The model ignores two-dimensional effects of pool walls and assumes that pool depth is much less than pool area. Conduction is calculated using the CTF equation, with the outside temperature determined by the outside heat balance and the inside surface temperature calculated using the pool-water heat balance; this is then lumped together with the inside surface heat balance.

5.4.1.6 Make-up Pool-water Supply

The energy associated with the energy used to heat the make-up pool-water supply is calculated by Equation 9:

$$Q_{fw} = m_{fw} \cdot c_w \cdot (T_p - T_{fw}) \qquad (9)$$

where

m_{fw} = Mass flow rate

c_w = Specific heat of water

T_p = Pool-water temperature

T_{fw} = Fresh water supply temperature

5.4.1.7 Heat Gain from People

The input for a swimming pool requires users to enter the maximum number of people in a pool, a schedule modifying the maximum number of people for different pool occupancies and a schedule detailing the heat gain by person for different activities. These three parameters allow for the calculation of a total heat gain during a given time. It is assumed that all of the heat gain from people is through convection to pool water.

5.4.1.8 Heat from Auxiliary Pool Heaters

The energy associated with the energy used by an auxiliary pool heater is calculated by Equation 10:

$$Q_{fw} = m_{hw} \cdot c_w \cdot (T_p - T_{hw}) \qquad (10)$$

where

m_{hw} = Mass flow rate (kg·s)

c_w = Specific heat of water (W/(m2K))

T_p = Pool-water temperature (°C)

T_{hw} = Heated water-supply temperature (°C)

5.4.1.9 Pool Heating to Control Pool-water Temperature

The equation used to determine the flow-rate request of hot water from a plant is an extremely simplified version of a pool's heat balance. This is because the mass of a pool is significantly larger than any of the other heat flows. As a result, and for the sake of establishing a heated-water flow rate, Equation 11 is used:

$$m_w c_p \Delta t (T_{set} - T_{old}) = \dot{m}_p \cdot c_p \cdot (T_{in} - T_{set}) \qquad (11)$$

where

m_w = Mass of pool water

cp = Specific heat of water

Δt = Time step length

T_{set} = Desired pool-water temperature

T_{old} = Temperature of water at the last time step

m_p = Needed mass flow rate of water from the plant

T_{in} = Inlet water temperature from the plant

This equation is rearranged to solve for the needed mass flow rate of water from the plant since all the other terms are known or given based on users' input. This establishes a flow request to the plant and is capped at the maximum value defined by that same input.

5.4.1.10 Pool or Surface Heat Balance Equation Summary

Equation 12 provides the basis for the pool or surface heat balance. Evidently, the pool water is 'merged' with the inside surface heat balance, which is essentially the same as lumping the entire water of the pool in the inside surface heat balance:

$$m_w \cdot c_p \Delta t(T_{set} - T_{old}) = Q_{cond} + Q_{conv} + Q_{lwrad} + Q_{swrad} + Q_{damp} + Q_{muw} + Q_{heater} + Q_{evap} \quad (12)$$

where

$m_w \cdot c_p \Delta t(T_{set} - T_{old})$ = The change in energy stored in the pool water

Q_{cond} = Net conduction to or from the pool water to the floor

Q_{conv} = Net convection between the pool water and the zone air

Q_{lwrad} = Net-long wavelength radiation between the pool water or floor and the surrounding surfaces, as well as from internal heat gains

Q_{swrad} = Net-short wavelength radiation to the pool water or floor from solar and internal heat gains

Q_{damp} = Standard damping term used in the inside heat balance to avoid large swings in the radiation balance, which sometimes cause instability in the solution (see the standard heat balance for more detail)

Q_{muw} = Net gain or loss from replacing water evaporated from the pool with make-up water

Q_{heater} = Net heat added to the pool through the plant loop (controlled to maintain a set point temperature)

Q_{evap} = Net heat loss due to evaporation of pool water to the zone air

5.4.1.11 Swimming Pool Flow Rate

The flow rate of the circulating pump is designed to circulate the entire volume of water in a pool in 6–8 hours, or 3–4 times in 24 hours. About 1% or 2% of the pumped circulation rate should be provided as continuous make-up water demand to overcome losses from evaporation, bleed-off and spillage. To fill a pool initially, a separate quick-fill line should be provided to perform the job in 8 to 16 hours; however, filling is usually done at off-peak hours. Thus, the demand flow rate does not need to be considered in the system demand calculations, unless it outweighs the demand of all other demands even during the off-peak period.

5.4.1.12 Comfort and Health

Typically, indoor pools are maintained between 50% and 60% relative humidity. This is for two reasons: swimmers leaving the water feel chilly at lower relative humidity due to evaporation off the body, and it is considerably more expensive (and unnecessary) to maintain 40% instead of 50% relative humidity.

5.4.1.13 Air-delivery Rates (Indoor Pool)

Most codes (such as ASHRAE's) require a minimum of six air changes each hour (ACH), except where mechanical cooling is used. However, this rate may prove inadequate for some occupancy and use. Where mechanical dehumidification is provided, air-delivery rates should be established to maintain appropriate conditions of temperature and humidity. The following rates are typically desired:

1. Pools with no spectator areas (4~6 ACH).
2. Spectator areas (6~8 ACH).
3. Therapeutic pools (4~6 ACH).

5.4.2 EnergyPlus Model

Once an IDF file has been transferred to EnergyPlus IDF editor, the location of the swimming pools is then added. EnergyPlus uses a three-dimensional Cartesian coordinate system for surface vertex specification. The coordinates of the swimming pools have to be drawn and recorded when constructing the model within DesignBuilder, as it uses construction lines to draw the swimming pool surface area within the pool hall. However, those construction lines are not included in the IDF file created by DesignBuilder, but instead must be manually recorded and added to EnergyPlus. Several indoor pools can then be inserted to the software; once entered, details of each pool such as depth, number of people and people heat gain can be included within the indoor swimming pool module. Subsequently, the pool temperature set point schedule, pool cover schedule and water make-up schedule are created within the EnergyPlus compact schedule section.

Evidently, the pool-heating system must be manually created in EnergyPlus using the IDF editor. The pool-heating system (such as the boiler) must be created and defined first, and its efficiency should also be carefully selected, as this will make a significant difference to energy use. Pipe-, pump- and pool-heating plants must then be created and linked to the pools, and the flow rates must to be sized to ensure the desired pool temperature is achieved and maintained. The heating load within the pool-heating plant and the pool-heating system must also be defined, including a set point manager, which, in fact, monitors the operation of the heating system. Heating sensors (defined as nodes in EnergyPlus) are also required and connected in the right positions (i.e., pipes, pool inlet pipes and heating system outlets), as without them, the pool temperature will neither be reached nor will the simulation work.

EnergyPlus documentation provides a guide and an example for how the swimming pool module works; however, based on this study, these documents and samples were found to be insufficient to build a working aquatic centre model. One's experience with the software must be adequate, otherwise sufficient time (months or ideally a year) must be allocated for training and allowing numerous trial and error runs with the program. Thus, once the model is built and running, evaporation rates, humidity levels, pool air temperatures and pool-water temperature will require ongoing monitoring and adjustment, if required. The most important factors that demand extra attention will be evaporation rates, evaporation heat loss and make-up water volume, as discussed in Section 5.4.3.

5.4.3 Evaporation, Heat Loss and Make-up Water Volume

Evaporation is an important phenomenon that must be considered in a simulation. Evaporation heat loss from the pool water and evaporation heat gain by the pool air temperature will have a significant effect on the simulation results. There are other heat gains and losses from a pool, such as convection and radiation from the water surface, for which EnergyPlus also accounts. However, since evaporation has the greatest effect on energy use, its subsequent handling requires further discussion.

As stated in the literature, there are several evaporation formulas that have been created by other researchers. However, as the ASHRAE method, which is similar to the EnergyPlus evaporation method, is more commonly used in the past, it too will be used to verify the evaporation results produced by EnergyPlus in this study. According to ASHRAE (1999a), the desirable temperature for swimming pools is 27 ^{o}C; however, this will vary by culture by as much as 5 ^{o}C. The sizing of the system for temperature and flow rate also depends on four considerations (ASHRAE 1999a), including the conduction through the pool walls, convection from the pool surface, radiation from the pool surface and the evaporation from the pool surface. Indeed, these are also considered in EnergyPlus.

Conduction is generally the least significant factor, unless a pool is above ground or in contact with cold groundwater. Convection losses depend on the temperature difference between the pool water and the surrounding air and wind speed, but this is substantially reduced for indoor pools and those using wind breaks. Radiation losses are also greater at night, especially for outdoor pools; however, solar gains are achieved during daytime, which may offset increased heat losses; additionally, a floating pool cover can reduce both radiation and evaporation losses.

Evaporation losses constitute the greatest heat loss from pools at around 50% to 60% in most cases (ASHRAE 1999a). The rate at which evaporation occurs is a function of air velocity and pressure difference between the pool water and the water vapour in the air (vapour pressure difference). As the temperature of the pool water increases or the relative humidity of the air decreases, the evaporation rate increases. An enclosure can reduce this loss substantially, and a floating pool cover can practically eliminate such loss. Swimming and other pool uses causing waves and splashing will also increase the surface area and, thus, the evaporation rate. A swimming pool hall will also require year-round humidity levels between 40% and 60% for comfort, energy consumption and building protection (ASHRAE 1999b). Essentially, any design must consider a multitude of variables, including humidity control, ventilation requirements for air quality (outdoor and exhaust air), air distribution, duct design, pool-water chemistry and evaporation rates.

According to ASHRAE (1999b, p. 48.19):

> humans are very sensitive to relative humidity. Fluctuations in relative humidity outside the 40 to 60% range can increase levels of bacteria, viruses, fungi and other factors that reduce air quality. For swimmers, 50 to 60% relative humidity is most comfortable. High relative humidity levels are destructive to building components. Mould and mildew can attack wall, floor, and ceiling coverings; and condensation can degrade many building materials. In the worst case, the roof could collapse due to corrosion from water condensing on the structure.

As such, the ASHRAE formula used in this study is defined in Equation 13. The evaporation rate can be estimated for pools of normal activity levels, thus, allowing for splashing and a limited area of wetted deck (ASHRAE 1995).

$$wp = A/y\,(Pw - Pa)\,(0.089 + 0.0785V) \times AF \qquad (13)$$

where

wp = Evaporation of water (kg/s)

A = Area of pool surface (m^2)

y = Latent heat required to change water to vapour at surface water temperature = 2,257 (kJ/Kg)

P_w = Saturation vapour pressure taken at surface water temperature (kPa)

P_a = Saturation pressure at room air dew point (kPa)

V = velocity of wind (m/s)

AF = Activity factor to alter the estimate of evaporation rate based on the level of activity

The following activity factors defined in Table 5.2 are applied to the area of specific features, and not to the entire wetted area (ASHRAE 1999b).

Table 5.2:
ASHRAE Activity Factor

Type of pool	Activity factor
Residential pool	0.5
Condominium	0.65
Hotel	0.8
Public, school	1
Whirlpool, spa	1
Wave pool, water slides	1.5

The saturation vapour pressure taken at surface water temperature and saturation pressure at room air dew point are calculated using the formula provided by Engineering Toolbox (2015). This is subsequently verified by the common values provided by ASHRAE (1999).

The formula listed in Equation 14 is next used to heighten precision and accommodate for the varying levels of pool hall air temperatures, pool-water temperatures and relative humidity listed in Tables 5.3 and 5.4.

Table 5.3:
ASHRAE Common Values for p_w

Water temperature (°C)	P_w (kPa)
15	1.7
20	2.34
25	3.17
30	4.25
35	5.63
40	7.38

Table 5.4:
ASHRAE Common Values for pa

Room temperature (°C)	40% Relative humidity (kPa)	50% Relative humidity (kPa)	60% Relative humidity (kPa)
20	0.94	1.17	1.7
25	1.27	1.58	1.9
30	2.12	2.12	2.55

Pw = Water vapour saturation pressure and Pa = Saturation vapour saturation at room dew point

$$P_w \text{ and } P_a = e^{(77.345+0.0057T-725/T)}/T^{8.2} \quad (14)$$

where

e = The constant 2.718

T = Dry-bulb temperature for the moist air dew point at a specific relative humidity and air temperature will be required to find P_a

The simulation results will be verified based on the formulas and ASHRAE guidelines provided. However, it is important to note that the ASHRAE evaporation formula does not consider the evaporation levels when pools are unoccupied during the night. EnergyPlus instead presents a possibility of adjusting the evaporation level throughout the day by creating a pool activity schedule within the software's compact schedule section. Indeed, this difference is considered when forming the comparison between the EnergyPlus and calculated ASHRAE evaporation rate and loss.

Essentially, this section has provided a significant amount of information on how evaporation levels in the simulation will be monitored and checked because, evidently, evaporation is an important factor that will affect the final results. Accordingly, Section 5.4.4 will provide details on how to select the most appropriate aquatic centre as a case study to examine.

5.4.4 Criteria for Selecting an Aquatic Centre for Simulation

Selecting an aquatic centre from the sample collected during this study is an important task that will contribute towards its successful completion. The questionnaires and information gathered were carefully examined to select the most appropriate aquatic centres to be used as case studies. It was also evident that simulating an entire aquatic centre comprising of several pools and several amenities would be a complex and time-consuming task. Based on this fact, only one aquatic centre was chosen as a case study to investigate the energy performance and water use of aquatic centres more generally. Hence, the criteria for selecting an aquatic centre for simulation included:

1. detailed floor plans and elevations, including access to its dimensions
2. majority completion of the questionnaire
3. managers or staff with sufficient knowledge about the operation of the centre, as well as its electromechanical systems
4. availability of architectural details such as external walls, materials used, roof type and glazing details
5. a compliant aquatic centre manager in agreement to use their facility as a case study, with added willingness to be contacted for more information or clarification
6. availability of sufficient details of all electromechanical systems, such as the HVAC and pool heating systems
7. 12 months of utility bills (gas, electricity and water) and occupancy data
8. a site visit to be performed with the possibility of follow-up trips
9. an aquatic centre with more than one indoor pool, as well as several amenities to represent more complex facilities and to account for the majority of the aquatic centres within the sample, which had more than one indoor swimming pools—importantly, simulating more than a pool will also allow for testing the capability of the software in simulating a complex aquatic centre
10. examining the floor plans and elevations, and confirming that a three-dimensional model of the aquatic centre can be built using DesignBuilder.

Once the majority of the criteria were followed, an aquatic centre could be selected for simulation purposes. The selection also required professional judgements from the researcher to ensure the major issues or factors than can cause difficulty in the simulation could be easily identified. An example of either is a very complex HVAC system, which would be too complicated to simulate using the listed software.

5.4.5 How to Simulate Water Consumption

The simulation and estimation of an aquatic centre's water consumption is challenging, as there is no known software that can model the complete (hot and cold) water cycle of such a building. Examples of hot-water consumption for an aquatic centre include the swimming pool make-up water needed to maintain the desired pool temperature and domestic hot water for showers, kitchens and sinks. Conversely, examples of cold-water consumption for an aquatic centre constitute water used in sinks, toilets and irrigation (if required), and the consumption of cold water related to swimming pools to compensate leaks, splashing of water by bathers and re-fill due to backwash water. However, two important variables can be simulated using EnergyPlus: the hot-water consumption from domestic hot water, and the make-up water due to evaporation. Domestic hot-water consumption arising from showers, kitchens and hand sinks as well as make-up water can be obtained from EnergyPlus, while the water consumption from toilet flushing, sinks, backwash water re-fill, leaks, splashing and irrigation (if required) is manually estimated based on information obtained from a literature review. Meanwhile, backwash water consumption can be based on the type of filter used, splashing can be based on the estimated number of bathers, while leaks and other uses such as irrigation and cleaning can be estimated based on the researcher's judgements. As such, Microsoft Excel will be used both to summarise the hot- and cold-water consumption obtained from EnergyPlus, and for manual calculations.

5.4.6 Model Calibration Process

A manual calibration method based on an iterative approach is used for calibration. This method is based on the researcher's experience and judgement, which includes trial and error approaches, and on an iterative manual tuning of the model input parameters, such as lighting levels and systems efficiencies. An iterative approach requires adjusting the selected parameters within reason until the reasonable calibrating levels are reached. A list of parameters that can be adjusted are, but not limited to, HVAC system efficiency, pool heating system efficiency, insulation values within external envelopes, glazing systems, evaporation levels, occupancy, equipment and lighting schedules, lighting density, equipment energy consumption, domestic hot-water energy use and water use, water fixture efficiencies and backwash water consumption.

The simulation results for each iteration will be compared against the two common statistical indices to verify how close the simulation is with actual consumption. The two main indices are MBE and CV(RMSE), and the threshold limits are listed in Table 5.5.

Table 5.5:
Statistical Indices Threshold Limit

Statistical indices	Monthly calibration
	ASHRAE Guideline 14
MBE	+–5%
CV(RMSE)	15%

A step by step process used for calibrating the simulation model is described below.

1. check the weather data used or make comparison between the weather data used and the real weather data to verify its suitability
2. run the simulation and check the simulation results for abnormalities such as excessive heat loads
3. perform the statistical indices threshold limit calculation to check how far the model is, from being considered calibrated
4. create a heat losses and energy loads chart to make comparisons
5. check non-weather dependent components/parameters such as lighting energy loads, equipment and pump energy loads and pool heating energy loads
6. check weather dependent components/parameters such building envelope heat losses and gains, evaporative heat loss, infiltration heat loss and ventilation heat loss and gain.
7. determine which components/parameters to adjust based on the chart.
8. adjust the necessary components/parameters and rerun the simulation.
9. redo the statistical indices threshold limit calculation to verify whether the model is calibrated.
10. if not within the threshold limit, examine the simulation results and make further adjustments until the model’s statistical indices are within the threshold limit.
11. check the evaporation heat losses by comparing the simulation model’s evaporative heat losses and ASHRAE’s manual calculation
12. once the model is considered calibrated and the evaporation rate is validated, further analysis such as parametric studies can be undertaken.

The calibration process is undertaken by comparing the total simulated electricity and gas consumption against the total measured gas and electricity consumption obtained from the sample centre's utility bills. Comparison of the energy use from specific components such as fan energy use, HVAC system energy use or pool heating system energy use is not possible because actual measured data from the aquatic centre's electromechanical system is not available. In addition, obtaining actual measured data is a very expensive and time-consuming exercise, which will require months of monitoring, the installation of sensors and regular access to several restricted areas of the aquatic centre, among other factors, which is beyond the scope of this study. Hourly calibration is neither possible due to similar reasons as for components calibration.

5.4.7 Parametric Studies

Once the simulation model of the aquatic has been calibrated, it will be used to analyse and investigate the effect of several features that can cause an increase or reduction in the energy and water use of the selected aquatic centre. Basically, a sensitivity analysis of the aquatic centre will be undertaken. Sensitivity analyses for buildings are a technique developed for optimising a number of their building and system parameters. This technique is also used in building energy efficiency to minimise energy consumption and to achieve the best load and energy characteristics, with respect to building input parameters and the deployment of computer simulation programs (Lomas & Eppel 1992). A list of parameters to be investigated include:

1. different wall and roof materials
2. insulation upgrades (external walls and roof)
3. glazing upgrades (double glazing)
4. pool hall air temperature reduction
5. pool-water temperature reduction
6. installation for pool covers
7. boiler efficiency
8. types of boilers
9. HVAC system upgrades and efficiency
10. solar heating
11. wind turbine
12. water-efficient fittings

13. light-emitting diode (LED) lighting.

A parametric study is also an important part of this research, as it will provide a detailed understanding of what features can make an aquatic centre perform more efficiently in relation to energy and water use. This understanding will enable a response that dually answers the third research question pertaining to these same concerns.

5.5 Energy Sources and Greenhouse Gas Conversions

This section describes the type of energy used in the analysis with added reasoning. Essentially, there are two forms of energy use that are often referred to when directly investigating the energy consumption of buildings (Energy Star 2018): site energy or final energy, and source energy. The first describes the amount of energy brought onsite or used by a building's end uses, such as air conditioning, pool-water heating, pool pumps, and both treatment and equipment. It is usually the combination of primary and secondary energy that is bought directly for onsite use. The second regards the total amount of energy used to produce and transport energy to a site. Basically, it is the total PE consumption, which is the site energy plus all the delivery and production losses.

Both site and source energy are useful depending on the situation. It is understood that to evaluate the energy performance of buildings, it is preferable to use the latter, as it includes the energy losses associated with generating and delivering fuel. Energy Star (2018b) provides site-to-source conversion factors, which are the multipliers to convert site energy into source energy for each fuel type; however, this applies to the US only. Deru and Torcellini (2007) defined the issue with this conversion regards its fluidity, in that these figures change from state to state, every day, or even hourly. This occurs because the power mix of an electric grid is constantly changing to meet load; for example, peaking power (versus average or base load) can have a significant effect. Further, as more renewable energy sources such as wind and solar are added to the grid, this source energy penalty will decrease (Deru and Torcellini 2007). In Victoria, site-to-source ratios to convert secondary energy to PE are not readily available. Therefore, such ratios could be difficult to create due to the complicated energy network supply in Victoria. For example, electricity is obtained by many sources and even by other Australian states, as shown by Figure 5.2.

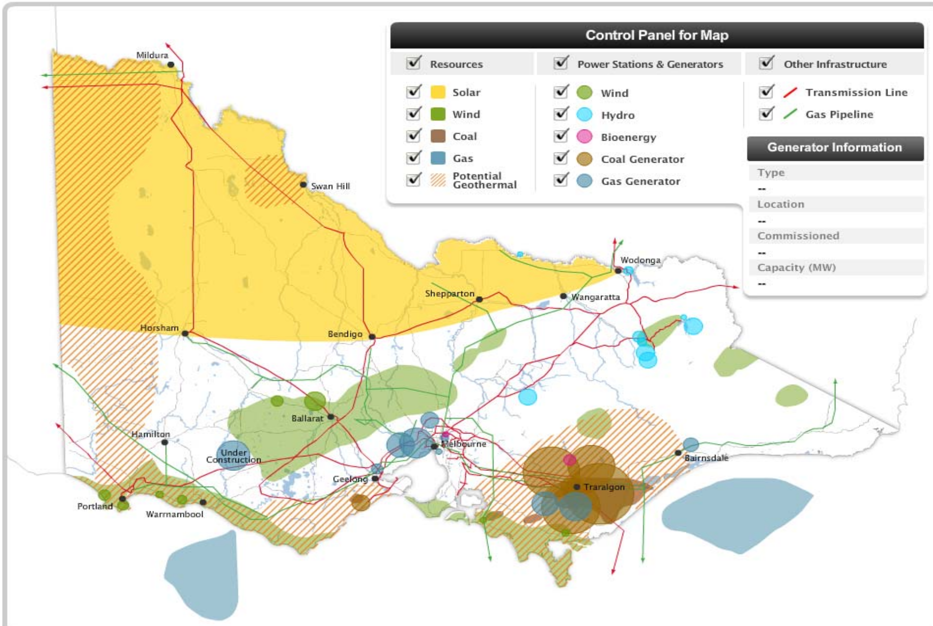


Figure 5.2. Energy sources in Victoria (State Government of Victoria 2018).

For the purpose of this study, site energy, or the total energy consumed onsite by an aquatic centre's end uses (i.e., air conditioning, pool-water heating, pool pumps and treatment equipment, as reflected on one's utility bills) was used for the analysis—a similar approach was, in fact, used in a study by the DCCEE (2012) to measure the baseline energy consumption of commercial buildings in Australia. Therefore, any reference to total energy use within this study refers to total site energy use. One such advantage is that aquatic centre operators will be able to utilise the energy analysis undertaken in this study to compare their own energy performance using the data obtained from their own utility bills, but without need to identify the source energy.

Additionally, aquatic centres in Victoria use two types of energy to operate: gas and electricity. However, it is understood that combining both can cause the latter to become over-represented, as gas generally costs less and, in most parts of Australia, has lower environmental bearing. Conversely, the US uses PE as its preferred metric, which also wrestles with environmental concerns, while the UK uses a deemed factor of ‘1’ for electricity and 0.4 for gas. To factor for PE and the environmental effect of energy sources in this study, greenhouse gas emissions conversion factors are, therefore, used as an alternative metric for benchmarking.

5.5.1 Greenhouse Gas Emissions Conversion

Greenhouse gas is commonly measured in units of CO_2 equivalent ($CO_{2equivalent}$), expressed as mass (e.g., an average passenger vehicle produces 5.48 metric tonnes of $CO_{2equivalent}$ each year). As stated in Section 5.5, the two main energy sources used by aquatic centres are gas and electricity, with each bearing a different greenhouse gas emissions conversion factor. These factors are used to propose an alternative benchmark category that not only accounts for the production, delivery and transmissions losses accounted by site-to-source conversions, but also for each energy source’s environmental effect. The greenhouse gas emissions conversion factors were obtained from the Department of the Environment and Energy (2017):

Gas: 55.43 kg/CO_{2e}/GJ

Electricity: 1.18 kg/CO_{2e}/kWh

Both factors are calculated at the point where natural gas and electricity are delivered to end users. They are only applicable to regions located in Victoria.

Each state in Australia has different conversion factors. It is also noted that the conversion factor for electricity is higher, as a large amount of electricity produced in Victoria still derives from the burning of fossil fuels, such as coal. The natural gas conversion factor includes the estimation of direct and indirect emissions attributable to the extraction, production and transport of gas to end users, while the electricity conversion factor includes both the estimation of direct and indirect emissions from the extraction, production and transport of fuel burned at generation, and the direct and indirect emissions attributable to the electricity lost in delivery to end users.

5.6 Conclusion

This chapter has identified the approaches, methods and procedures used to investigate the energy performance and water usage of aquatic centres in Victoria. Quantitative methodology proved the preferred method to perform the analysis, while a review of the literature revealed both benchmarking and simulation methods require detailed information about a facility's architecture, electromechanical systems and operational data, the details of which were collected by a questionnaire, site visits and onsite measurements.

Several aquatic centres in Victoria were contacted, and detailed information from 22 was obtained and carefully analysed. All the methods and techniques were also chosen based on their ability to respond to the research questions. Benchmarking will attempt to respond to Research Questions 2, 3 and 4, while simulation will respond to Question 5. In addition, statistical regression-based benchmarking was chosen to establish the energy and water benchmarks for an aquatic centre, with several variables being identified to normalise both usage measures. Correlation analysis and multiple linear regression techniques will be used to determine which variables have the strongest correlation and the most significance to the energy and water use in aquatic centres. In turn, this will justify the appropriate EUI and WUI for such buildings. Data collection will also be employed to investigate which features determine why some aquatic centres perform better than others within the sample. However, accounting for the possibility that this method might not provide sufficient information as to why certain aquatic centres are more energy and water efficient, building simulations have been identified as a suitable schema to heighten accuracy.

Simulations are used to investigate in detail the features that enhance an aquatic centre's efficiency. This method will provide several advantages, particularly in supplying information on energy end-use breakdowns and comparisons between systems and make-up water use—an otherwise difficult feat to achieve when using only statistical regression-based methods. In turn, DesignBuilder and EnergyPlus proved the two preferred software to perform the building simulation. The former will be used to facilitate the construction of the three-dimensional aquatic centre model and the input process, while EnergyPlus will be used to perform the simulations. Version 8.3 of that program is the first to include an indoor swimming pool module and, thus, make possible the goal to model an entire aquatic centre, including all its indoor swimming pools. A simulation will also be performed to estimate water use using data obtained from EnergyPlus and from manual calculation, particularly as no software has been identified to model such information.

Once the simulation model has been created, calibration will be required to ensure the simulated results closely match the actual energy and water use of the chosen aquatic centre. Several calibration techniques have been identified; however, the manual calibration with several iterations will be used. The calibration process will then be verified using statistical indices (MBE and CV(RMSE)), and the model will be calibrated against measured energy data (utility bill data); hand calculations will also be performed to verify specific loads, such as evaporation. Once created and calibrated, parametric studies of key variables will be undertaken with regard to site energy.

Overall, this chapter has provided detailed descriptions of the methodologies, techniques and processes used to perform the required analysis and, hence, respond to the research questions. Chapter 6 subsequently presents the analysis and results obtained using the statistical regression-based methodology.

Chapter 6: Statistical Regression-based Benchmarking of Aquatic Centres

6.1 Introduction

After collecting and sorting the data obtained from questionnaires and subsequent onsite measurements, statistical regression-based benchmarking was conducted to investigate the energy performance and water usage of aquatic centres in Victoria. Essentially, this technique uses the existing data collected to discover correlations between several variables with respect to both energy and water consumption. As such, multiple tables listing the different energy and water usage intensities have been created to allow for comparison with other studies.

The initial portion of this chapter will propose a definition for the term 'aquatic centre' and provide a guideline for identifying and benchmarking aquatic centres. The chapter will then focus on an energy analysis. In turn, two levels of statistical regression analyses were used: linear regression and multiple regression. Thereafter, this chapter will focus on water use and benchmarking. Evidently, water studies are not as common as energy studies on swimming pools facilities. Even then, with the available comprehensive guidelines on the water consumption of aquatic centres prepared in Australia by several organisations, there remains some uncertainty as to how they defined and selected these buildings for analysis. There is also a greater range of water performance indicators for swimming pool facilities, and this has made it difficult when deciding which of those are for aquatic centres. Nonetheless, water use is divided into several variables and a similar analysis process to that performed for gauging energy is undertaken. Linear and multiple regression analyses are then undertaken to discover the appropriate variable applicable to aquatic centres and, hence, propose a water benchmark.

This chapter then compares the proposed energy and water benchmarks to existing benchmarks. Detailed information about the architecture, electromechanical systems and operational data of the aquatic centres have also been collected and arranged. This information is then used to identify if any distinct features specifically determine whether aquatic centres comparatively operate more efficiently in relation to both energy and water use. Essentially, this chapter will attempt to respond to Research Questions 1–4. As such, Section 6.2 will begin by discussing the proposed definition of an aquatic centre and the benchmark guidelines before investigating the energy benchmark of aquatic centres based on the collected data.

6.2 Proposed Definition of an Aquatic Centre

To clarify and define what constitutes an aquatic centre, those operating within Victoria were first investigated. Evidently, aquatic centres are expected to include swimming pool facilities made available to the general public. It was also assumed that the majority of the state's aquatic centres currently use the internet to advertise their services and amenities offered. Based on this dual assumption, the web proved a logical avenue to locate aquatic centres within the state. Both Swimming Australia's (2015) and YMCA (2015) Australia's websites were the main digital sources used to complete this search. Once identified, each aquatic centre's website was thoroughly investigated to determine what types of amenities were included. Data were then collected from approximately 110 aquatic centres and used to categorise aquatic centres based on the amenities provided.

According to the data collected, aquatic centres can include indoor and outdoor recreational pools, lap swimming pools, diving pools, hydrotherapy pools, family and toddler pools, gymnasiums, fitness centres, saunas and spas, stadiums, childcare facilities and cafes. Offices and reception areas were omitted from the amenities, as it is assumed all centres contain at least a small office and a reception area. Figure 6.1 shows the percentages of the main groups of aquatic centres based on their amenities. Hence, for the purpose of this study, an aquatic centre will be defined based on the first three largest categories in Figure 6.1, which together constitute 78% of the aquatic centres located within Victoria. Additionally, an aquatic centre, thus, becomes defined as a community or public venue that provides at least an indoor pool and three different types of other amenities (e.g., gymnasium, sauna or spa, cafe, creche or indoor stadium). They can also include several pools including outdoor pools, but with the stipulation that one of them is indoor.

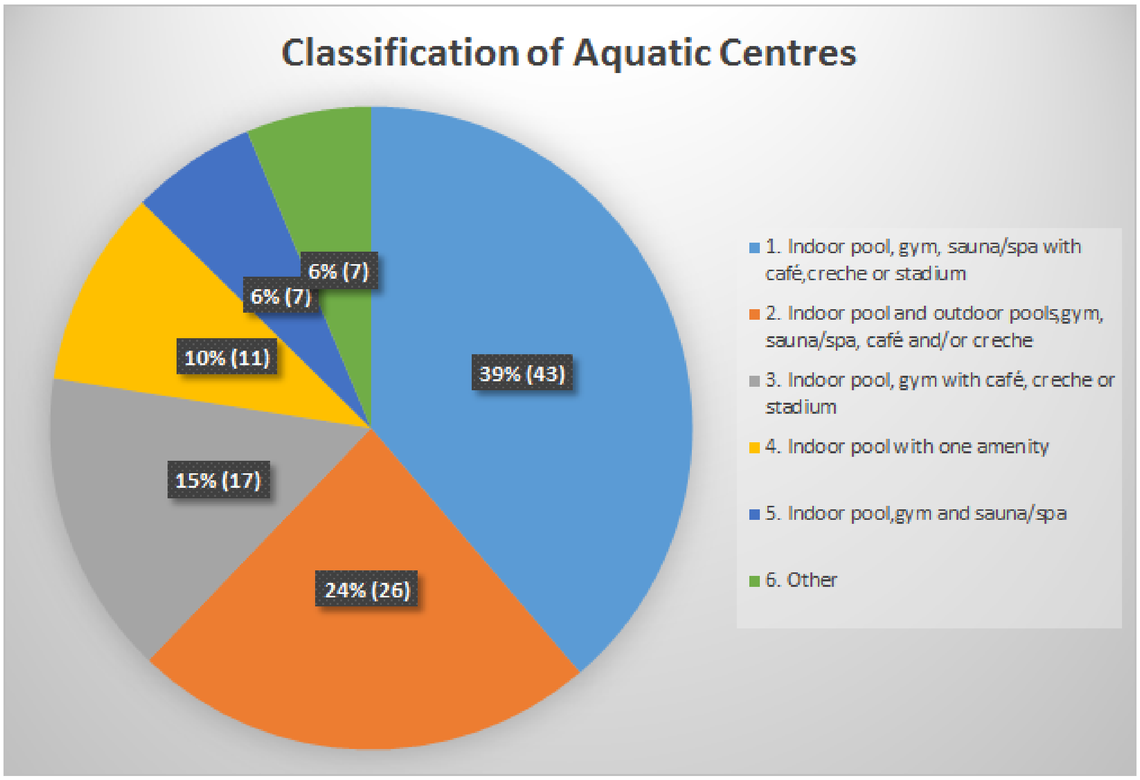


Figure 6.1. Classification of aquatic centres in Victoria, Australia.

This definition can be readily applied to similar building types worldwide, as the majority of the centres known under different names include similar amenities.

Further, Kampel, Aas and Bruland (2014) stated that leisure pool facilities can include a pool, a diving platform, different water attractions and relaxation areas, including a restaurant, spa or sauna. Step2Sport (2015) similarly refers to these buildings as sports complexes that constitute indoor swimming pools, gymnasiums and sports halls, while Good, Debruyn and Whitehead (2007) describe a recreational facility as a building that can include lap, leisure, outdoor and whirl pools with a gymnasium, fitness studio, ice arena, offices and even a library. According to Costa et al. (2011) and Trianti-Stourna et al. (1998), sport facilities can also include several types of pools with offices, restaurants, shops, training areas and other smaller amenities such as saunas and spa. In addition, swimming baths described by Saari and Sekki (2008) include a main pool area with several amenities such as gymnasiums, meeting rooms, cafeterias and saunas.

This research revealed that the number of aquatic centres identified in Victoria is different to the number of aquatic centres provided by several organisations and previous studies. For example, the ARV (2014) stated Victoria has in excess of 500 aquatic facilities, with 277 (55%) belonging to the local government; the remaining 233 (45%) include private swim schools and educational institutions. However, it is unclear what aquatic facilities means. That is, are outdoor swimming pool facilities included in these numbers? In this investigation, the number of aquatic centres identified was also different to the number of aquatic centres listed by the ARV; alas, this discrepancy is possibly related to the lack of clarity in defining an aquatic centre. Hence, upon identifying what an aquatic centre means or consists of, this study will provide a better understanding of the importance a clear definition bears when comparing aquatic centre studies for benchmarking purposes.

6.3 Aquatic Centres' Energy and Water Benchmarking: A Guideline

Evidently, Figure 6.1 was used to categorise aquatic centres according to the number and types of amenities they offer. Based on this data, an aquatic centre has, therefore, been defined as a community or public venue that includes at least an indoor swimming pool and three different types of amenities (e.g., a gymnasium, sauna or spa, a cafe and crèche). Centres with only outdoor swimming pools are consequently not classified or defined as an aquatic centre. Additionally, the majority of outdoor swimming pools in Victoria are usually only opened during the summer seasons.

The benchmark comparison performed in Chapter 2, Section 2.5 confirmed that there are no universal guides for benchmarking and assessing the energy and water performance of aquatic centres, particularly in comparison to other buildings types (such as offices, residential buildings and hotels), which otherwise bear several standards (e.g., CIBSE, NABERS and Energy Star). Additionally, it is also understood that the term 'aquatic centre' may neither be used universally (see Chapter 2 for a list of other terms). In turn, guidelines for defining aquatic centres as well as benchmarking energy and water use are proposed, particularly to facilitate a comparison between future aquatic centre studies. Many of the amenities (e.g., cafes, gyms, offices, creches and meeting rooms) have similar controlled environments (e.g., air temperature and humidity) that can be grouped in the same zone (e.g., the dry zone). Naturally, all indoor swimming pools including spas and saunas within an aquatic centre will then be contained within the same pool hall (i.e., the wet zone). In fact, regardless of the amenities, the number of those available and how many indoor pools are included, an aquatic centre will always have these two zones. Theoretically, the same facilities are subsequently compared; however, outdoor pools cannot be listed as a third zone because they are exposed to external environments that cannot be controlled and are usually only opened during the summer seasons.

In turn, the proposed guidelines for identifying aquatic centres (or buildings with swimming pool facilities) considers several factors:

1. The centre must have at least an indoor swimming pool open to the general public, but can include several swimming pools including those located outside. Centres with only an outdoor swimming pool are not included in this category because they are only usually open during the warmer seasons and since outdoor environments cannot be controlled.
2. The centre must have at least three other amenities, including a gymnasium, sport hall, fitness studio, office, cafe or restaurant, creche or childcare facility, indoor court, sauna or spa, meeting room or library.
3. The researchers must clearly state what types of amenities are included within their evaluation.
4. If the researchers decide to include or exclude some amenities in their definition, they must clearly state their reasons why.

The proposed guidelines for benchmarking energy and water use of aquatic centres are as follows:

1. Researchers must clearly define the aquatic centres under investigation, the rules for which as mentioned in the above list or similar must be followed.
2. Reasons must be provided regarding why particular performance indicators have been chosen.

6.3.1 Energy

Researchers must consider using kilowatts of energy used by unit of floor area (kWh/m^2_{ua}) instead of kilowatts of energy used by unit of water surface area (kWh/m^2_{ws}). This is because aquatic centres have several dry areas. Additionally, kWh/m^2_{ws} can be used when only assessing a swimming pool hall, while kWh/m^2_{ua} will allow for direct comparison between other building types. Next, researchers must clearly define the area used in their benchmarking and provide reasons for their choices. There are several terms that could be used when describing said amount of building area, including:

1. gross floor area, or the total floor area contained within the building measured to the outer face of the external walls
2. gross internal area, or the floor area contained within the building measured to the inner face of the external walls
3. usable floor area, which is the gross internal area less the floor areas taken up by stairs, escalators, lifts, thick columns or risers.

The researchers must also clearly state whether the floor areas chosen in their analysis are based on conditioned or unconditioned areas (or both) and provide reasons for their inclusion or exclusion. If possible, unconditioned areas must be excluded from their analysis unless they used a significant amount of energy or water. For example, an unconditioned sports hall should not be included (if possible), as this area (which is typically large) in a benchmark analysis will lower a centre’s energy intensity compared to a centre that does not have such a space. Calculations can be made to estimate the total electricity used by the sports hall lighting and then deducted from the centre’s overall electricity usage. This calculation can be achieved by obtaining information through audits and lighting plans, or by using the building code of that particular country. For example, the NCC’s energy efficiency requirement allows a maximum illumination power density of 10 W for every square metre of a stadium. Assuming that the stadium lighting is on for eight hours each day, the overall lighting electricity usage of the stadium for a year could be 10 W x the area of the stadium x eight hours x 365 days. Examples of other unconditioned areas are enclosed car parks, store rooms and plant rooms.

6.3.2 Water

Careful consideration must be made when choosing a performance indicator or unit for water usage. Kilolitres or litres by person are appropriate performance indicators in place of kilolitres by bather because aquatic centres also have dry amenities such as gyms, sport halls and childcare facilities for which to account. Kilolitres by centre should neither be used because the majority of these buildings have different layouts and areas. Further, units judged by person will account for a mixture of people using the swimming pools facilities and the dry areas amenities, including gyms, sport halls and child care. Indeed, some aquatic centres record the number of people using the swimming pool facilities and the dry area amenities separately. Some calculations and averages will be next required to estimate the number of persons for benchmarking purposes. A possible method for calculating this figure could see one bather signify one person. Thus, every 5.5 persons utilising the dry area amenities or visiting the centre will be counted as one bather, as they typically use more water. The ratio provided is based on the calculations and assumptions listed in Table 6.1.

Table 6.1:
Calculating the Ratio of Bathers to Visitors

Water use	WELS rating	L/bather	L/visitor
Shower (3 minutes)	3 (> 7.5 L/min, but < = 9 L/min)	27	
Toilet	3 (4 L per flush)	4	4
Tap (hand basin; 15 seconds)	4 (> 6 L/min, but < = 7.5 L/min)	2	2
Total		**33**	**6**

Indeed, researchers may also decide to select different performance indicators and provide sufficient evidence to justify their choice. However, it is advised that they also utilise the listed performance indicators to facilitate a comparison of their benchmark results to other studies.

Figure 6.2 is a process map created to facilitate the classification of an aquatic centre for benchmarking purposes; this is configured according to the categories listed in Figure 6.1, with Categories 4, 5 and 6 omitted and not classified as an aquatic centre. Once the building is selected as falling within Categories 1, 2 and 3, the building can be classified as an aquatic centre and, therefore, be included in the benchmarking process.

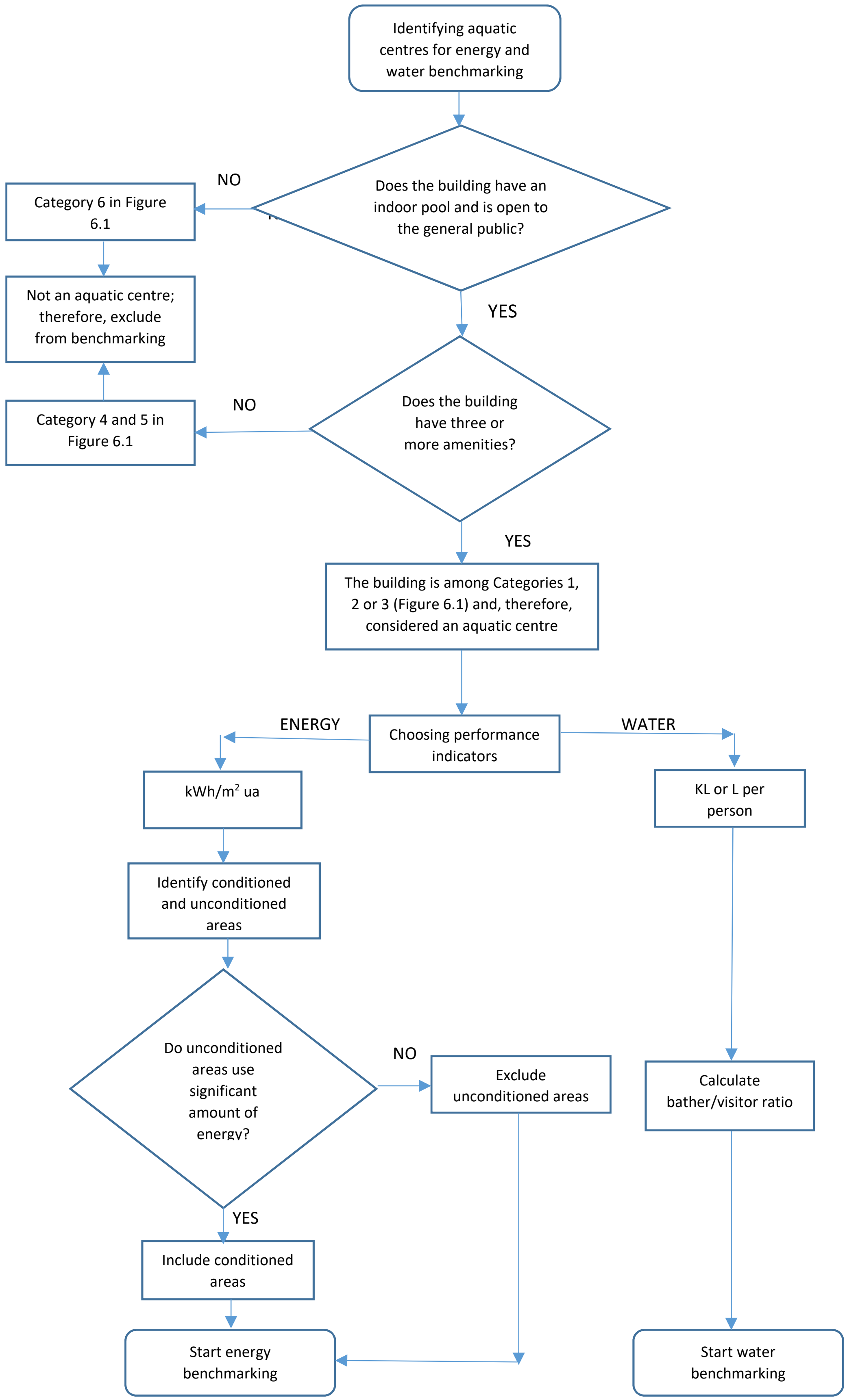


Figure 6.2. Process map for identifying aquatic centres for energy and water benchmarks.

6.4 Energy Benchmarks for Aquatic Centres

Once a definition of an aquatic centre and a guideline for benchmarking were proposed, it was easier to select aquatic centres for energy and water analysis. A total of 50 aquatic centres were contacted and 22 of them sent back the completed questionnaire with sufficient information to be part of the analysis. Table 6.2 displays the types of amenities available within the surveyed aquatic centres, and shows that they fit within the proposed definition as such.

Table 6.2:
List of Surveyed Aquatic Centres and Amenities Available

Aquatic centres	Indoor pools	Outdoor pools	Gym	Sport hall	Cafe	Creche	Spa	Sauna	Program rooms
C1	3	N	Y	Y	Y	Y	N	N	Y
C2	3	1	Y	Y	Y	Y	Y	Y	Y
C3	4	N	Y	N	Y	Y	Y	Y	Y
C4	1	1	Y	N	Y	Y	N	N	Y
C5	2	N	Y	Y	Y	N	N	N	Y
C6	3	N	Y	N	Y	Y	Y	Y	Y
C7	4	2	Y	N	Y	Y	Y	N	N
C8	3	4	Y	N	N	N	Y	Y	Y
C9	4	N	Y	N	Y	N	Y	Y	Y
C10	4	N	Y	N	Y	Y	Y	Y	Y
C11	3	N	Y	Y	N	Y	Y	N	Y
C12	4	1	Y	Y	Y	Y	Y	Y	Y
C13	3	N	Y	N	Y	Y	Y	N	N
C14	3	N	Y	N	Y	Y	Y	Y	Y
C15	4	1	Y	Y	Y	Y	Y	Y	Y
C16	2	1	Y	N	N	Y	Y	Y	Y
C17	4	N	Y	Y	Y	Y	Y	Y	Y
C18	1	2	N	N	Y	N	N	N	Y
C19	5	N	Y	N	Y	Y	Y	Y	Y
C20	3	N	Y	N	Y	Y	N	N	N
C21	2	3	Y	Y	N	Y	Y	Y	Y
C22	2	1	Y	N	Y	Y	Y	N	Y

‘N’ stands for not present within the centre and ‘Y’ stands for present within the centre

Rajagopalan (2014) stated that the average proportion of gas and electricity used in aquatic facilities is around 75% and 25%, respectively. As such, both were collected to determine the total annual energy consumption of each aquatic centre listed in Table 6.3. These figures were obtained from utility bills and not from a building management system

(BMS). Consequently, the average proportion of gas and electricity usage based on the data collected for aquatic centres in Victoria was approximately 78% and 22%, respectively. Table 6.3 provides a summary of the data collected from the 22 aquatic centres.

Table 6.3:
Summary of Data Collected

Aquatic centre	Gross internal area (m^2)	Conditioned usable floor area (m^2)	Indoor water surface area (m^2)	Indoor and outdoor water surface area (m^2)	Non -pool area (m^2)	Stadium area (m^2)	Water (kL per year)	Gas (MWh per year)	Electricity (MWh per year)	Total energy (MWh per year)	Total greenhouse gas emissions (tonnes CO_{2e} per year)
C1	10,589	3,232	713	713	9,232	6,930	10,051	2,637.5	1,408.8	4,046.3	2,188.7
C2	5,776	4,093	780	1,205	4,085	1,295	23,769	5,580.8	1,277.5	6,858.3	2,621.1
C3	5,880	5,195	1,488	1,488	2,593	N/A	48,301	5,060.8	2,132.8	7,193.6	3,526.6
C4	3,843	3,274	240	1,176	3,395	N/A	7,280	4,052.5	1,195.2	5,247.7	2,219
C5	3,150	2,297	768	768	2,123	540	9,783	2,563.6	781.8	3,345.4	1,434.1
C6	3,555	3,338	719	719	2,232	N/A	16,241	3,664.7	1,109.8	4,774.5	2,040.9
C7	5,950	5,421	1,600	2,150	2,500	N/A	33,975	6,161.1	1,378.3	7,539.4	2,855.8
C8	3,468	3,118	260	1,192	2,300	N/A	20,760	1,460.6	658.8	2,119.4	1,068.8
C9	10,565	8,540	2,440	2,440	6,499	N/A	29,214	10,815.8	3,532.7	14,348.5	6,326.9
C10	2,944	2,724	640	640	1,387	N/A	13,500	4,184.4	708.5	4,892.9	1,671
C11	6,100	4,946	1,072	1,072	3,897	950	11,047	2,293.1	912.4	3,205.5	1,534.2
C12	10,401	7,293	1,344	1,902	7,784	2,375	24,330	6,613.6	1,122.3	7,735.9	2,644
C13	3,100	2,995	703	703	2,203	N/A	16,143	2,596.4	854.6	3,451	1,526.5
C14	5,287	4,623	1,438	1,438	2,379	N/A	24,000	4,888.9	1,960	6,848.9	3,288.4
C15	10,607	7,355	1,690	2,760	7,546	2,560	36,545	7,125.6	2,525.7	9,651.3	4,402.2
C16	4,480	3,846	395	1,245	3,725	N/A	28,336	3,333.6	922.9	4,256.5	1,754.2
C17	7,625	6,068	1,494	1,494	3,906	1,268	38,409	8,000.2	1,861.5	9,861.7	3,793
C18	2,215	2,114	227	1,352	1730	N/A	19,459	4,441.1	983.3	5,424.4	2,046.5
C19	9,010	8,490	1,985	1,985	4,730	N/A	21,118	6,759.5	4,374.2	11,133.7	6,510.4
C20	2,799	2,647	580	580	1,795	N/A	20,710	1,586.4	625.7	2,212.1	1,054.9
C21	2,554	2,342	440	1,600	1,665	N/A	13,995	3,135	473	4,046.3	1,183.7
C22	2,715	2,515	700	2,550	1,645	N/A	33,817	8,478.9	433.8	6,858.3	2,203.8

'N/A' signifies no stadium

Table 6.4 lists the annual total number of visitors and bathers. The majority of the aquatic centres only record the total number of visitors, regardless of which amenities (such as swimming pool, gym, spa and cafe) they are using. Only some aquatic centres separately record the number of people utilising only their wet zones (swimming pools), which is noted once attendees scan their purchased tickets or membership card to access swimming pool areas. Additionally, occupancy will be used primarily for water benchmarking, but can also serve energy benchmarking. Careful consideration must be made when choosing a performance indicator or unit for water usage. For water benchmarking, kilolitres or litres by person is an appropriate performance indicator rather than kilolitres by bather, as aquatic centres also have dry amenities such as gyms, sport halls and childcare facilities. As bathers are expected to use more water than the other visitors, the number of visitors listed in Table 6.4 will also be divided based on the estimated amount of water used by each group (bathers and visitors).

Table 6.4:
Occupancy of Aquatic Centres

Aquatic centre	Number of visitors	Number of bathers	Number of persons
C1	875,130	211,010	331,759
C2	820,000	N/A	149,091
C3	963,715	350,171	461,724
C4	113,751	77,490	84,083
C5	332,243	90,456	134,417
C6	472,640	N/A	85,935
C7	565,000	205,000	270,455
C8	232,595	N/A	42,290
C9	795,044	N/A	144,553
C10	275,420	N/A	50,076
C11	314,514	N/A	57,184
C12	1,100,000	N/A	200,000
C13	167,607	N/A	30,474
C14	490,532	N/A	89,188
C15	1,200,000	N/A	218,182
C16	500,000	89,650	164,259
C17	484,222	263,144	303,340
C18	176,380	116,589	127,460
C19	549,959	452,157	469,939
C20	290,441	N/A	52,807
C21	137,039	N/A	24,916
C22	1,136,915	909,532	950,874

As shown, Table 6.4 provides the assumed number of bathers and visitors. The questionnaire lists two options where survey participants can include the total amount of visitors and the number of bathers only. A simple assumption of each group's water use (bathers to use 33 L and visitors to use 6 L) is instead listed in Table 6.2. The efficiency of the fittings was also taken into consideration under the WELS rating.

Based on Table 6.2, a ratio of 5.5:1 is next calculated. That is, every 5.5 persons using the dry zone amenities or visiting the centre will be counted as one bather. Hence, the number of persons is obtained using Equation 15:

$$Number\ of\ persons = \frac{No\ of\ Vistiors - No\ of\ Bathers}{5.5} \qquad (15)$$

Tables 6.3 and 6.4 summarise all the necessary data, which have been examined and sorted to be used in the statistical analysis.

Energy use by unit area or EUI is the most commonly used indicator for benchmarking buildings. While the standard EUI unit used for most building categories is kWh/m^2, this becomes kWh/m^2_{ua} (usable area) and kWh/m^2_{ws} (water surface) for swimming pool facilities. However, using the water surface area as a performance indicator will complicate energy comparisons between aquatic centres and other types of buildings such as residential, retail and office buildings. Thus, CIBSE (2008) stated that a common unit for energy building benchmarking is the kilowatt hours of energy used by unit of floor area (kWh/m^2), which is measured over one year. They also highlighted that developing a benchmark based on energy consumption by a building's unit of floor area will allow for direct comparison with other buildings. Table 6.5 shows the other EUIs and energy benchmarks included for the 22 aquatic centres in this study, as based on nine applicable variables.

Table 6.5:
Energy Usage Intensities Annually for the Investigated Aquatic Centres in Victoria

1	2	3	4	5	6	7	8	9	10
Aquatic centre	Total energy by conditioned usable floor area (kWh/m^2_{ua})	Total energy by gross floor area (kWh/m^2)	Total energy by indoor water surface area only (kWh/m^2_{ws})	Total energy by indoor and outdoor water surface area (kWh/m^2_{ws})	Total energy by visit (kWh/visit)	Total energy or water use (kWh/kL)	Total gas by conditioned usable floor area (kWh/m^2_{ua})	Total electricity by conditioned usable floor area (kWh/m^2_{ua})	Total greenhouse gas emissions by conditioned usable floor area (kg CO_{2e}/m^2_{ua})
C1	1,252	373	5,675	5,675	4.6	402.6	816.1	435.9	677.2
C2	1,676	1,165	8,793	5,692	8.4	288.5	1,363.5	312.1	640.4
C3	1,385	1,196	4,834	4,834	7.5	148.9	974.2	410.6	678.8
C4	1,603	1,329	21,866	4,462	46.1	720.9	1,237.8	365.1	677.8
C5	1,456	1,039	4,356	4,356	10.1	341.9	1,116.1	340.3	624.3
C6	1,430	1,304	6,640	6,640	10.1	294	1,097.9	332.5	611.4
C7	1,391	1,216	4,712	3,507	13.3	221.9	1,136.5	254.3	526.8
C8	680	589	8,152	1,778	9.1	102.1	468.5	211.3	342.8
C9	1,680	1,309	5,881	5,881	18	491.2	1,266.5	413.7	740.8
C10	1,796	1,585	7,645	7,645	17.8	362.4	1,536.2	260.1	613.4
C11	648	507	2,990	2,990	10.2	290.2	463.6	184.5	310.2
C12	1,061	722	5,756	4,067	7	318	906.9	153.9	362.5
C13	1,152	981	4,909	4,909	20.6	213.8	866.9	285.3	509.7
C14	1,481	1,273	4,763	4,763	14	285.4	1,057.5	424	711.3
C15	1,312	895	5,711	3,497	8	264.1	968.8	343.4	598.5
C16	1,106	925	10,773	3,418	8.5	150.2	866.6	239.8	456.1
C17	1,625	1,256	6,601	6,601	20.4	256.8	1,318.4	306.8	625.1
C18	2,566	2,308	23,896	4,012	30.8	278.8	2,100.8	465.2	968.1
C19	1,311	1,167	5,609	5,609	20.2	527.2	796.2	515.2	766.8
C20	836	768	3,814	3,814	7.6	106.8	599.3	236.4	398.5
C21	1,541	1,364	8,200	2,255	26.3	257.8	1,338.6	202	505.4
C22	3,544	3,155	12,732	3,495	7.8	263.6	3,371.4	172.5	876.3

The annual total energy consumption has been divided by several types of floor areas and variables. Multiple EUIs have also been listed to facilitate a comparison with past studies. Notably, the benchmark comparison undertaken in Section 2.5.1 demonstrates that several EUIs have been used to benchmark swimming facilities, but with no explanation for why and how the samples were chosen, notwithstanding Kampel et al. (2016), who otherwise included all swimming pools facilities (from small school pools to leisure pool facilities) within their analysis.

6.4.1 EUIs for Aquatic Centres

Based on Table 6.5, the total EUIs vary from 373 kWh/m^2 to 3,155 kWh/m^2 (gross floor area) and 648 kWh/m^2 to 3,544 kWh/m^2 (conditioned usable floor area). Indeed, total annual energy use divided by conditioned usable floor area is a more reliable measure for benchmarking. For example, the EUI for aquatic centre C1 is 373 kWh/m^2 using gross floor area, but this increases to 1,252 kWh/m^2 when conditioned usable floor area is applied; as such, the guideline proposed in Section 6.3 was followed with respect to stadia and unconditioned areas. Aquatic centre C1 also has a total gross floor area of 10,589 m^2, which includes a stadium with a floor area of 6,930 m^2.

During the site visits, it was noted that the stadium was not artificially conditioned for comfort; however, extraction and ventilation fans were used occasionally, as advised by the centre’s manager. The energy use from these mechanical devices was minimal, so adjustments to remove its energy use were not required. The other energy usage was electricity used for lighting. Naturally, this was much larger than the energy consumed by the extraction fans, as lighting was expended every day in the stadium due to insufficient natural daylight penetration. However, since insufficient information could be obtained about the wattage of each lighting within the stadium, calculations to estimate the amount of energy used as such were consequently performed based on the guidelines proposed.

Including the stadium area outlines that the EUI of C1 was 373 kWh/m^2, which is significantly low for an aquatic centre. Thus, with the guidelines suggesting to exclude all areas without artificial conditioning, the stadium (which uses electricity for lighting) had to be deducted first to remove both its electricity energy use and floor area to facilitate accurate comparisons with aquatic centres without large stadiums. This process changed the EUI of aquatic centre C1 to 1,252 kWh/m^2 (conditioned usable floor area), which was within a more acceptable range of the other aquatic centres. The same procedure was applied to all aquatic centres with stadiums since the majority were neither artificially conditioned for comfort. The differences in some of the EUIs between Columns 4 and 5 are due to the significant discrepancies between indoor water surface area and the total indoor and outdoor water surface areas. For example, aquatic centre C4 has an indoor water surface area of 240 m^2; however, by adding the outdoor water surface areas, its total water surface area becomes 1,176 m^2.

Outdoor pools also have different operating periods and heating requirements than indoor pools. For example, some outdoor pools are only opened during the summer seasons, while others are opened year round; some are heated, while others are not, and some are heated by solar only. However, this analysis offers some misleading results that can occur in the form of major gaps between the lowest and highest figures (total EUI range from 2,990 kWh/m^2_{ws} to 23,866 kWh/m^2_{ws}) when outdoor water surface areas are not included; for example, an EUI of 23,866 kWh/m^2_{ws} for an aquatic centre appears to be unrealistic when compared to past studies. In turn, combining indoor and outdoor water surface areas reduced these ranges between 1,778 kWh/m^2_{ws} and 7,645 kWh/m^2_{ws}.

Another type of EUI listed in Table 6.5 is the total energy use divided by the total number of visits (the occupancy rate of the aquatic centres), as based on the number of visitors (which ranges from 4.6 kWh/visit to 46.1 kWh/visit). The significant difference between the lowest and the highest values raises concern regarding whether this type of EUI is applicable to aquatic centres. Indeed, occupancy rates will fluctuate each year, which can cause uncertainty when using this type of benchmark. Further, the EUI in Column 7 is total energy use divided by the total water use ranging from 102 kWh/kL to 721 kWh/kL. The energy and water nexuses were the factors with which to create this type of EUI, as both elements are (generally) inextricably linked, especially for aquatic centres, which typically consume large amounts of each. However, this link will be tested and investigated in Section 6.4.2 below by identifying any correlations between energy and water use. Additionally, Columns 8 and 9 outline the main two energy sources (electricity and gas) divided by conditioned usable floor area. The EUI for gas use ranges from 468.5 kWh/m^2_{ua} to 3,371 kWh/m^2_{ua} and the EUI for electricity use ranges from 153.9 kWh/m^2_{ua} to 515.2 kWh/m^2_{ua}. The final column (10) is a benchmark based on greenhouse gas emissions ranging from 310.2 kg CO_{2e}/m^2_{ua} to 968.1 kg CO_{2e}/m^2_{ua}. The box and whisker plots in Figure 6.3 were next used to visually assess and compare the distribution of this energy consumption in different benchmark categories from Table 6.5. Accordingly, Table 6.6 displays the information obtained from the plots, such as first and third quartile (Q1 and Q3), median and any outliers that are useful to interpret the selected benchmark variable. The first box and whisker plot in Figure 6.3 is the conditioned usable floor area; this shows that a maximum outlier has been identified, but, when referring to Table 6.6, actually confirmed the existence of two outliers. Excluding these outliers, the range of energy consumption from the variable (conditioned usable floor area) can be reduced to 648 kWh/m^2 and 2,283 kWh/m^2. The same process can be used to examine the other variables and identify an appropriate EUI range for each.

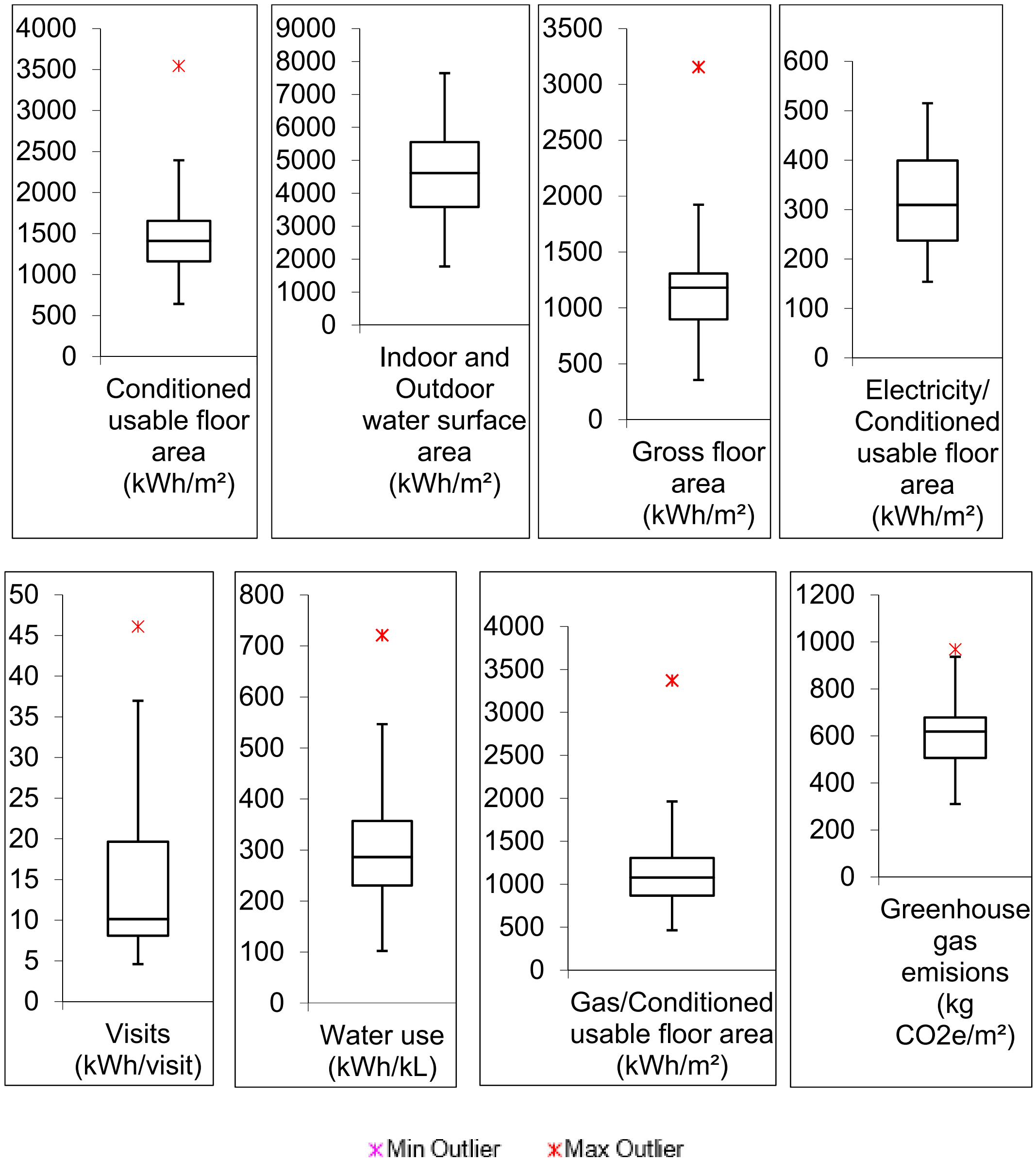


Figure 6.3. Box and whisker plots of energy usage intensities.

Table 6.6 contains more detailed information pertaining the Q1, Q3, the median and the IQR from each plot, which can prove useful to understand the distribution of the selected EUIs. Once further statistical analysis (regression analysis) has been performed to identify the most appropriate EUI applicable to energy use, a corresponding plot will be examined further.

Table 6.6:
Box and Whisker Analysis Results (Energy)

Labels	Conditioned usable floor area (kWh/m^2_{ua})	Gross floor area (kWh/m^2)	Indoor and outdoor surface water area (kWh/m^2_{ws})	Visits (kWh/visit)	Water (kWh/kL)	Gas/conditioned usable floor area (kWh/m^2_{ua})	Electricity/ conditioned usable floor area (kWh/m^2_{ua})	Greenhouse gas emissions (kg CO_{2e}/m^2_{ua})
Min	648	373	1,778	4.6	102	464	154	310.2
Q1	1,177	902.5	3,499.5	8.1	230.6	866.7	237.3	506.5
Median	1,410.5	1,181.5	4,409	10.2	282.1	1,077.7	309. 5	618.9
Q3	1,619.5	1,307.8	5,658.5	19.7	335.9	1,305.4	399.2	678.6
Max	3,544	3,155	7,645	46.1	720.9	3,371.4	515.2	968.1
IQR	442.5	405.3	2,159	11.6	105.3	438.8	161.9	172.1
Upper outliers	2	2	0	1	2	2	0	1
Lower outliers	0	0	0	0	0	0	0	0
Upper whisker	2,283	1,916	7,645	37	494	1,964	515	937
Lower whisker	648	373	1,778	4.6	102	464	154	310

Table 6.7 offers a comparison between the existing EUIs from past studies and the EUIs proposed in this study. According to British Swimming (2008) and Carbon Trust (2005), the energy benchmark for swimming pools facilities generally ranged between 700 kWh/m^2 and 1,600 kWh/m^2 (floor area), and between 2,002 kWh/m^2 and 4,419 kWh/m^2 (water surface area) (Kampel, Aas & Bruland 2013). The proposed EUI based on the adjusted scale from the plot analysis for Victoria's aquatic centres instead ranges between 648 kWh/m^2_{ua} and 2,283 kWh/m^2_{ua} using the conditioned floor area, and between 1,778 kWh/m^2_{ws} and 7,645 kWh/m^2_{ws} using the water surface area (indoor and outdoor pools combined). Indeed, several EUIs have been included to allow for comparison between existing and future aquatic centre studies.

Table 6.7:
Comparison Between Proposed and Existing EUIs

EUI (kWh/m²)			Unit	Source	Comments
Low	Typical/average	High	ua or ws		
< 510	510–745	> 745	ua	CIBSE (1997)	Sport centre with pool
725	1,573		ua	British Swimming (2008)	Swimming pool building only
	1,375		ua	CIBSE (2008)	Swimming pool hall, changing and ancillaries
737	1,579		ua	Carbon Trust (2005)	Centre with leisure pool
437		544	ua	Step2Sport (2015)	Sports complexes with indoor pools and gymnasium and/or sports halls (by conditioned floor area)
632		2,247	ua	Rajagopalan (2014)	Swimming pools with other facilities
	4,300–5,200		ws	Trianti-Stourna et al. (1998)	Swimming pools only
2,002		4,419	ws	Kampel, Aas and Bruland (2013)	Swimming facilities only
648		2,283	ua	Proposed energy benchmark	Aquatic centre (conditioned usable floor area); total energy use
1,778		7,645	ua	Proposed energy benchmark	Aquatic centre (water surface area) Total energy use
141		318	ua	CERM PI (2014)	Aquatic centre; electricity usage only
154		515	ua	Proposed energy benchmark	Aquatic centre (conditioned usable floor area); total electricity use

However, as the aim of this study is to identify the most appropriate EUI applicable to aquatic centres, this was subsequently achieved by using linear and multiple regression techniques. As such, Section 6.4.2 will statistically analyse the results to determine the most appropriate indicator for aquatic centre energy benchmarks.

6.4.2 Energy Statistical Analysis

The simplest statistical approach is the OLS method, or a linear regression-based statistical technique. OLS is an effective manner in which to estimate EUIs. As the factors contributing to these variables are assumed to be linearly related, the OLS determines its best fit over multiple measures. Both linear regression and multiple regression techniques have been used to determine the correlation and significance between all the variables used for the energy and water benchmarks pertaining to each's usage within aquatic centres. As shown, Table 6.8 provides the correlation coefficients (R^2) between energy consumption and variables such as total energy, gross floor area and water surface area.

The second column (total energy) displays the correlation coefficient (R^2) between that and other variables such as gross floor area, conditioned usable floor area and water surface area; these are the most important figures in this study. For example, the R^2 between the total energy and gross floor area is 0.64 ($R^2 = 0.64$), and the R^2 between total energy and conditioned usable floor area is 0.8. The third column next shows the correlation coefficient between total gas use and several variables; for example, the correlation coefficient between total gas use and conditioned usable floor area is 0.69 ($R^2 = 0.69$). Thus, the correlation coefficients between total energy, total gas and electricity displayed in the second column are ignored, as the two energy sources (gas and electricity) are directly linked to total energy—this was obtained by adding total gas and total electricity. Indeed, any changes in gas or electricity use will directly affect total energy use.

The purpose of this section is to identify variables other than energy sources. Therefore, the second column indicates that total energy has strong correlations to conditioned usable floor area, gross floor area and water surface area. However, the strongest correlation (with an R^2 of 0.80) is for conditioned usable floor area, which, as explained in Section 6.3.1, is the preferred variable for energy benchmarking because aquatic centres consist of both dry and wet areas.

Additionally, with gas being the primary source of fuel to heat pool water in Australia, this is outlined in Table 6.8 in which total gas use has a high correlation coefficient (R^2 = 0.81) to water surface area. Moreover, with electricity being the primary source of fuel for air conditioning in aquatic centres, the total electricity has a high correlation coefficient (R^2 = 0.84) to conditioned usable floor area. As such, additional analyses were performed using the multiple regression technique to verify the significance of the variables used in Table 6.8.

Table 6.8:
Energy Correlation Analysis for Six Variables

R^2	Total energy	Total gas	Total electricity	Gross floor area	Conditioned usable floor area	Water surface area	Number of persons	Water	Number of visitors
Total energy	1								
Total gas	0.97	1							
Total electricity	0.79	0.61	1						
Gross floor area	0.64	0.54	0.70	1					
Conditioned usable floor area	0.80	0.69	0.84	0.85	1				
Water surface area	0.79	0.81	0.50	0.49	0.64	1			
Number of persons	0.48	0.53	0.22	0.19	0.18	0.54	1		
Water (kL)	0.58	0.61	0.35	0.29	0.47	0.62	0.52	1	
Number of visitors	0.58	0.62	0.35	0.65	0.52	0.62	0.64	0.61	1

Evidently, Table 6.8 contains a summary of the several correlation analyses relevant to aquatic centres. This is the first step in determining relevant variables to be used for benchmarking the energy use of aquatic centres in Victoria. Although this technique has provided valuable information, further analysis was still required to determine the most appropriate energy performance indicator for such benchmarking. As such, a multiple regression analysis was performed to verify the significance of the relevant variables, hence, providing enough information to enable a selection of the most appropriate variables for benchmarking such energy use. Table 6.9 provides these results as obtained by ANOVA. The regression model was significant at the 0.0001 level ($F(6, 15) = 10.13451$, $p = 0.000$), and the squared multiple correlation (R^2) was 0.802 with adjusted R^2 = 0.722. The linear combination of six variables accounted for

80.2% of the variance in the total energy use, with the coefficients, standard errors and t-stat provided in Table 6.9.

Evidently, conditioned usable floor area and water surface area have the highest coefficients of 996.745 and 1,482.549, respectively, thus, highlighting their significance in relation to energy use. However, the conditioned usable floor area has the lowest p-value, which, for each variable, tests the null hypothesis that the coefficient is equal to zero (no effect). Essentially, a low p-value (< 0.05) indicates that the null hypothesis can be rejected or is likely to be a meaningful addition to the model, as changes in the variable's value are related to changes in the response variable (total energy use).

Table 6.9:
Total Energy Use Multiple Regression Analysis for Six Variables

	Coefficients	Standard Error (SE)	t	p	Overall R^2
Intercept	–404,085.506	1,043,553.738	–0.387	0.704	0.802 0.722^a
Gross floor area	–70.772	336.521	–0.210	0.836	
Conditioned usable floor area	996.745	487.415	2.044	**0.005**	
Water surface area	1,482.549	946.512	1.566	**0.013**	
Number of persons	3.639	2.544	1.430	**0.017**	
Water (kL)	7.040	54.711	0.129	0.089	
Number of visitors	–0.666	2.325	–0.287	0.077	

'a' stands for adjusted R^2

Other variables were next eliminated from the analysis to help verify the three most significant in Table 6.9 with the lowest p-value (conditioned usable floor area, water surface area and number of persons). In doing so, significance F should decrease, thus, indicating that the selected variables are, in fact, the strongest variables related to total energy use. This is shown in Table 6.10, which demonstrates that the regression model was significant at the 1.90588E-06 level ($F(3, 18) = 23.484$, $p = 0.000$). The p-value of conditioned usable floor area is also well under 0.05 ($p < 0.001$), thus, suggesting that this variable is the most important predictor of an aquatic centre's total energy usage. Based on this analysis and for benchmarking purposes, it, therefore, seems most appropriate to divide the energy use of such buildings by conditioned usable floor area.

Table 6.10:
Total Energy Use Multiple Regression Analysis for Three Variables

	Coefficients	SE	t	p	Overall R^2
Intercept	–401,218.452	864,836.581	–0.463	0.648	0.796 0.762[a]
Conditioned usable floor area	865.053	221.378	3.907	**0.001**	
Water surface area	1,537.201	810.084	1.897	0.073	
Number of persons	3.075	1.929	1.594	0.128	

Other multiple regression analyses were performed to understand which variables would be relevant should energy use be spilt between gas and electricity. Tables 6.11 and 6.12 provide these figures for gas and electricity, with the exclusion of less relevant variables. Particularly, Table 6.11 indicates that the regression model was significant at the 9.11041E-06 level ($F (2, 19) = 22.73$, $p = 0.000$), with its p-value for water surface area being well under 0.05 ($p < 0.001$), thus, suggesting its utmost importance when predicting gas usage. Conversely, Table 6.12 indicates that the regression model was significant at the 8.06667E-07 level ($F (1, 20) = 49.43$, $p = 0.000$), with its p-value for conditioned floor usable area being well under 0.05 ($p < 0.0000008$), thus, likewise suggesting its importance to predict electricity usage.

Table 6.11:
Multiple Regression Analysis for Gas

	Coefficients	SE	t	p	Overall R^2
Intercept	56,947.543	785,692.26	–0.07	0.943	0.801 0.754[a]
Conditioned usable floor area	347.767	194.48	1.79	0.090	
Water surface area	2,346.309	611.08	3.84	**0.001**	

Table 6.12:
Multiple Regression Analysis for Electricity

	Coefficients	SE	t	p	Overall R^2
Intercept	–385,278.678	281,848.672	–1.367	0.186	0.712 0.704[a]
Conditioned usable floor area	411.643	58.553	7.031	**0.000**	

Evidently, it appears statistical regression analysis for energy use has provided some valuable information relevant to this study. Section 6.5 will next focus on the water use of aquatic centres using similar techniques and processes pertaining to energy to identify the most relevant variables for creating a water benchmark of aquatic centres.

6.5 Water Benchmarks for Aquatic Centres

The previous section provides detailed statistical analysis in order to propose a set of energy benchmark for aquatic centres. This section will perform similar analyses to identify a set of water benchmark. Information such as areas, water consumption and occupancy listed in Table 6.3 and Table 6.4 is also used for water analysis.

6.5.1 WUIs for Aquatic Centres

Compared to energy benchmark studies in which common performance indicators are used (kWh/m^2_{ua} and kWh/m^2_{ws}), water benchmark studies have indicated a wider range of performance indicators (kL by centre, kL by bather, kL by person, kL by m^2 and kL by visit), which have, thus, complicated the comparative process. Further, exists no clear explanation as to how those results were actually obtained. As such, this thesis will propose a water benchmark for aquatic centres by providing a clear indication of the data used and how they are calculated. Table 6.13 shows the total annual water use divided by several variables.

Table 6.13:
Water Usage Intensities for Aquatic Centres

1	2	3	4	5	6	7	8	9
Aquatic centre	L/visitor	L/person (L)	kL/Indoor water surface area (kL/m^2)	kL/Indoor and outdoor water surface area (kL/m^2)	kL/Gross floor area (kL/m^2)	kL/Conditioned usable floor area (kL/m^2)	Water use/total energy use (L/kWh)	Water use/gas use (L/kWh)
C1	11	30	14.1	14.1	0.9	3.1	2.5	3.8
C2	29	159	30.5	19.7	4	5.8	3.5	4.3
C3	50	105	32.5	32.3	8	9.3	6.7	9.5
C4	64	87	30.3	6.2	1.8	2.2	1.4	1.8
C5	29	73	12.7	12.7	3	4.3	2.9	3.8
C6	34	189	22.6	22.6	4.4	4.9	3.4	4.4
C7	60	126	21.2	15.8	5.5	6.3	4.5	5.5
C8	89	491	79.8	17.4	5.8	6.7	9.8	14.2
C9	37	202	12	12	2.7	3.4	2	2.7
C10	49	270	21.1	21.1	4.4	5	2.8	3.2
C11	35	193	10.3	10.3	1.7	2.2	3.4	4.8
C12	22	122	18.1	12.8	2.3	3.3	3.1	3.7
C13	96	530	23	23	4.6	5.4	4.7	6.2
C14	49	269	16.7	16.7	4.5	5.2	3.5	4.9
C15	30	167	21.6	13.2	3.4	5	3.8	5.1
C16	57	173	71.7	22.8	6.2	7.4	6.7	8.5
C17	79	127	25.7	25.7	4.9	6.3	3.9	4.8
C18	110	153	85.7	14.4	8.3	9.2	3.6	4.4
C19	38	45	10.6	10.6	2.2	2.5	1.9	3.1
C20	71	392	35.7	35.7	7.2	7.8	9.4	13.1
C21	102	562	31.8	8.7	5.3	6	3.9	4.5
C22	30	36	48.3	13.3	12	13.4	3.8	4

Column 2 indicates the WUI using the number of visitors as a variable ranges from 11 L/visitor to 110 L/visitor, while Column 3 indicates water use divided to the number of persons. The difference between those calculated by visitor and by person is based on the suggested calculation published by Duverge, Rajagopalan and Fuller (2017), which acknowledges the difference in water use between bathers and visitors using a suggested ratio of 1:5.5 to calculate individual water consumption. This is based on the fact that bathers are expected to use more water (e.g., for showers) than visitors utilising only stadium or gym facilities. However, a statistical analysis will still be performed to verify the relevance and significance of this variable in relation to the water use of aquatic centres.

The wide gap between the lowest and the highest figures (30 kL/person to 530 kL/person) causes uncertainties for this type of WUI (Columns 4 and 5 show water use divided to water surface area). A similar approach to the energy analysis in relation to indoor water surface areas and outdoor water surface areas was subsequently undertaken; this involved a process of combining both indoor and outdoor water surface area. The WUI using this fusion then ranged from 6.2 kL/m^2_{ws} to 35.7 kL/m^2_{ws}.

Columns 6 and 7 are WUIs indicating water use divided to gross floor area and conditioned usable floor area, respectively. The WUI for gross floor area ranges from 0.9 kL/m^2 to 12 kL/m^2, and from 2.2 kL/m^2_{ua} to 13.4 kL/m^2_{ua} for conditioned usable floor area. Column 8 is based on the water and energy nexus (as outlined in the energy analysis), and displays a range between 1.4 L/kWh to 9.8 L/kWh. Meanwhile, Column 9 provides the WUI using total gas consumption as a variable ranging from 1.8 kL/kWh to 14.2 kL/kWh. This figure was included because the majority of the aquatic centres used gas as their primary fuel source to heat swimming pool water. As such, a strong correlation was identified between gas and water surface area during the energy analysis.

Similar to energy, box and whisker diagrams (as shown in Figure 6.4) have been used to present the distribution of the water usage in aquatic centres for several benchmark categories from Table 6.13. Several outliers can be identified for multiple variables, including the ranges, quartiles and medians for each (see Figure 6.4).

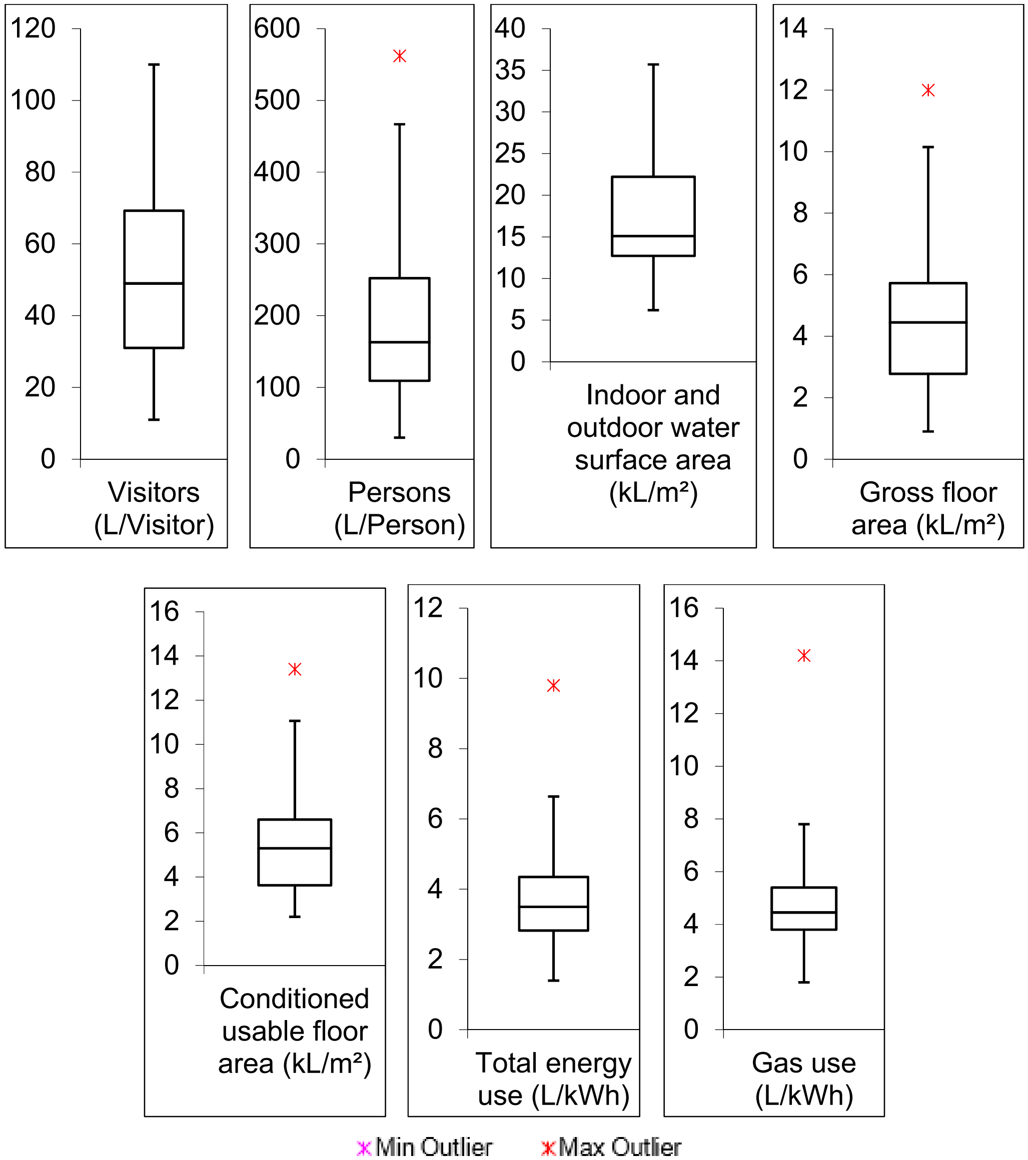


Figure 6.4. Boxplots of water-usage intensities.

Table 6.14 displays the values for data such as Q1, Q3, median and IQR variables from the box and whisker plots. The ranges of each can be adjusted based on the data provided in Table 6.14 and by examining the outliers. Similar to energy, these plots for a selected WUI will be used and considered when identifying an appropriate range for the water benchmark.

Table 6.14:
Box and Whisker Analysis Results (Water)

Labels	Visitors	Persons	Indoor and outdoor water surface area	Gross floor area	Conditioned usable floor area	Total energy use	Gas use
Min	11	30	6.2	0.9	2.2	1.4	1.8
Q1	31	109	12.8	2.8	3.7	3	3.8
Median	49	163	15.1	4.5	5.3	3.6	4.5
Q3	69	252	22.3	5.9	6.6	4.4	5.4
Max	110	562	35.7	12	13.4	9.8	14.2
IQR	38	143	9.5	3	3	1.4	1.6
Upper outliers	0	3	0	1	1	4	4
Lower outliers	0	0	0	0	0	0	0
Upper whisker	110	467	35.7	10.2	11.1	6.5	7.8
Lower whisker	11	30	6.2	0.9	2.2	1.4	1.8

Table 6.15 provides the comparison between the proposed WUIs and existing WUIs, with the range of the former being based on the data obtained from the box and whisker analysis. According to Kampel, Aas and Bruland (2014), a WUI of around 65 L to 154 L for each person was noted; however, no explanation regarding whether this calculation was based on the number of bathers or visitors (or both) was provided. Likewise, CERM PI (2014) reported water-use intensities between 26 L and 117 L for each centre visit, and between 2.2 kL and 7.4 kL by square metre. However, it is unclear if the authors actually divided the water use to conditioned floor area, water surface area or performed a combination of both. Additionally, the case study in Maglionico and Stojkov (2015) of a public swimming pool offered an overall water consumption of around 96 L for each person.

The benchmarks figures listed in Table 6.15 are comparable to several of these efforts regarding WUIs. For example, the WUI for visitors have values between 11 L/visitor and 110 L/visitor, which are similar to both CERM PI's (2014) and Kampel, Aas and Bruland's (2014) figures. However, for the purpose of this study, the most reliable water performance indicator for benchmarking the water use of Victorian aquatic centres will instead be determined using similar statistical approaches used to obtain energy data.

Table 6.15:
Comparison Between Existing and Proposed WUIs

Water use intensity (kL)			Unit	Source	Comments
Low	Typical/average	High			
< 0.02	0.02–0.04	> 0.06	Per bather	Sydney Water (2011)	Aquatic centres including facilities
0.065		0.154	Per person	Kampel, Aas and Bruland (2014)	Swimming facilities only
2.2		7.4	Per m^2	CERM PI (2014)	Aquatic centre
0.026		0.117	Per visit	CERM PI (2014)	Aquatic centre
0.025		0.144	Per visit	CERM PI (2013)	Aquatic centre
0.03		0.47	Per person	Proposed water benchmark	Aquatic centre
0.011		0.11	Per visitor	Proposed water benchmark	Aquatic centre
0.9		10.2	Per m^2	Proposed water benchmark	Aquatic centre (gross floor area)
2.2		11.1	Per m^2	Proposed water benchmark	Aquatic centre (conditioned usable floor area)

6.5.2 Water Statistical Analysis

Table 6.16 provides the correlations (R^2) between water use and seven variables, including the number of visitors and persons, the gross floor area, conditioned usable floor area, water surface area, total energy and gas use. It should be noted that the water surface area, number of visitors and total gas have the strongest correlation in relation to water use. However, when compared to the correlation analysis undertaken for energy use (in which some strong correlations between energy use and a couple of variables were identified), the correlation analysis for water use is not as strong. Instead, the highest correlation coefficients are water surface area (R^2 = 0.62), number of visitors (R^2 = 0.614) and gas (R^2 = 0.605), which each bear similar R^2 values. Nonetheless, further analysis is required to determine the most relevant variable for benchmarking these water consumption data. As such, multiple regression analyses were undertaken in several steps.

Table 6.16:
Water Correlation for Seven Variables

R^2	Water	Number of visitors	Number of persons	Gross floor area	Conditioned usable floor area	Water surface area	Total energy	Total gas
Water	1							
Number of visitors	0.614	1						
Number of persons	0.521	0.640	1					
Gross floor area	0.296	0.650	0.189	1				
Conditioned usable floor area	0.474	0.522	0.178	0.851	1			
Water surface area	0.620	0.623	0.535	0.485	0.642	1		
Total energy	0.582	0.582	0.477	0.635	0.800	0.787	1	
Total gas	0.605	0.616	0.528	0.543	0.690	0.810	0.968	1

Table 6.17 lists the multiple regression analysis for water use based on all seven variables; the model of which is significant at the 0.028 level ($F (7, 14) = 3.246$, $p = 0.000$). The three key variables with the lowest p-value based on this analysis are the conditioned usable floor area, the gross floor area and the number of visitors. As such, several different variables that were not evident in the correlation analysis have since been identified. However, one of the variables—the number of visitors—still remains with a p-value of 0.079, while gross floor area pales with the lowest p-value at 0.049. All three variables have been further analysed, with the results shown in Table 6.18.

Table 6.17:
Water Use Multiple Regression Analysis for Seven Variables

	Coefficients	SE	t	p	Overall R^2
Intercept	8,178.958	4,758.408	1.718	0.107	
Number of visitors	0.020	0.011	1.894	**0.078**	
Number of persons	0.004	0.014	0.287	0.778	
Gross floor area	–3.076	1.432	–2.147	**0.049**	0.618
Conditioned usable floor area	4.279	2.760	1.550	**0.143**	0.428[a]
Water surface area	0.591	5.228	0.113	0.911	
Total energy	–0.0001	0.003	–0.052	0.959	
Total gas	0.0004	0.004	0.099	0.921	

Table 6.18 indicates that the regression model was significant at the 0.00056 level ($F (3, 18) = 9.468$, $p = 0.000$). There is also a noticeable improvement in the adjusted R^2 from 0.428 to 0.547 shown in Tables 6.17 and 6.18, respectively. The main difference between R^2 and the adjusted R^2 is the former assumes that every variable explains the variation in the dependent variable (water use). Meanwhile, the adjusted R^2 shows the percentage of variation explained by only the independent variables that actually affect the dependent variable. For example, if more unrelated variables are added to the model, the adjusted R^2 will decrease, but if more related variables are added, it will increase. The p-values of all three variables are now well under 0.05, thus, suggesting they are important predictors of total water use in an aquatic centre. However, the number of visitors with a p-value of 0.0008 is the most significant and likewise possesses one of the highest correlation coefficients ($R^2 = 0.61$). Those two facts justify the number of visitors as the most appropriate variable to be used when water benchmarking aquatic centres. If this is not available, the next best variable is conditioned usable floor area with a p-value of 0.0052.

Table 6.18:
Water Use Multiple Regression Analysis for Three Variables

	Coefficients	SE	t	p	Overall R^2
Intercept	8,782.099	3,806.977	2.306	0.0331	
Number of visitors	0.024	0.006	4.012	**0.0008**	0.612
Gross floor area	–3.402	1.107	–3.071	0.0065	0.547[a]
Conditioned usable floor area	4.664	1.468	3.176	0.0052	

6.6 Comparative Evaluation of the Proposed Energy and Water Benchmarks

The analysis performed indicates the variables conditioned usable floor area and number of visitors have the strongest correlation and significance in relation to the energy and water used in aquatic centres. Therefore, the proposed energy benchmark for aquatic centres ranges between 648 kWh/m^2 and 3,544 kWh/m^2 (conditioned usable floor area), while the proposed water benchmark for aquatic centres ranges between 11 L/visitor and 110 L/visitor. Additionally, aquatic centres have both large dry and wet areas when compared to other swimming pool facilities such as school pools, private clubs' indoor swimming pools and natatoriums; therefore, using water surface area as a variable is not appropriate when dealing with aquatic centres. It is also understood that this variable has been used in past studies to benchmark swimming pool facilities, but the majority of which neither clearly defined what is covered in swimming pool facilities, nor included all swimming pool facilities (from small school pools to aquatic centres) within the same category.

The variables selected for benchmarking the energy performance of aquatic centres can also allow for direct comparison with other building types such as supermarkets, hotels and shopping centres. For example, a DCCEE (2012) study listed the Australian average energy intensity for a range of commercial buildings including shopping centres (445 kWh/m^2), hotels (460 kWh/m^2), hospitals (465 kWh/m^2), universities (268 kWh/m^2) and supermarkets with an overall average energy intensity of

937 kWh/m^2. However, according to this study, aquatic centres generally range between 648 kWh/m^2 and 3,544 kWh/m^2, which is, evidently, well above any other commercial buildings' energy intensities. Based on the statistical analysis performed, there is also a stronger correlation and significance between water use and the number of visitors compared to the number of persons, as proposed in Section 6.3.2. The data collection as well as the site visits also indicated that many aquatic centres do not separately record the number of people using wet and dry areas.

When forming water-usage comparisons with other commercial buildings, commercial offices have an average water intensity of 1.8 kL/m^2, while shopping centres have a 1.7 kL/m^2 (Sydney Water 2011). However, this study instead found that over 70% of the aquatic centres within the sample have water intensities above 4 kL/m^2 when using conditioned usable floor area as a variable, which is twice the water intensities of these other commercial counterparts.

The proposed benchmark for the energy use of aquatic centres has been further examined by using the results from box and whisker analyses. As provided in Figure 6.5, the plot results for conditioned usable floor area identify two EUI outliers, which are positioned significantly further from the others, and that can certainly affect the energy benchmark range. Additionally, the IQR represents the middle 50% of the EUIs and the whiskers represent the ranges for the bottom 25% and the top 25% EUIs, excluding outliers. Therefore, the whiskers were used to adjust the proposed energy benchmark range to 648 kWh/m^2 and 2,283 kWh/m^2.

The energy benchmark can be categorised into three groups: aquatic centres between 1,177 kWh/m^2 (Q1) and 1,619 kWh/m^2 (Q3) can be classified as medium energy users, centres below 1,177 kWh/m^2 (Q1) can be low energy users and centres above 1,619 kWh/m^2 (Q3) can be high energy users. Therefore, the median EUI for aquatic centres is 1,410 kWh/m^2.

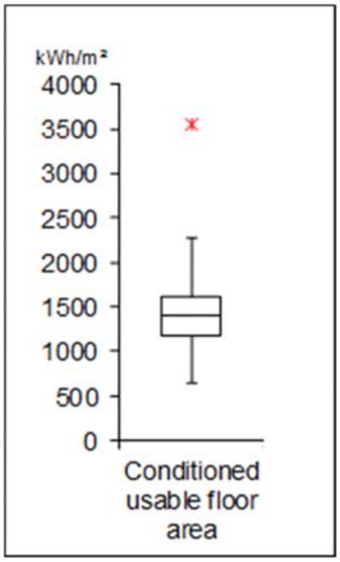


Figure 6.5. Box and whisker analysis results for conditioned usable floor area.

Labels	Conditioned usable floor area
Min	648
Q1	1,177
Median	1,410.5
Q3	1,619.5
Max	3,544
IQR	442.5
Upper outliers	2
Lower outliers	0
Upper whisker	2,283
Lower whisker	648

Figure 6.6 provides the box and whisker plot results for the number of visitors used to examine the water benchmark. No outlier has been identified for this variable, which defines the corresponding benchmark between 11 L/visitor and 110 L/visitor. However, this can also be categorised into low, medium and high water users, as shown in Figure 6.6, with low consumers dipping below 31 L/visitor (Q1), medium being between 31 L/visitor (Q1) and 69 L/visitor (Q2), and high water users topping above 69 L/visitor (Q3). Therefore, the median WUI for aquatic centres is 49 L/visitor.

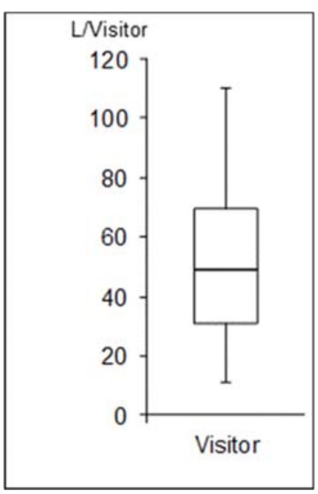


Figure 6.6. Box and whisker analysis results for the number of visitors.

Labels	Visitor
Min	11
Q1	31
Median	49
Q3	69
Max	110
IQR	38
Upper outliers	0
Lower outliers	0
Upper whisker	110
Lower whisker	11

6.7 Features Influencing Energy and Water Use of Surveyed Aquatic Centres

The aim of this section is to identify any noticeable features that define some aquatic centres as more energy and water efficient than others within the sample. All the necessary data collected through the questionnaire, site visits and onsite measurements are summarised in Tables 6.19 and 6.20, and are rearranged in the order of lowest EUI and WUI to highest.

6.7.1 Features Influencing Energy Use

The aquatic centres with the highest EUI ranges (aquatic centres C18 and C22) have heated outdoor pools. With an outdoor pool that comprises 75% of its total water surface area heated year round, aquatic centre C22 (whose EUI is 3,544 kWh/m^2) has a significant temperature difference between its average indoor pool temperature and average pool hall air temperature (7.8 ^{o}C), and an average relative humidity recorded at 42%, which is comparatively low for such a space. Maintaining the relative humidity at 42% will require more demand from the HVAC system. This major difference in both water and air temperature as well as low relative humidity is likely to also increase pool-water evaporation and, hence, increase heat loss through evaporation, thus, resulting in more energy to heat the pool water as required. When investigating the electricity and gas use of this facility, it should be noted that its gas usage by usable floor area (3,371.3 kWh/m$^2{}_{ua}$) is significantly greater than all the other aquatic centres, therefore, suggesting that a large amount of gas was likely used for pool-water heating. Additionally, the aquatic centres within the middle range (1,177 kWh/m^2 and 1,619 kWh/m^2) have similar energy-efficiency features, including solar instantaneous gas-boosted hot-water systems for domestic use, internal LED lighting with sensors, solar PV systems, double glazing and a low air or water temperature difference (Table 6.19). Note that there is not a noticeable energy difference between aquatic centres that do and do not use cogeneration systems, the most plain of which may be centre C8's use of a solar pool-water heating system for its outdoor pools, which resulted in a low EUI (680 kWh/m^2) when compared to those without such facilities. Of brief mention here is also a study performed by Fuller, Rajagopalan and Duverge (2016), which investigated the benefits and advantages of utilising solar thermal energy to heat aquatic centres in Victoria.

6.7.1.1 Cogeneration Systems

Several aquatic centres have installed or plan to install a cogeneration system to reduce their energy consumption. The most common type of which is the CHP system, which generates power and makes use of the heat that is produced during the process to heat up pool water. Around 40% of the aquatic centres within the sample have already installed this system; however, there is no noticeable difference in ranking between aquatic centres with and without such facilities. As site energy is used for this analysis, the advantage of using CHP—that is, the reduced loss in production storage, transport and delivery of fuel to the sample building—is not obvious.

6.7.1.2 Solar Photovoltaic Systems

Solar PV systems were installed in four aquatic centres within the sample. The majority of the systems are connected to the grid, and any electricity produced is used onsite with the excess then exported back to the grid. As the systems ranged from 40 kW to 100 kW, the aquatic centres with solar PV systems came within the low–medium range on the proposed energy benchmark ranking. However, more samples are required to properly verify the effectiveness of these facilities on the total energy use of an aquatic centre, as the majority of this total is instead derived from gas usage.

6.7.1.3 Domestic Hot Water

Domestic hot water used in aquatic centres can account around 4–10% of an aquatic centre's total energy. Therefore, any improvement in these systems will only provide small reductions in the total energy consumed. Based on the data collected, gas storage and instantaneous hot-water systems are the main types of systems used, while no apparent differences exist in terms of energy efficiency between aquatic centres that used either method. Conversely, solar domestic hot-water systems are instead used by nearly 50% of the aquatic centres within the sample but, again, with no apparent differences in energy usage.

6.7.1.4 Solar Pool-heating Systems

Pool heating consumes a major portion of energy in aquatic centres. Several studies have investigated the potential to reduce energy consumption, but Fuller, Rajagopalan and Duverge (2016) necessitate certain mention here. Among the sample in this study, there was only one aquatic centre that used solar thermal energy for heating pool water likewise with aquatic centre C8 (albeit, for heating outdoor pools) in this study, which, too, presented one of the lowest recorded EUIs. Indeed, solar pool heating might be an effective system in heightening an aquatic centre’s energy efficiency, but this must be verified by collecting more samples of centres using this technique, or through thermal simulation.

6.7.1.5 Pool-heating Systems

The majority of the aquatic centres in the sample use gas boilers, with the exception of one, which combined them with heat pumps. All the aquatic centres with CHP also combined both the boilers and the CHP systems, but, unfortunately, details on the efficiency of these boilers could not be obtained, thus, making the comparison with respect to boiler efficiency impossible.

6.7.1.6 Building Management System

The majority of the aquatic centres within the sample have a BMS. Unfortunately, the site visits proved such systems were not used to their full capacity. That is, staff only had limited knowledge of how to run basic commands and monitor data, such as temperature settings. Nonetheless, no apparent difference was noticed between aquatic centres with and without a BMS.

6.7.1.7 Types of Glazing

Glazing characteristics were recorded to determine whether specific types of glazing systems made a significant difference in energy use within the sample collected. As such, around 50% of the aquatic centres had double glazing; however, no difference in energy use between aquatic centres with single and double glazing could be detected. During site visits, it was observed that a significant difference between glazing and pool hall floor area between aquatic centres was present.

6.7.1.8 Types of Lighting System and Sensors

More than 50% of the aquatic centres use LED lighting, while the remainder use halogen and compact fluorescent lighting. However, most centres use a combination of all three types of lighting, which, thus, made comparison difficult. There are several centres that also use daylight and motion sensors, and it is observed that those fell within in the low–medium range in the proposed benchmark ranking. Evidently, it appears each can help contribute towards energy reduction.

6.7.1.9 Pool Circulating Pumps

Circulating pumps are important devices used to circulate pool water. Fixed speed and variable speed pumps are both used in the sample aquatic centres; however, based on the literature, the latter are said to be more energy efficient. Although approximately 35% of the aquatic centres use this method, no trend was discovered in relation to energy use between either type.

6.7.1.10 Pool Covers

The aim of pool covers is to reduce evaporation. Based on the data collected, over 35% of the aquatic centres have pool covers for indoor pools and 80% for outdoor pools. However, during discussions with staff, it was understood that several aquatic centres do not utilise the available pool covers due to health and safety reasons. Covering and uncovering pools certainly requires effort; as they are bulky and heavy, and mostly manually operated, this often discourages centres from utilising such facilities. No trend in terms of energy efficiency between aquatic centres with and without pool covers was recorded.

6.7.1.11 Temperature and Humidity

Onsite measurements of pool halls' air temperature, relative humidity levels and pool-water temperature were recorded to identify relevant trends, as those characteristics particularly affect the energy used in aquatic centres. While no trends were discovered as such, a significant difference between air and water temperature and relative humidity was observed, despite there existing specific recommended guidelines on temperature and humidity settings for aquatic centres. Failure to follow these can consequently result in manipulated evaporation rates, which, thus, affects both energy and water consumption. Alas, it was observed that some staff did not have the necessary knowledge regarding the importance of temperature settings.

While few distinct energy-efficient features were discovered, the following might have contributed towards classifying aquatic centres on the low–medium rather than high range on the proposed energy benchmark ranking: solar PV systems, solar-heating systems for pool water and daylight or motion sensors for lighting. Based on this assessment, it is suggested that more samples are required and that building simulations can help identify distinct energy-efficiency features in aquatic centres.

Table 6.19:
Energy Features of Surveyed Aquatic Centres

ID	kWh/m^2	Cogeneration	Solar PV	Solar domestic hot water	Domestic hot water	Solar pool heating; indoor pool	Solar pool heating; outdoor pool	Pool heating	Building management system	Glazing	Lighting	Light sensor	Circulating pump	Indoor pool covers	Average pool-water temperature	Average pool air temperature	Pool and water temperature difference	Average relative humidity	Outdoor pool opening	Heated outdoor pool	Average outdoor pool temperature	Outdoor pool covers
C11	648			✓																		
C8	680	×	×	✓		×	✓	Gas boilers	×	S	Hal & CFL	×	F	×	32	24	8	74	S	✓	28	×
C20	836	×	✓	×	Gas storage	×	×	Gas boilers	✓	S & D	LED &CFL	×	F	✓	30.5	26.4	4.1	67				
C12	1,061			✓																		
C16	1,106	✓	×	×	Gas storage	×	×	Gas boilers	✓	D	LED, Hal & CFL	✓	V	✓	31.5	25.6	5.9	50	A	✓	27.5	✓
C13	1,152																					
C1	1,252	✓	×	×	Ins. gas	×	×	Gas boilers	✓	S	LED & Hal	✓	V	×	29.7	27.7	2	64				
C15	1,312			✓					✓	D			V	✓								✓
C19	1,311	✓	×	✓	Ins. & gas storage	×	×	Gas boilers	✓	D	LED & Hal	✓	F	×	32	27.1	4.9	50				
C3	1,385	×	✓	×	Gas storage	×	×	Gas boilers	✓	D	LED	✓	F		31.5	31	0.5	49				
C7	1,391	×	✓	✓	Ins. & storage gas	×	×	Gas boilers	✓	S	Hal & CFL	×	V & F	×	30.6	29	1.6	70	A	×		×
C6	1,430	×	✓	×	Gas storage	×	×	Gas boilers	×	D	LED & CFL	✓	F	✓	31.2	30.6	0.6	48				
C5	1,456	×	×	×		×	×	Gas boilers	✓	S	LED	×	F	×	31	26.2	4.8	57				
C14	1,481																					

C21	1,541	✓	×	✓		×	×	Gas & electric	✓	S & D	LED	✓	F	✓	30.4	26.3	4.1	77	S	✓	28	✓
C4	1,603	✓	×	✓	Ins. gas	×	×	Gas boilers	✓	D	LED	×	V	✓	33.5	29.4	4.1	46	A	✓	27.8	✓
C17	1,625	×	×	×	Gas storage	×	×	Gas boilers	×	D	LED, Hal & CFL	×	F	×	32.5	26.2	6.3	54				
C2	1,676	✓	×	×		×	×	Gas boilers	✓	S	LED & CFL	×	V	✓	31.5	28	3.5	66	A	✓	28.5	✓
C9	1,680	✓	×	×	Gas storage	×	×	Gas boilers	✓	D	Hal & CFL	×	V	×	30	29	1	48				
C10	1,796																					
C18	2,566	✓	×	✓	Ins. gas	×	×	Gas boilers	✓	D	CFL & Hal	×	F	×	32.3	26.2	6.1	61	A	✓	28	✓
C22	3,544	✓	×	✓		×	×	Gas boilers	✓	S	LED	×	V & F	✓	30.9	26.1	7.8	42	A	✓	27	✓

6.7.2 Features Influencing Water Use

Water efficiency is just as important as energy efficiency in aquatic centres due to their typically high annual water consumption rates. Similar to energy, data were collected on the water systems and operational features in aquatic centres, and then selected from the questionnaires and site visits to be summarised in Table 6.20. Some of the initiatives recorded for this study include recycling and re-use of backwash water for irrigation and make-up water, rainwater harvesting, types of filters and treatments, pool covers, water-efficient fittings and any other alternative water-recycling features. It should be noted that during this investigation, it was not possible to determine the efficiency of water devices (e.g., bathroom taps, WC and showers), as the majority of the aquatic centres did not have any corresponding information. During site visits, it was also too difficult and time consuming to inspect all water fittings, and gaining access to all areas (e.g., showers) proved problematic. Despite these obstacles, an assessment was performed to identify whether any distinct factors or features determine whether certain aquatic centres are more water efficient than others.

6.7.2.1 Types of Filters and Treatments

The type of filter used for swimming pools can help reduce water consumption. Based on the literature, vacuum filters require much less water compared to gravity and pressure filters; however, the majority of the aquatic centres within the sample opt for the latter, with only one using a gravity filter; as such, this made water-efficiency comparisons impossible. There are also several treatment methods that are used for treating public swimming pool water, the main types of which (based on the data collected) are UV sanitisation, chlorine, CO_2, sodium and ozone methods. The majority of the aquatic centres used a combination of different treatments, with around 40% within the sample opting for a blend of UV and chlorine care.

6.7.2.2 Backwashing

Backwashing is an important process that uses large volumes of water to clean filters. According to Sydney Water (2011), make-up water including backwashing can account for around 36% of an aquatic centre's water usage. The majority of those sampled use manual techniques, with only few opting for automatic backwashing. The former poses some advantages, notably that its filters are cleaned only when they are dirty, which allows for the option of extending the backwash cycle and, hence, using less water over a longer period. Although not the case with automatic backwashing, a comparison between both methods was not possible due to most of the aquatic centres sampled selecting the manual option. This assessment still defined one distinct feature that determines increased water efficiency and highlighted the key difference between low–medium range and high-range WUIs in the form of recycling backwash and re-using either make-up water or irrigation. Approximately 30% of the aquatic centres (seven aquatic centres) within the sample recycle their backwash water and two re-use this for irrigation, while the remainder do so for make-up water (swimming pool refill) using reverse osmosis systems.

6.7.2.3 Circulating Pumps

Circulating pump characteristics were included within this investigation, as this device is constantly used to circulate swimming pool water. It was observed that the majority of the aquatic centres using fixed speed pumps are located towards the high end of the water-benchmarking ranking.

6.7.2.4 Pool Covers

As pool covers reduce the amount of water lost through evaporation, several of the aquatic centres within the sample did so for both indoor and outdoor pools. Similar to the energy analysis, there is no visible difference in the water consumption between aquatic centres that do and do not have pool covers.

6.7.2.5 Rainwater Harvesting

Rainwater harvesting is an excellent way of reducing consumption from the water main, with rainwater tanks being among the most common water-saving initiatives used by a wide range of building types. Approximately 50% of the sample aquatic centres have rainwater tanks used for irrigation, toilet flushing, backwashing and topping up swimming pools. However, depending on the use of rainwater, treatment can be required. It was observed that the majority of the aquatic centres with such tanks are located within the low–medium range of the proposed water benchmark, thus, suggesting this method can be considered a potential water-efficient characteristic that determines whether an aquatic centre is more water efficient.

6.7.2.6 Alternative Water Recycling

Other than recycling backwash water, there is only one aquatic centre that recycles grey water for irrigation and toilet flushing.

Table 6.20: Water Features of Surveyed Aquatic Centres

ID	L/visitors	Filters	Treatment type	Backwashing	Recycling backwashing	Re-use of backwash water	Circulating pump	Indoor pool covers	Rainwater tank	Alternative water recycling	Use of rainwater tank	WELS	Outdoor pool covers
C1	11.5	Pressure	UV & chlorine	M	✓	Irrigation	V	×	✓	×	Make-up		
C12	22.1												
C2	29	Pressure	Ozone & chlorine	M	✓	Make-up	V	✓	✓	×	Backwashing		✓
C5	29.4	Pressure/ gravity	UV, sodium & ozone	A	×		F	×	✓	×		3	
C22	29.7	Pressure	Chlorine	M	×		F &V	✓	×	×			✓
C15	30.5	Pressure		M	✓	Irrigation	V	✓	✓				✓
C6	34.4	Pressure	Chlorine	M	×		F	✓	✓	×			
C11	35.1												
C9	36.7	Pressure	UV & chlorine	M			V	×	✓				
C19	38.4	Pressure	UV, chlorine & CO_2	M	✓	Make-up	F	×	✓	Osmosis	Backwashing		
C14	48.9												
C10	49												
C3	50.1	Pressure	Chlorine	M	✓	Make-up	F			×		3	
C16	56.7	Pressure	UV & sodium	M	×		V	✓	×	×			✓
C7	60.1	Pressure	UV, chlorine & calcium	M	P	Make-up	F & V	O	P	Osmosis	Make-up	3 & 4	O
C4	64	Pressure	UV & chlorine	M	✓	Make-up	V	✓		Grey			✓
C20	71.3	Pressure	Chlorine & CO_2	M	×		F	✓	×	×			
C17	79.3	Pressure	UV & chlorine	M	×		F	×	×	×			
C8	89.3	Pressure	Chlorine	M	×		F	×	×	×			×

C13	96.3										
C21	102.1	Pressure	Chlorine, CO_2 & sodium	M	×	F	✓	✓	×	Toilet & irrigation	✓
C18	110.3	Pressure	UV & chlorine	M	×	F	×	✓	×	Toilet & irrigation	✓

Overall, only a few water-efficient features have been identified; however, two distinct features (recycled backwash water for make-up water and rainwater harvesting) have been observed to place aquatic centres among the low–medium range of the proposed water benchmark. Essentially, both investigations (energy and water characteristics) have provided some valuable information to understand both how aquatic centres in Victoria operate and what common types of systems (water and energy) are being used.

6.8 Conclusion

This chapter has provided a comparatively clearer definition of an aquatic centre to past studies, which otherwise present inconsistencies in relation to both energy and water benchmarks. As such, this study defined an aquatic centre as a community or public venue that provides at least one indoor swimming pool and three different types of amenities, such as a gymnasium, sauna or spa, a cafe and a creche. A guideline has also been proposed so that buildings with indoor swimming pool facilities can be easily identified for future research; essentially, this will facilitate the classification or categorisation of aquatic centres around Australia and beyond. The proposed set of rules for benchmarking energy and water use in such buildings aims to reduce the discrepancies and confusion in this sector, and, hence, streamline future comparisons between aquatic centre studies.

Many past studies have separately investigated these elements; although, combining this assessment (as demonstrated in this study) is both logical and useful, despite its failure to reveal a strong correlation between the two. However, this is justifiable based on the fact that aquatic centres contain large dry areas such as stadiums, cafes and gyms, where energy use can generally be high. Nonetheless, it fills a gap in understanding whether a direct effect of water use on energy use in such facilities (and vice versa) exists.

Based on the regression analysis, it is also more relevant to divide the energy use of aquatic centres to conditioned usable floor area and the water use to the number of visitors. As such, the proposed energy benchmark for aquatic centres ranged between 648 kWh/m^2 and

2,283 kWh/m^2, while the proposed water benchmark ranged between 11 L/visitor and 110 L/visitor. Despite the study sample's relatively low involvement, with only 22 participating aquatic centres, the data collection was carefully performed to ensure that only those as defined in Section 6.2 were included. The sample also represents all the aquatic centres within Victoria in terms of size (aquatic centres with gross floor areas from 2,215 m^2 to 10,964 m^2) and amenities.

The majority of past studies on swimming pool facilities have also failed to clearly define their research measures or justify how they devised their definitions, thus, raising questions regarding the types of swimming pool facilities considered. It also queries whether the benchmarks proposed are applicable to all other swimming pool facilities, including school pools, private clubs' swimming pools, outdoor public swimming facilities and resort swimming pools.

Indeed, it should be noted that even with this detailed investigation of aquatic centres, it was not possible to identify many noticeable energy- and water-saving features that differentiate one aquatic centre's efficiency from another. However, this is due mainly to significant differences in the architectural and electromechanical design of an aquatic centre itself. Nonetheless, the use of solar pool-heating systems, solar PV systems and daylight or motion sensors for lighting provided some positive outcomes in relation to energy saving within the sample collected—with recycled backwashing for swimming pools' make-up water and rainwater harvesting further indicating apparent water reductions.

Further studies using computer-modelling simulations of an aquatic centre could certainly be used, as such technology can provide a better understanding of the effect and influence of several features, including double glazing, pool covers, glazing-to-floor-area ratios, solar energy, better mechanical and electrical systems, and rainwater tank usage on energy and water consumption. Accordingly, Chapter 7 will attempt just that.

Chapter 7: Simulation of An Existing Aquatic Centre

7.1 Introduction

Statistical regression-based modelling was performed in Chapter 6 to investigate the energy performance and water use of aquatic centres. While several valuable results were obtained from the statistical analysis, there are still some areas that require further investigation to provide a better understanding of these two key factors. Essentially, what and how can specific parameters or design features influence the energy and water use of an aquatic centre? Several features have been identified from information collected by questionnaires, site visits and onsite measurements. However, due to the size of the sample and the complexity of this type of building, more analysis is required. Notably, building simulation is a common method to investigate the energy performance of buildings and has in this study been identified to better examine aquatic centres. This method can provide a breakdown of specific end use (such as space heating, pool heating and lighting), which is otherwise not possible with statistical analysis.

This chapter will describe the process and results of simulating an aquatic centre based on a building from the sample. The model will first be described, followed by an explanation of its construction process. Once the model is built, all the data inputs will be performed within DesignBuilder and then transferred to EnergyPlus (version 8.7). Calibration and validation of the simulation model will be performed and described thereafter. Parametric studies will next be completed to investigate what features determine energy and water efficiency. As such, this chapter directly relates to research Question 5.

7.2 Case Study

Among the samples collected, one aquatic centre was prepared to provide the majority of the information required for simulation. The aquatic centre selected is located within the inner suburbs of Melbourne in Victoria. The aquatic centre consists of multiple functional sections, including a:

1. main pool hall (1,607 m^2)
2. stadium (6,930 m^2)
3. gymnasium (301 m^2)
4. program rooms (175 m^2)
5. entrance foyer (120 m^2)
6. cafe, kitchen and coolroom (108 m^2)
7. offices and staff meeting rooms (160 m^2)
8. external mechanical plant room and pool plant room (280 m^2)
9. pool change rooms, toilets and showers (251 m^2)
10. circulation and corridors (342 m^2)
11. stadium toilets and change rooms (180 m^2)
12. creche (135 m^2).

The gross floor area of the building is 10,839 m^2, which houses three swimming pools, a 25 m lap pool consisting of eight lanes, a warm water pool and a kids' pool. Figures 7.1 and 7.2 are floor plans of the aquatic centre, and Figure 7.3 is an internal photo of the swimming pool hall.

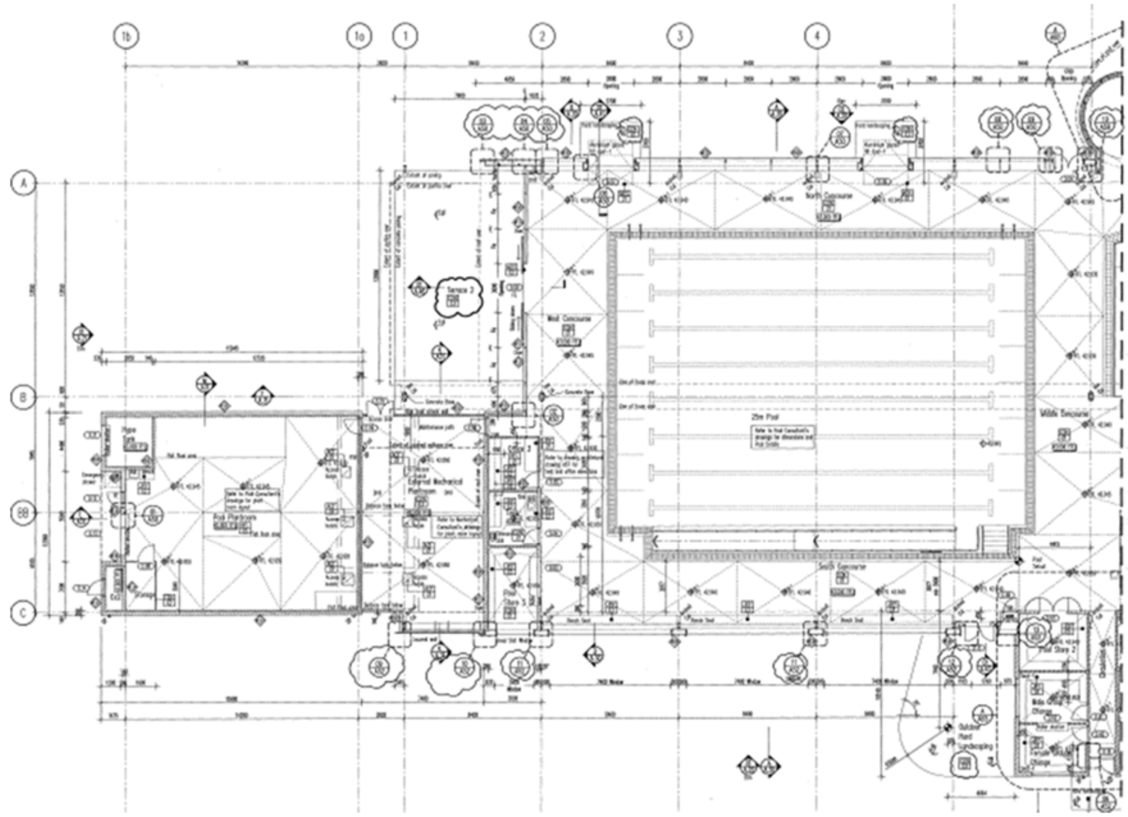


Figure 7.1. Floor plan of the sample swimming pool hall (west wing).

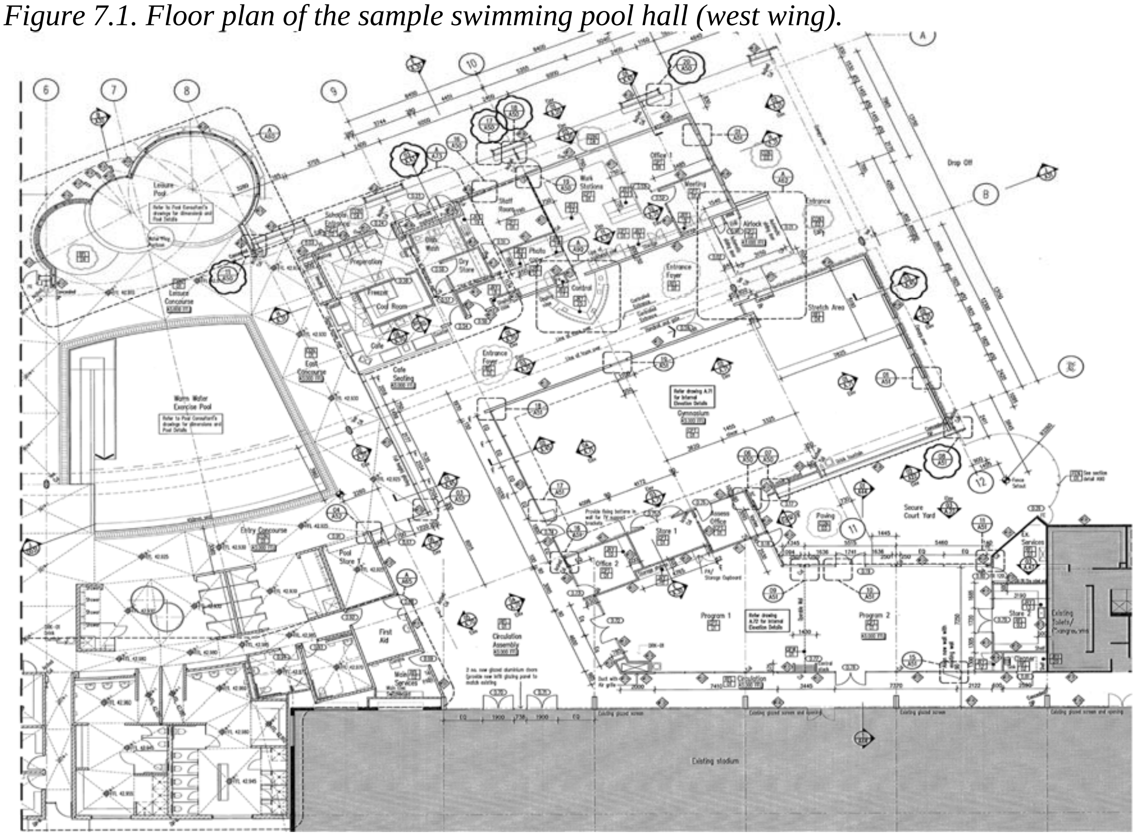


Figure 7.2. Floor plan of the sample swimming pool hall and other amenities (east wing).

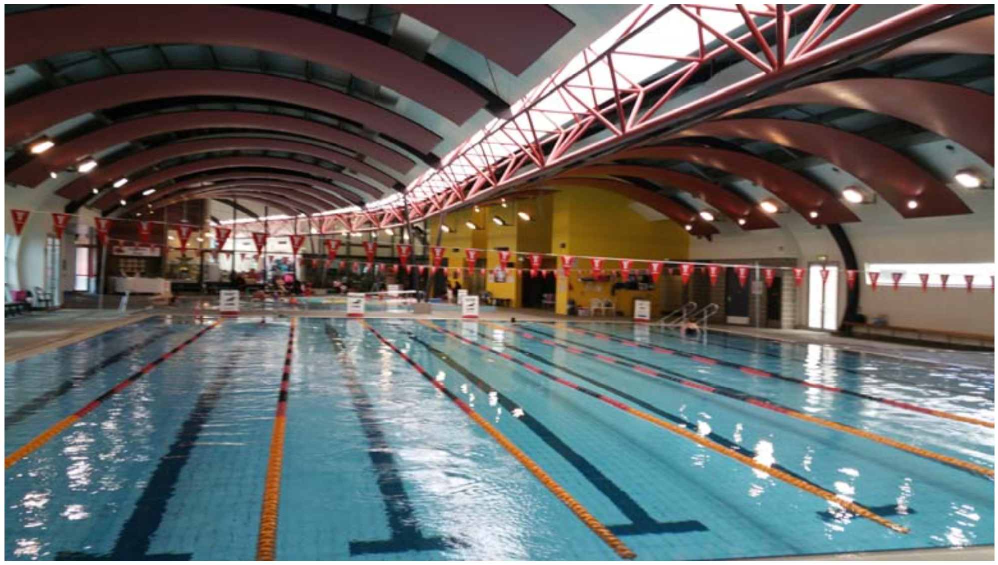


Figure 7.3. Internal photo of the sample swimming pool hall.

7.2.1 Selection of Data for Simulation Purpose

All the data collected from the questionnaire, site visits, onsite measurements, interviews and information provided by the sample aquatic centre's manager are used to build the simulation model. The data are separated into three groups of architecture (i.e., building materials), electromechanical specification (i.e., HVAC systems) and operational information (i.e., pool temperature and operating hours), with each summarised in Tables 7.1, 7.2 and 7.3, respectively. More details about the material specification is also summarised in Table 7.1a Once this information is sorted, the next step is to construct the three-dimensional model of the aquatic centre, as described in Section 7.3.

Table 7.1:
Architectural Information

Elements	Description
Floor	Concrete slab- 350mm
External walls	Blockwork -240mm (wall thickness including cavity) Metal cladding- 90mm
Roof	Flat metal roof with internal plasterboard- 300mm thick
Glazing	Single glazing (U value of 6.7 and SGHC of 0.65
Internal walls	90mm lightweight (plasterboard) Single glazing separation between foyer and swimming pool hall
Window frames	Aluminium frame
External door	Glazed doors (Single glazing U Value of 6.5 and SHGC of 0.63) Metal doors
Skylight	Single glazing (U value of 7.0 and SHGC of 0.69)
Insulation	External walls: R-2.0 (bulk insulation) Roof: R-3.5 (roof blanket)

Table 7.1a:
Material Specification

Material	Conductivity (W/m.K)	Density (kg/m^3)	Specific Heat (J/kg.K)	Thermal Absorptance	Solar Absorptance
Concrete	1.4	2100	840	0.9	0.6
Metal-Zinc	113	7000	390	0.9	0.6
Metal-Aluminium	45	7680	420	0.9	0.6
Concrete block	0.51	1400	1000	0.8	0.6
Plasterboard	0.16	950	840	0.9	0.5
Gypsum plasterboard	0.25	900	1000	0.9	0.5
Standard insulation	0.04	12	840	0.9	0.7
Glass-fibre batt insulation	0.043	12	840	0.9	0.7

Table 7.2:
Electromechanical Information

Location	Item	Description
Swimming pool hall	HVAC system	Packaged air handling connected to a gas boiler Efficiency 80%
	Pool-heating system	3x boilers Efficiency 80%
	Pool pump	5x variable pumps
	Lighting	Metal halide and LED; 10.5 W/m^2
	Types of filters	3x sand filters
	Types of treatment	UV and chlorine
	Ventilation requirement	Six ACH
Pool staff room	HVAC system	Split system air conditioning unit COP (Heating) 3.0 & EER (Cooling) 2.89
Stadium	Air handling Lighting	4x ventilation draw units (extraction fans) LEDs; 10 W/m^2
Programs rooms	HVAC	2 x split system air conditioning unit COP (Heating) 3.0 & EER (Cooling) 2.89
Main foyer and cafe area	HVAC	Packaged air handling unit COP (Heating) 2.9 EER (Cooling) 2.75
General office	HVAC	Split system air conditioning units COP (Heating) 3.0 & EER (Cooling) 2.89
Gym	HVAC	Packaged air handling unit
	Gym equipment	15 W/m^2
	General lighting	LED and halogen lighting + daylight/occupancy sensors; average of 9.5 W/m^2
	Domestic hot water	Gas instantaneous system 50 L/person using the swimming pools 5 L/person to remaining occupants
	Equipment (other areas)	5 W/m^2
	Infiltration rate (other areas)	0.5 ACH

Table 7.3:
Operational Information

Location	Characteristics	Description
Swimming pool hall	Air temperature	31 ºC
	Lap pool water temperature	29 ºC
	Kids' pool-water temperature	29 ºC
	Warm pool-water temperature	31 ºC
	Operating hours	5:30 am to 9 pm (Monday to Thursday) 5:30 am to 8 pm (Friday) 5:30 am to 7 pm (weekends and public holidays)
	HVAC operating hours	24 hours
	Lighting operating hours	8 hours with daylight sensors
	Occupant density	16 m^2 per person
Gym and program room	Air temperature	21–23 ºC
	Operating hours	24 hours (open to public)
	HVAC operating hours	24 hours
	Lighting operating hours	24 hours
	Occupant density	3 m^2 per person
Cafe and foyer	Air temperature	21–23 ºC
	Operating hours	5:30 am to 9 pm (Monday to Thursday) 5:30 am to 8 pm (Friday) 8 am to 7 pm (Weekends and public holidays)
	HVAC operating hours	12–16 hours
	Lighting operating hours	8 hours with daylight sensors
	Occupant density	10 m^2 per person
Office and others area	Air temperature	21–23 ºC
	Operating hours	5:30 am to 9 pm (Monday to Thursday) 5:30 am to 8 pm (Friday) 8 am to 7 pm (Weekends and public holidays)
	HVAC operating hours	12–16 hours
	Occupant density	10 m^2 per person
Stadium	Air temperature	No air conditioning (extraction and ventilation fans are rarely used)
	Operating hours	6 am to 9 pm (Monday to Thursday) 6 am to 8 pm (Friday) 8 am to 7 pm (Weekends and public holidays)
	Occupant density	45 m^2 per person

7.3 Simulation Model

Building the simulation model can be a time-consuming exercise. Two key processes are involved in this task. The first is to build the three-dimensional model of the aquatic centre to then transfer to EnergyPlus using DesignBuilder. EnergyPlus allows for text editing without offering any visual aids, while DesignBuilder is a user-friendly software that allows users to import floor plans and then build a model as required. This is incredibly time saving, as this method eliminates the need to check dimensions. Other important information such the lighting schedule and HVAC systems are also added using DesignBuilder (the process for which is described in Section 7.3.1). However, the one important component that cannot be added is the swimming pool. The second part of the simulation process is to transfer the model to EnergyPlus. DesignBuilder uses the EnergyPlus engine and can create an IDF file that can then be opened in the program's Editor component. EnergyPlus is then used to create the swimming pools within the pool hall by using the indoor swimming pool module located in the internal gain section. Figure 7.4 provides the shape of the main building.

Figure 7.4. External view of the aquatic centre showing its curved roof design.

The main part of the building, which includes the swimming pool hall, has a skylight in the middle that connects the two curved roofs; several zones were created to model this space. All the floor plans and elevations received were properly dimensioned, which facilitated the three-dimensional model building. Windows and glazed doors were scaled off the plans, while the large rectangular-shaped stadium attached to the main part of the aquatic centre was also noted.

7.3.1 DesignBuilder Simulation

DesignBuilder is a common tool used to simulate energy consumption in the built environment. As mentioned in Section 7.3, DesignBuilder was not only used to construct the three-dimensional model of the aquatic centre but also to enter additional information, including:

1. building material envelopes, such as external walls, internal walls, roofs, windows, doors, skylights and floors
2. insulation and glazing specifications—importantly, as the details on each factor were not available during investigation, the insulation levels in both walls and roof were based on NCC data, while the glazing specifications were based on values of a 6 mm clear glazing with aluminium frame
3. HVAC systems
4. the range of internal temperatures and plant operating times, such as heating and cooling set points
5. humidity levels for both the swimming pool hall and the remaining areas
6. the building occupancy schedule based on the occupancy rate provided in the questionnaire
7. internal artificial lighting levels in the aquatic centres were based on the data obtained from the building operator and the NCC, where it was difficult to obtain exact wattage of lights within some of the areas of the aquatic centre
8. internal heat gains, including people, lighting, appliances, gym equipment and other electric power loads
9. metabolic rates for people
10. domestic hot-water temperature and rate of use
11. infiltration values and ventilation requirements (at least six ACH for swimming pool halls and 0.5 ACH for remaining areas)
12. the operating schedules for both lighting and HVAC systems.

The first step was to import the appropriate floor plan in DesignBuilder. Figure 7.5 provides the construction of the swimming pool hall in the model.

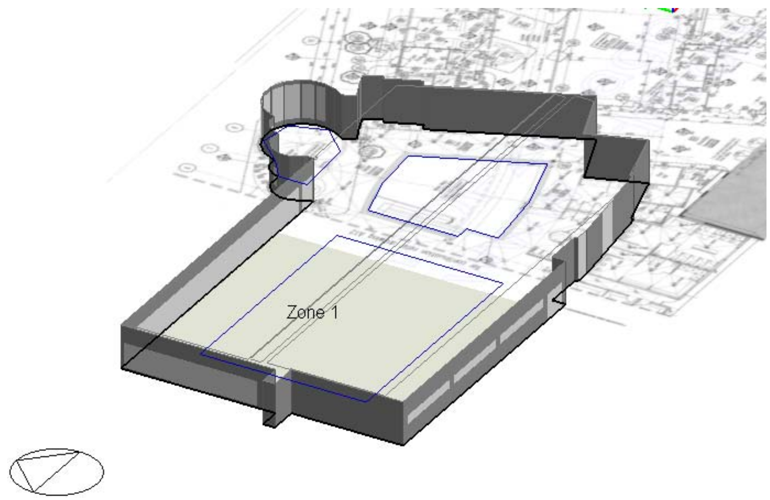


Figure 7.5. Three-dimensional construction of the swimming pool hall.

Several zones had to be built to represent all the amenities within the aquatic centre. Amenities or areas with similar HVAC systems, temperature set points and occupancy schedules were merged together in a particular zone to simplify the simulation process. The amenities and zones were also merged based on the observations made during site visits.

Accordingly, 10 zones were created with descriptions pertaining to their various amenities:

Zone 1: pool hall, pool circulation, pool showers and toilets, and the two roof spaces above the pool hall.
Zone 2: cafe, kitchen, creche, gym, gym office, office 1 and 2, foyer, circulation hall, staff and meeting room, and stadium hall.
Zone 3: stadium.
Zone 4: external mechanical room.
Zone 5: program rooms.
Zone 6: stadium change rooms and toilets.
Zone 7: pool change room.
Zone 8: first-aid room and services.
Zone 9: office 3.
Zone 10: pool plant room.

As such, Figures 7.6 and 7.7 illustrate the aquatic centre model in DesignBuilder.

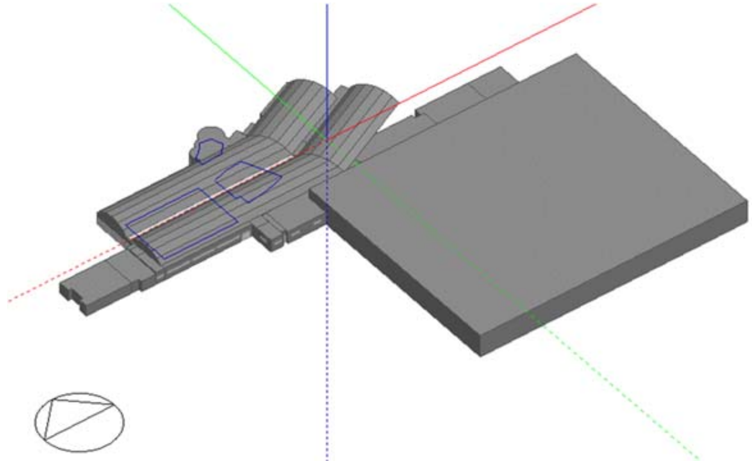


Figure 7.6. Three-dimensional model of the sample aquatic centre (south view).

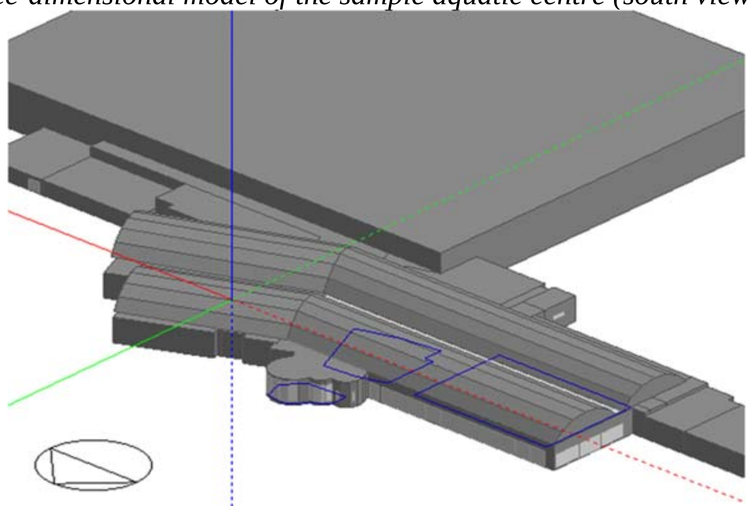


Figure 7.7. Three-dimensional model of the sample aquatic centre (north view).

After the building envelopes were thoroughly checked, all the information (including the HVAC system, lighting levels and schedules) was added to the model. While the majority of the information was transferred to DesignBuilder, some of the inputs required some adjustment once relocated to EnergyPlus. Once all the data were added, a few simulation runs using DesignBuilder were performed. To identify any major problems with the model that would prevent the simulation from running, several simulations runs were performed with no major issues identified. Subsequently, the simulation model was exported to EnergyPlus, as described in Section 7.3.2.

7.3.2 EnergyPlus Model

The weather file is then loaded on the EnergyPlus launch. The first step is to run the file to ensure it contains no issues before making any additional adjustments. An error report is next produced with the results, and this is verified to identify any issues that might cause problems. Once performed, the aquatic centre IDF is loaded onto the IDF editor to add the necessary information. The first component of which is adding the swimming pool locations within the pool hall, which, as explained in Section 7.3.2.1, must be performed in a particular manner.

7.3.2.1 Pool Hall and Indoor Swimming Pools

The sample aquatic centre has three pools: a 25 m lap pool, a warm water pool and a children's pool. As defined, swimming pools cannot be added in DesignBuilder, while EnergyPlus is not user-friendly enough to perform such a task. Thus, the following steps explain how swimming pools can be added to the IDF file.

The first step is identifying the swimming pool coordinates. When building the three-dimensional model in DesignBuilder, these positions can be added using construction lines (Figure 7.8). However, as these features are not included in the IDF file, the locations and coordinates of the swimming pools must be recorded manually. Notably, EnergyPlus uses a three-dimensional Cartesian coordinate system for surface vertex specification.

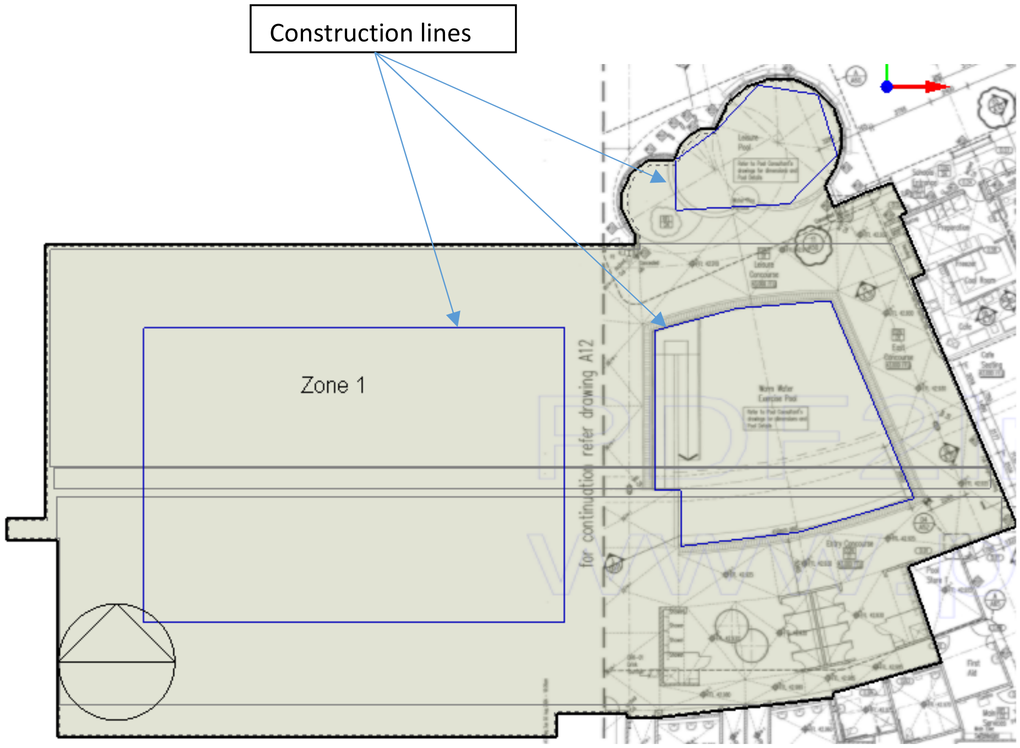


Figure 7.8. Swimming pool construction lines.

Next, users must identify the swimming pools in EnergyPlus. Once the coordinates have been entered, one must differentiate the floor type of the swimming pools from the other floors within the pool hall. Importantly, the floor material of the swimming pools must also be different to the floor material of the pool hall so that EnergyPlus can recognise them as the pool-water surface. This is done by creating a concrete slab with a different material density or with a different slab thickness in the construction tab within the surface construction elements in the IDF file. For example, as shown in Figure 7.9, the tab 'Construction Name' is where the water surface area of the pool 'FLOOR-SLAB-1' is selected and assigned to the specific pool.

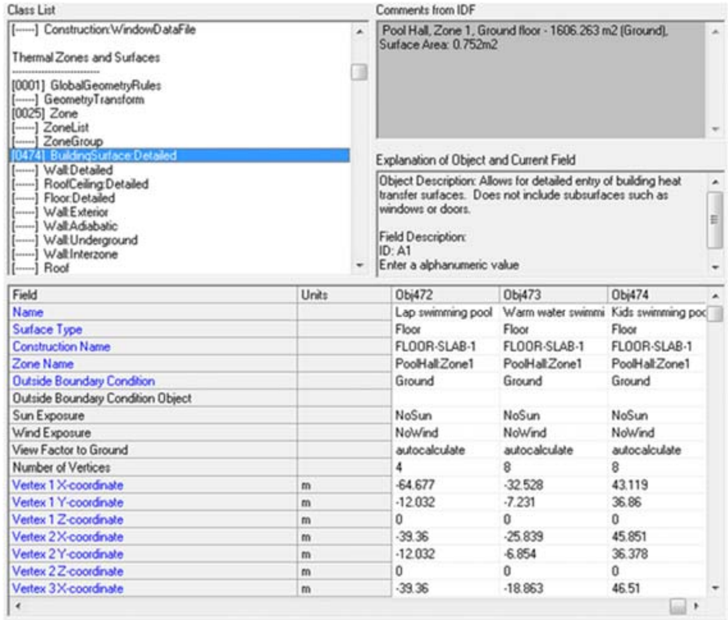


Figure 7.9. EnergyPlus swimming pool coordinates.

The third step concerns the details of the swimming pools in EnergyPlus. Once the physical locations of each swimming pool are present within the EnergyPlus IDF file, the swimming pools need to be created in the indoor swimming module located within the internal gain section and, thus, be linked to the swimming pool surface entered in the thermal zones and surfaces section. Multiple data, as shown in Figure 7.10, must also be entered in the indoor swimming pool module, including:

1. name of the swimming pools
2. average depth of the pool
3. activity factor schedule
4. make-up water supply schedule
5. swimming pool cover schedule
6. cover evaporation, convection and radiation factors
7. connection to pool-heater systems
8. pool pump equipment power
9. set point temperature schedule of each swimming pool
10. maximum number of people in the swimming pools, people schedule and people heat gain schedule.

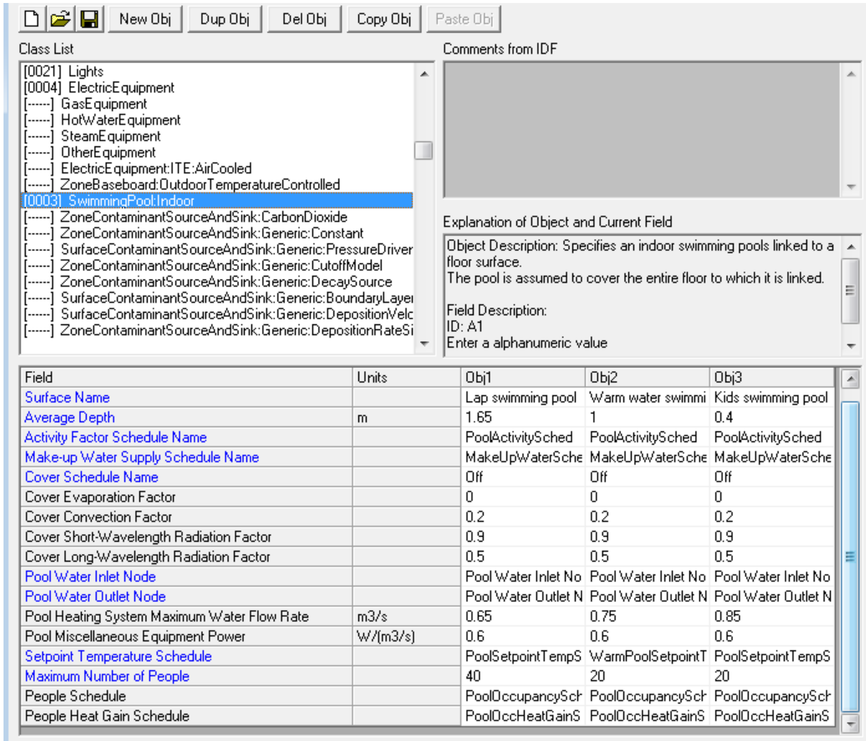


Figure 7.10. EnergyPlus swimming pool data input table.

Next, the swimming pool schedules are created; this contains all the information from the water temperature to the occupancy schedule for the swimming pools. The compact schedule section is the area where all the information is added. Some examples of the information added are:

1. pool hall air-heating set point schedule
2. pool activity factor schedule
3. make-up water schedule
4. pool set point temperature schedule for each swimming pool
5. pool occupancy schedule.

As no study has been identified to simulate an aquatic centre using the indoor swimming pool module within EnergyPlus, all the above steps were created in this thesis to successfully model an aquatic centre with several indoor swimming pools. As such, Section 7.3.2.2 will detail the procedure for creating the pool-heating system based on the data collected.

7.3.2.2 Pool-heating Systems

Based on the data collected, each swimming pool has its own heat exchanger and boiler. An investigation on the sample centre's boilers (notably Raypak) was performed since there were no available data on their efficiency under both full- and part-load conditions.

According to the manufacturer’s specifications, Raypak boilers have an efficiency of around 70–82% depending on the types of systems used. Since pool-heating systems were not be created in DesignBuilder, those for each swimming pool had to be created initially using the EnergyPlus IDF editor.

To do so, users must first select the appropriate pool-heating system. For example, a Raypak system, as specified, can be modelled in EnergyPlus using a water-heater mixed model, which is located within the water heaters and thermal storage section. As such, each swimming pool will have its own heating system according to the data collected. Naturally, several data are required within the water-heater mixed module, including:

1. a pool-water set point schedule, which is created within the compact schedule section and determines the temperature at which to heat the water
2. the maximum temperature limit
3. the heater’s maximum capacity
4. the heater control type (cycle or modulate)
5. heater fuel type (natural gas, as defined by the data collected)
6. heater thermal efficiency (set as 80%)
7. connections to the pool.

Next, users must create a plant for the pool-heating system. Each one created in EnergyPlus requires a plant that will need to be sized if specific data about the actual system is missing or unavailable. Essentially, a plant refers to the subset of HVAC that involves hydronic equipment for heating, cooling and service water heating. The input to create a plant is needed to autosize both plant loop flow rates and equipment capacities, and this information is initially used by components that use water for heating or cooling features such as hot or chilled water coils to calculate their maximum water flow rates. These flow rates are then summed for use in calculating the plant loop flow rates. The correct flow rates are important, as they will determine whether pool water can reach its required temperature.

The third step is creating loops for a pool’s hot-water system. This step is crucial, as it is difficult to identify any errors if such loops have not been properly created. Plant loops are further divided into half loops or semi-loops for organisational clarity and simulation logistics. Plant loops are then broken into supply and demand sides, the latter of which for half-loops contain equipment that places a load on the primary equipment, which is the swimming pool. The load is met by primary equipment such as chillers or boilers on the supply-side half-loop, and these are then defined by branches, connectors and components. The controls for each loop are set after the loop has been completed, and these are next linked to the swimming pool's heating systems. Importantly, such loops must be created using the node-branch management section and several components, including a branch, splitter connector, mixer connector, adiabatic pipe and node list. These must be done so in the correct order or the simulation will not run.

The next step is selecting a water pump, which is another important component that drives the flow in plant loops by pushing hot water from a heating system to a swimming pool. The pump is simulated first on the supply-side loop after the demand-side loop has determined what the demand on the loop will be. The pumps are created using the pump section and the variable speed pump is chosen to allow more flexibility. In EnergyPlus, if users designate a pump that is operating continuously, it will run regardless of whether there is a load. If the pump operates intermittently, the pump will run at its capacity if a load is sensed and, thus, shut off if there is no load on the loop.

Step five then concerns the pool-heater controls. Plants loops must have some mechanism for controlling the operation of the loop and which equipment is available under what conditions. Since there may be multiple control schemes that are assigned to various priorities associated with each loop, an overall operation scheme must be defined. The overall scheme consists of the object name, an identifying name that is referenced in the main plant loop statement and a list of operation schemes. Each operation scheme must then have the type of operation scheme, its identifying name and the schedule that defines its availability. Each of these control components are next added in the plant-condenser control using modules such as the plant equipment list, the plant equipment operation, heating load and plant equipment operation schemes.

The final step is setting the pool temperature's monitoring system. Set temperature monitoring is used to identify when the required pool-water temperature is reached. This is achieved by using the scheduled set point manager located in its corresponding section. Set point managers are one of the high-level control constructs in EnergyPlus that can access data from any of the HVAC or heating system nodes to calculate a set point (usually a temperature set point) for one or more HVAC system nodes. Controllers then use these set points as a goal for their control actions.

Adding an indoor swimming pool to the model is a complex exercise due to the large number of components involved, including plant loops, branches, pipes and heating systems. Evidently, this can make it difficult to identify any errors within the EnergyPlus swimming pool module and plant components, and even harder when all the swimming pools are present at once. Therefore, it is advised that an indoor swimming pool and its components should be added individually within the model and a simulation run should be performed to check if any major simulation errors occur.

7.3.3 Verifying Indoor Swimming Pool Modules and Weather Files

Preliminary analysis (i.e., simulation of the sample centre's swimming pool hall) was performed to verify the results obtained from the new indoor swimming module in EnergyPlus (version 8.3). During this, some implementation and coding problems were identified, including unrealistic make-up water volume, flow-rate issues, issues with pool covers and evaporation rates. The issues were reported to EnergyPlus's technical team by email and have since been corrected in the version (8.7) used in this study.

EnergyPlus also requires weather files as an add-on to run simulations and appear in the standard EnergyPlus Weather (EPW) file format. Real weather file for the same period (2015) was first obtained for the location closest to the site of the aquatic centre. However, it was noticed that important data such dew point temperature, global horizontal radiation, direct normal radiation and diffuse horizontal radiation were missing from the real weather file.

Therefore, real weather file could not to be used. As such, the Australian Representative Meteorological Year (RMY) Climate Files were selected as weather data. The Moorabbin Airport (946930) weather file was next chosen to perform the simulation, as this file is based on a location that is the closest to the selected aquatic centre. A comparison was made between the real weather file and the RMY weather file, to verify if there are major differences between the air temperature and relative humidity of the two weather files. Figure 7.11 below shows the hourly plot of the air temperature of the real weather file and the RMY weather file for a year period while Figure 7.12 displays the hourly plot for the relative humidity.

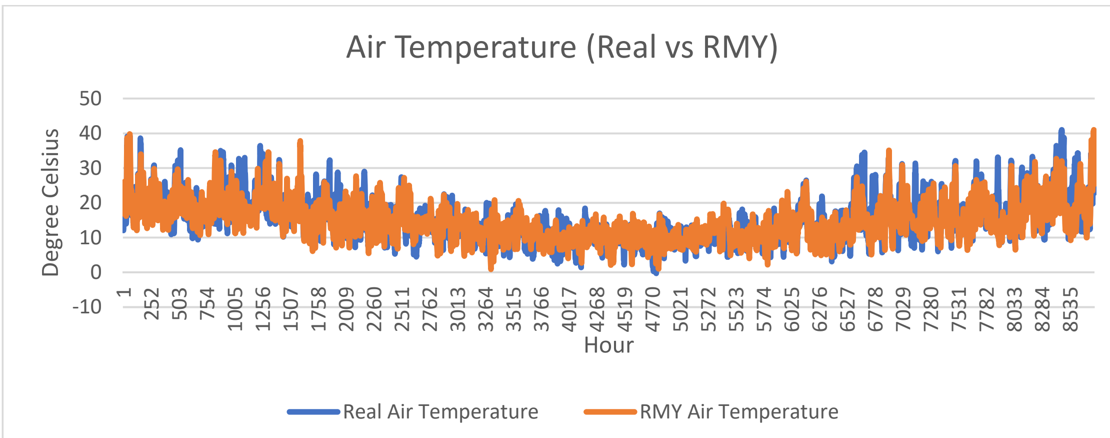


Figure 7.11. Air Temperature comparison (Real weather file vs RMY weather file)

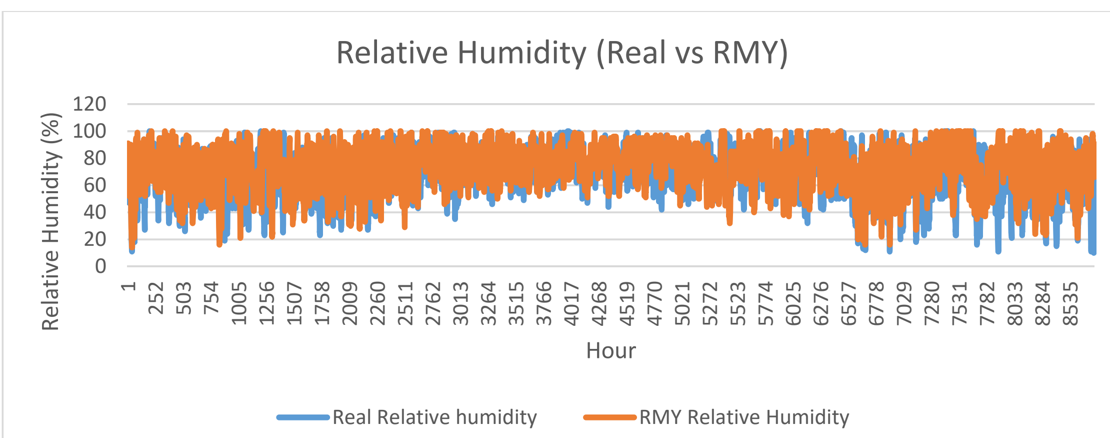


Figure 7.12. Relative humidity comparison (Real weather file vs RMY weather file)

It can be viewed from the two charts above that the RMY air temperature and relative humidity have similar trend for both the warmer and cooler months compared to the real weather data. Therefore, the RMY weather file was used for the simulation. Table 7.4 below displays the monthly average data such as temperature and radiation from the RMY weather file and the monthly average ground temperature at specific depth. The latitude of the site is -37.98, longitude of 145.1 and altitude of 13 m.

Table 7.4:
Ground temperature and weather data

	Ground Temperature (ºC)		Dry Bulb Temperature (ºC)	Relative Humidity (%)	Wind Speed (m/s)	Radiation (Wh/m^2)		
	0.5 m Depth	2 m Depth				Global	Direct	Diffuse
January	17.56	17.06	19.3	68.6	4.9	276.4	220.2	118.8
February	15.74	16	19.4	71.0	4.2	253.0	223.8	101.1
March	13.67	14.57	17.1	67.7	4.1	197.5	177.2	89.0
April	12.15	13.39	14.5	75.5	4.1	130.8	117.4	69.3
May	10.07	11.51	12.3	85.0	3.6	86.6	70.5	56.2
June	9.68	10.81	10.1	80.4	4.5	68.7	45.4	51.1
July	10.46	10.99	9.7	82.0	4.8	85.1	70.6	56.5
August	12.24	12.01	10.8	73.5	5.6	102.3	65.0	71.4
September	14.52	13.59	11.2	73.5	5.0	157.0	111.2	92.9
October	16.61	15.25	13.4	75.2	4.9	191.8	115.8	115.5
November	18.06	16.62	14.4	76.1	4.6	249.1	163.8	133.2
December	18.4	17.27	16.4	70.6	4.9	271.9	205.2	122.8

7.4 Simulation Results

As this section aims to provide the simulation results for the sample aquatic centre, both calibration and validation are required to ensure its accuracy. Once the data have been checked and added to the IDF file, the EnergyPlus EP-Launch can be used to run the simulation. The IDF file together with the weather file are next loaded, and, depending on the processor and memory of the computer used, the simulation runs can take up to 10–30 minutes if no major error is present. The error tab can then be viewed to identify any critical errors that require additional fixing.

Table 7.5 provides the subsequently end-use energy consumption. As expected, the combined heating load for air and pool water is much higher than the other end uses, while lower energy use during the summer season (December–February) and higher energy use for the winter season (June–August) is predictably observed. The first simulation runs showed reasonable results and no noticeable abnormalities, such as excessive energy consumption by individual end users.

Table 7.5:
Initial End-use Energy Use (Simulation 1)

	Air heating (MWh)	Air cooling (MWh)	Pool-water heating (MWh)	Lighting (MWh)	Domestic hot water (MWh)	Equipment and pump (MWh)
January	59.1	37.1	59.8	101.7	23.8	35.6
February	53	33	63.8	92	21.3	32.2
March	67.2	33	75.6	102.9	26.3	35.6
April	75.1	27.5	80.8	96.9	27.1	34.5
May	87.1	26.8	81.4	102	32.3	35.6
June	92.8	24.9	83.8	99.3	36.03	34.5
July	96.4	25.6	90.5	100.5	37.5	35.6
August	91.6	26.1	85.9	102.9	35.5	35.6
September	84.5	25.5	82.7	98.1	32.3	34.5
October	79	27.8	81.5	101.7	29.7	35.6
November	71	27.9	75.1	99.3	27.6	34.5
December	67.4	31.1	78.4	100.5	25.4	35.6
Total	**924.2**	**346.4**	**939.5**	**1,198.9**	**354.9**	**419.2**
Percentage	**22%**	**8%**	**23%**	**27%**	**8%**	**10%**

Figure 7.13 shows the trendlines of heat losses and energy loads within the simulation. It can be noticed from the chart below that the aquatic centre is mainly and internal-load dominated building. Heat losses through the building envelop are small compared to the internal-loads such as pool water heating, air heating and lighting. Additionally, it can be viewed that the evaporative heat loss is amongst the highest heat losses within the simulation.

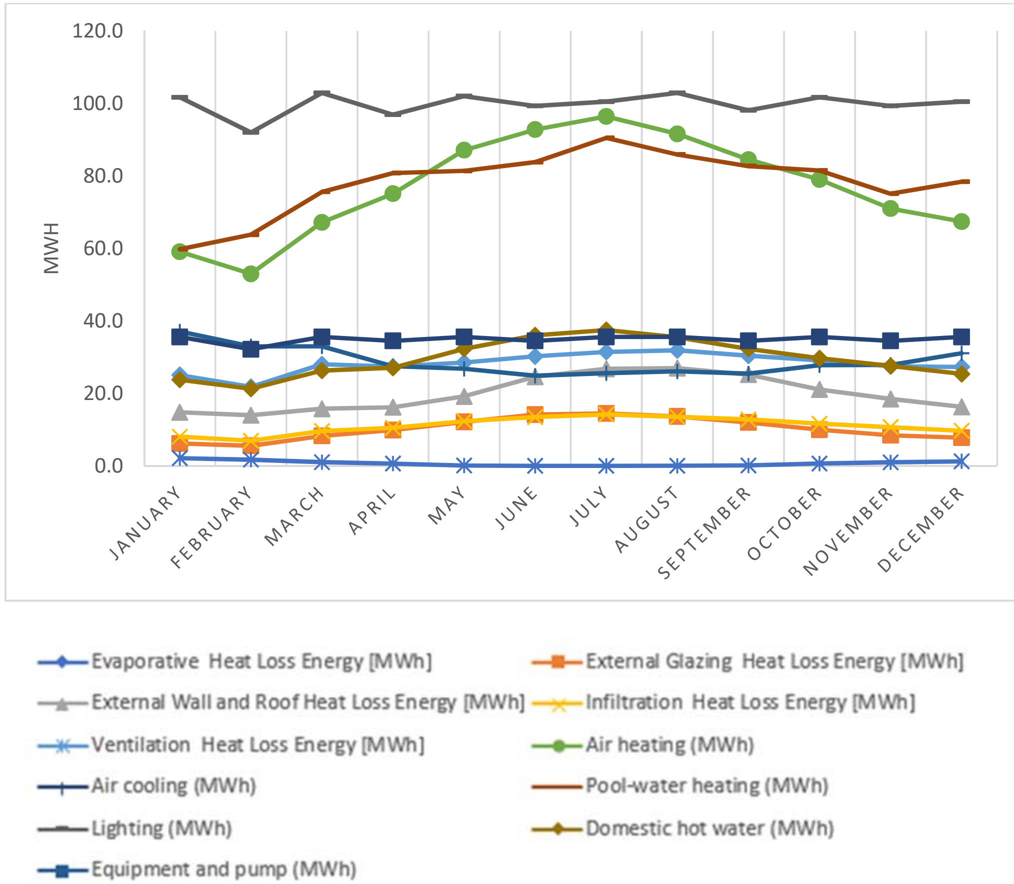


Figure 7.13. Heat losses and energy loads chart.

Table 7.6 offers the simulation results for energy use based on the swimming pool hall only. Evidently, the pool hall consumes the most total air-heating energy use at over 90%. Together with the pool-water heating energy, the swimming pool hall consumes a sizeable portion of the aquatic centre’s total energy (as expected), thus, confirming the literature findings. The swimming pools’ required temperatures are also reached, which suggests any such problems regarding water temperature have been corrected. The required relative humidity level is also as anticipated, as it was set to the appropriate level in the EnergyPlus HVAC system.

Table 7.6:
Swimming Pool Simulation Results

	Pool hall air-heating energy (MWh)	Pool hall water-heating energy (MWh)	Pool hall average relative humidity (%)	Average water temperature (°C)		
				Lap pool	Warm water pool	Kids' pool
January	57.8	59.8	62.9	29	31	29.6
February	52.2	63.8	63.5	29	31	29.6
March	64.9	75.6	62	29.1	31	29.7
April	71.7	80.8	56	29.1	31	29.6
May	82	81.4	58.1	29.1	31.1	29.6
June	86.1	83.8	55.8	29.1	31.1	29.6
July	89.1	90.5	52.6	29.1	31.1	29.6
August	85.5	85.9	54.3	29.1	31.1	29.6
September	78.9	82.7	50.5	29.1	31.1	29.6
October	75	81.5	49.2	29.1	31	29.6
November	68	75.1	54.3	29.1	31	29.7
December	65.2	78.5	56.8	29.1	31	29.6
Total	**874.6**	**939.4**				

Table 7.7 next indicates the amount of make-up water required to top each swimming pool and provides an indication on the amount of heat loss incurred from evaporation; however, this loss will be converted to sensible heat gain by the pool air. EnergyPlus provides some useful information to gain a better understating of the underlying results (heat losses and gains) caused by this phenomenon arising in swimming pool halls.

Table 7.7:
Simulated Make-up Water and Evaporation Heat Loss

	Lap pool		Warm pool		Kids' pool	
	make-up water (kL)	Evaporation heat loss (MWh)	make-up water (kL)	Evaporation heat loss (MWh)	make-up water (kL)	Evaporation heat loss (MWh)
January	18.86	12.7	15.92	10.7	2.59	1.7
February	16.23	10.9	14.01	9.4	2.28	1.5
March	21.84	14.7	17.02	11.4	2.95	2
April	21.41	14.4	16.64	11.2	2.79	1.9
May	22.18	14.8	17.42	11.7	2.95	2
June	24.01	16.1	18	12.1	3.06	2.1
July	25.08	16.8	18.61	12.4	3.20	2.1
August	25.52	17.1	18.77	12.6	3.27	2.2
September	24.30	16.3	17.96	12	3.08	2.1
October	22.89	15.4	17.51	11.7	3	2
November	21.49	14.4	16.62	11.2	2.90	1.9
December	21.14	14.2	16.77	11.2	2.81	1.9
Total	**264.9**	**177.8**	**205.3**	**137.7**	**34.9**	**23.4**

The simulation results also provide the total amount of water used for domestic hot water. Hence, the total amount of that as well as the make-up water for the swimming pools is approximately 4,617 kL, while the measured total water use for the sample aquatic centre is 10,051 kL. Evidently, there is a big discrepancy between the measured total water consumption and the simulated total water consumption, mainly because only hot-water consumption is included within the simulation results. Conversely, cold-water consumption for toilet flushing, kitchen use and backwash water use are not included and need to be estimated at a later stage for overall comparison. Overall, the simulation results for the selected aquatic centre have been within acceptable limits, but require calibration to match actual consumptions. As suggested in the methodology, a manual calibration method based on an iterative approach will be used and compared to monthly utility data, and subsequently measured using statistical indices. Validation of the evaporation rate will also be performed using manual calculations. As such, Section 7.4.1 will describe the several steps for calibrating the centre's simulation.

7.4.1 Calibration

The calibration process adjusts the simulation inputs so that the simulated energy consumption closely matches the measured energy consumption. Both MBE and CV(RMSE) factors are used as statistical indices (Table 7.8) to evaluate whether a model can be considered fully calibrated. These measures have been recommended by three main international bodies, including ASHRAE, the IPMVP and within FEMP's M&V Guidelines.

Table 7.8:
All Relevant Statistical Indices Threshold Limits

Statistical indices	Monthly calibration		
	ASHRAE Guideline 14	IPMVP	FEMP
MBE	+–5%	+–20%	+–5%
CV(RMSE)	15%		15%

These indices are then calculated using Equations 16, 17, 18 and 19.

$$\textbf{MBE (\%)} = \frac{\sum period(\text{S}-\text{M})\text{interval}}{\sum period\ \text{M interval}}\ x\ 100\% \qquad (16)$$

$$\textbf{A}_{\textbf{period}} = \frac{\sum period\text{M interval}}{\text{N interval}} \qquad (17)$$

$$\textbf{RMSE}_{\textbf{period}} = \sqrt{\frac{\sum(S-M)^{2}\text{interval}}{\text{N interval}}} \qquad (18)$$

$$\textbf{CV(RMSE}_{\textbf{period}}\textbf{)} = = \frac{\textbf{RMSE period}}{\textbf{A period}}\ x\ 100\% \qquad (19)$$

Table 7.9 displays the comparison between measured energy use and the original simulation energy use. The energy use is split into two categories of electricity and gas, as they constitute the two main energy sources used in aquatic centres. No other fuel type such as diesel is used. Figures 7.14 and 7.15 next offer the comparison of actual and simulated energy, with both showing similar trends. However, it appears the simulated electricity use is much higher than the measured electricity use, while the reverse is noticed with gas consumption.

Table 7.9:
Comparison Between Measured Data (Utility Bills) and Simulation Results

	Electricity (MWh)		Gas (MWh)	
	measured	Simulated	measured	Simulated
January	116.7	174.4	162.5	142.7
February	118.8	157.2	165.3	138.2
March	118.8	171.6	201.9	169.1
April	113.6	158.8	202.8	183
May	118.8	165.4	233.9	200.9
June	113.9	158.7	250.6	212.6
July	122.3	161.8	281.9	224.4
August	126.1	164.7	278.1	213
September	109.9	158.1	234.4	199.5
October	126.4	165.2	241.7	190.3
November	113.1	161.6	216.1	173.7
December	110.5	167.2	196.9	171.3
Total	**1,408.8**	**1,964.5**	**2,666.1**	**2,219**

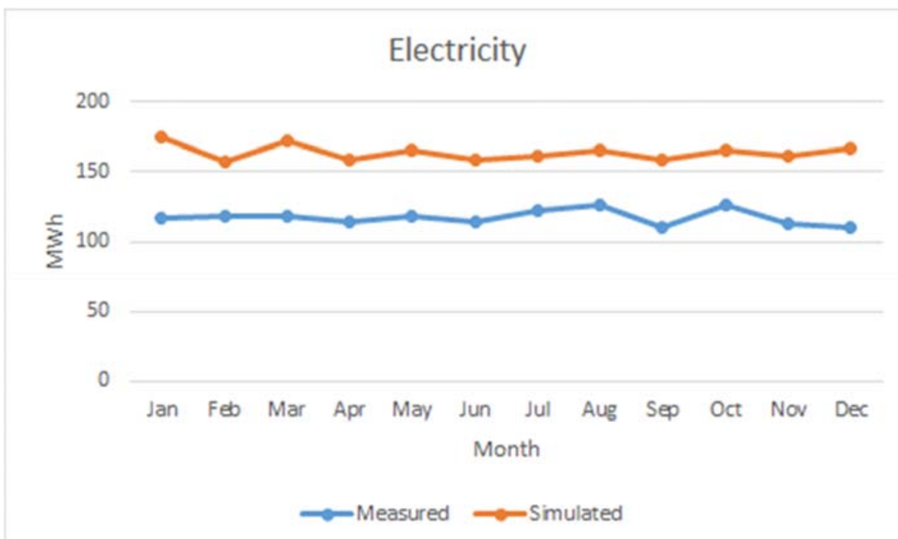


Figure 7.14. Comparison between measured and original simulated electricity use.

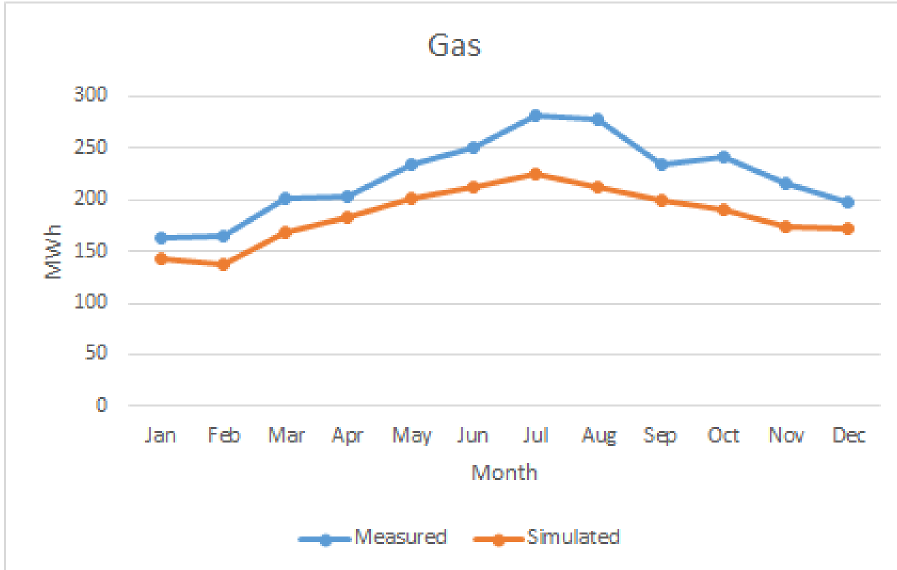


Figure 7.15. Comparison between measured and original simulated gas use.

Both the MBE and CV(RMSE) for the original simulation results have been calculated and shown in Table 7.10. The two statistical indices indicate that both the simulated electricity use and the gas use are not within the required range for the model to be considered calibrated. Indeed, this process was undertaken by manually adjusting simulation inputs such as boiler pump efficiencies, lighting levels and lighting schedules (see Section 7.4.1.1 for the first round of calibration).

Table 7.10:
Statistical Indices for Original Simulation Results

Statistical indices	Monthly calibration	
	Electricity	Gas
MBE	39.4%	16.8%
CV(RMSE)	39.8%	17.8%

7.4.1.1 First Round of Calibration

Based on the statistical indices, electricity use bears the largest difference between simulated and measured data. Table 7.11 shows the various end uses examined to gain an insight into which areas require adjustment. As electricity consumption consists of air cooling, lighting, equipment and pumps, the percentage of which for the former appears reasonable and within the limits of the energy-use breakdown provided by Sydney Water (2011); this is likewise the case for both equipment and pumps. Its 27% of total energy use for an aquatic centre seems excessive based on Sydney Water's (2011) findings, which otherwise estimated it as low as 3%.

Conversely, gas is used for pool hall air and water heating, and domestic hot water. Air-heating energy is predominately consumed by swimming pool halls, which employ a packaged air-heating system coupled with gas boilers. As such, the domestic hot-water system energy use appears reasonable based on previous literature as well as Sydney Water's (2011) estimate of 6% total energy use (Figure 7.16). Hence, according to Table 7.11, the simulated domestic hot-water energy use is around 8% of the total simulated energy use.

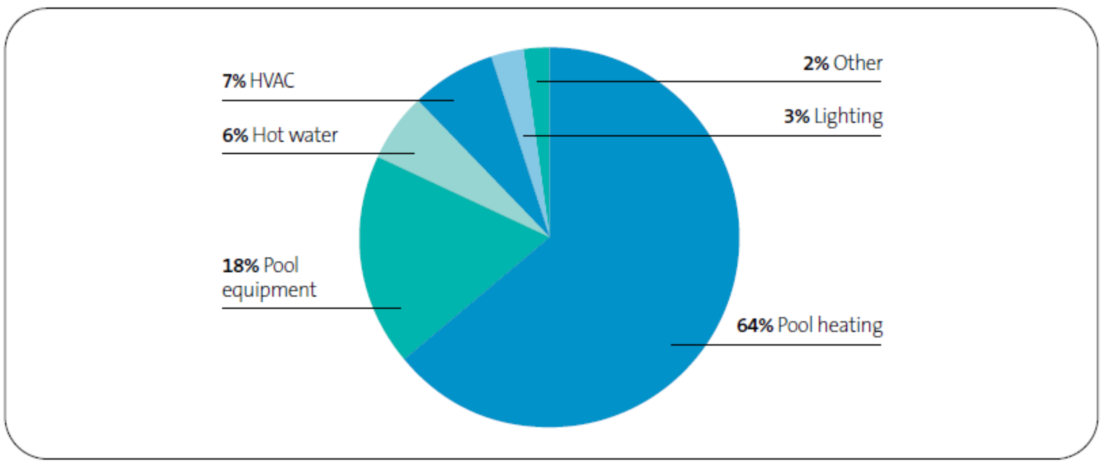


Figure 7.16. Energy use of a typical aquatic centre (Sydney Water 2011).

Table 7.11:
Simulated Results of Breakdown for Aquatic Centres' Annual End Uses

	Air heating (MWh)	Air cooling (MWh)	Pool-water heating (MWh)	Lighting (MWh)	Domestic hot water (MWh)	Equipment and pump (MWh)
Total	924.2	346.4	939.5	1,199.9	355	419.2
Percentage	22%	8%	23%	27%	8%	10%

Therefore, based on this comparison, the main end uses that require adjustment are lighting energy use, and pool air and water heating. First, lighting levels were adjusted in pool halls and stadium areas, as a 10 W for each square metre of a stadium was, in actuality, excessive once the overall figures were examined. As observed during the site visits, the swimming pool hall has access to natural daylight through a large skylight in its centre, in addition to not fully utilising all the lights at all times. The stadium also has some skylights, which provide some daylight penetration. Therefore, lighting levels in those areas were reduced by 10% within the simulation.

Next, the lighting occupancy schedule entered in DesignBuilder was based on an on–off schedule (night and day), which was assumed to remain unchanged year round. In reality, the lighting schedule varies constantly, especially when daylight is available—indeed, this can extend up to 7.00 pm in the evenings during summer in Victoria, which is particularly pertinent given that daylight sensors are also installed throughout the sample centre. It is likewise expected that both the winter months and daylight saving periods can cause additional variations to such energy use. Therefore, the lighting schedule was adjusted by reducing the number of hours artificial lighting is required during the day.

In addition, both boiler efficiency and pools' packaged air conditioning were reduced by 5% to account for the simulation's partiality to always run systems at optimum levels. Hence, in combination with Raypack boilers' apparent 80% efficiency rate, this may prove problematic and, therefore, unrealistic to systems that otherwise run less efficiently than stated in their technical manuals, especially at part load and this can be caused by several factors such as aged boiler, ambient temperature of areas surrounding the distribution system and excessive losses through old pipes and ducts. Using nominal values stated by the supplier as boiler's efficiency in simulations might not represent the actual performance of the boiler. Kenna and Bannister (2009) demonstrated a reduction of at least 15% in boiler efficiency using simulations and manual calculations compared to the nominal efficiency values from the supplier.

Table 7.12 shows the simulated electricity and gas use after the first round of calibration. As such, the improvement between simulated and measured data can be observed. Figure 7.17 next shows the trend lines for electricity energy use; evidently, the gap between the measured and simulated variables has been reduced considerably when compared to Figure 7.14. Further, Figure 7.18 presents similar results to electricity energy use, in that the gap between measured and simulated gas energy use also appears to have narrowed. It is positive to observe the curve of the two gas trend lines, as this signals their similarity.

Table 7.12:
Comparison Between Measured Data and Simulated Data for First-round Calibration

	Electricity (MWh)		Gas (MWh)	
	measured	Simulated	measured	Simulated
January	116.7	136.8	162.5	152.2
February	118.8	123	165.3	147.8
March	118.8	132.8	201.9	181.7
April	113.6	121.9	202.8	198.3
May	118.8	126	233.9	218.9
June	113.9	120.7	250.6	231.9
July	122.3	123.3	281.9	245
August	126.1	125.3	278.1	232.2
September	109.9	120.6	234.4	216.4
October	126.4	126.5	241.7	205.6
November	113.1	124	216.1	186.9
December	110.5	129.5	196.9	183.9
Total	**1,408.8**	**1,510.3**	**2,666.1**	**2,401**

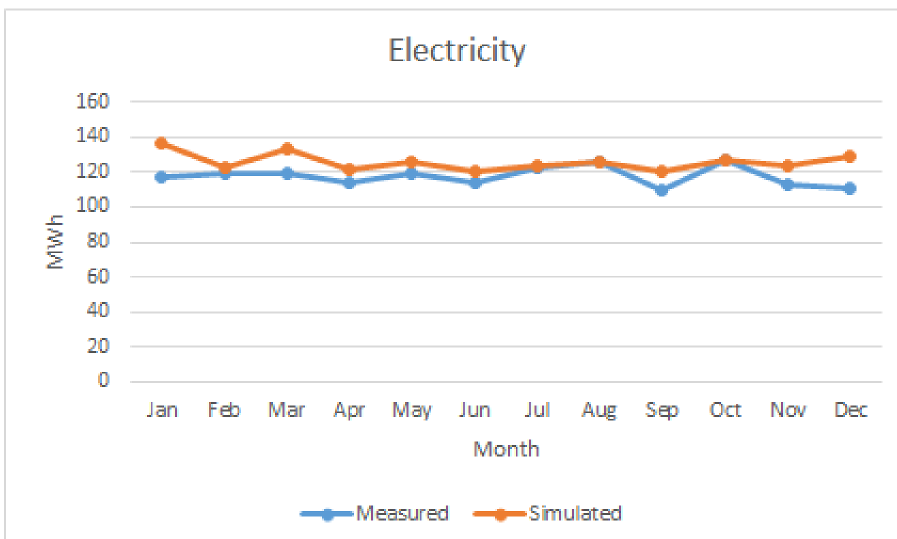


Figure 7.17. Comparison chart between measured and simulated electricity use (first-round calibration).

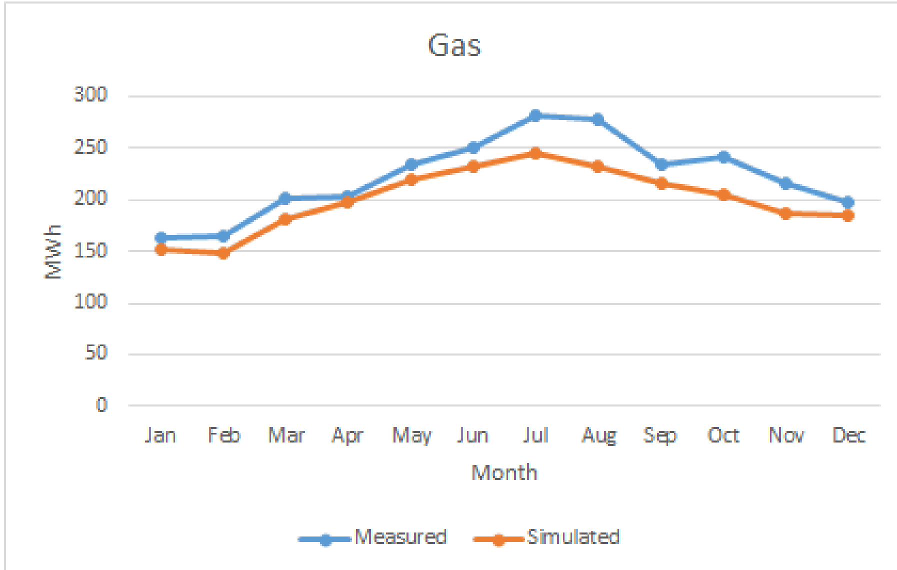


Figure 7.18. Comparison chart between measured and simulated gas use (first-round calibration).

Table 7.13 provides the two statistical indices after the first round of calibration. Evidently, a significant improvement with both MBE and CV(RMSE) is apparent when compared to Table 7.10. While MBE is very close to the required limits (+–5%), the simulation results are already within that of CV(RMSE), which must be below 15%. However, for the simulation to be considered fully calibrated, both MBE and CV(RMSE) must be between the thresholds. Therefore, a second round of calibration was required.

Table 7.13:
Statistical Indices of Simulation Results for First-round Calibration

Statistical indices	Monthly calibration	
	Electricity	Gas
MBE	7.3%	5.4%
CV(RMSE)	9.2%	7%

7.4.1.2 Second Round of Calibration

The first round of calibration addressed several issues, which, indeed, bore significant improvements; however, the simulation results still did not match the measured consumption required by the statistical indices. The boiler efficiencies were reduced by only 5%, with the lighting levels and schedules for both swimming pool halls and stadiums adjusted thereafter. Nonetheless, more are required to further improve the simulation results. First, lighting levels can be additionally adjusted in the entry foyer and cafe area, which has access to natural daylight through a large skylight in the middle of the roof. Likewise, the entry has a large area of glazing that permits a reasonable amount of daylight penetration, including the addition of daylight sensors. Therefore, lighting levels in this area were reduced within the simulation by decreasing the number of hours for daytime artificial lighting.

Second, the energy required for various equipment can be adjusted. This usage variable was an estimate based on the number of electrical equipment ranging from computers, fridges, printers and gymnasium gear such as treadmills and electric bikes. As it is difficult to gain access to or monitor the measured energy use (electricity) of these utilities, the required electricity was, thus, adjusted by reducing the overall wattage by 10%. Next, occupancies within the swimming pool hall and swimming pools were adjusted, as they affect heat gain and loss. For example, when analysing the simulated results of the swimming pool, it was noted that up to 300 people were always in the lap pool, but this was changed to a more reasonable number of 25 people at one time. Additionally, the insulation value used in the roof was R-3.5. However, upon reviewing the data collected from the site visits, it was noticed that the flat metal roof and the dome-shaped roof would probably only fit roof insulation blankets, which otherwise have an R value of around 1.8. Therefore, the insulation R value within the simulation was reduced. Finally, the boiler efficiency for pool-water heating was next adjusted by reducing its efficiency by 5%. Hence, their efficiency upon revision became 70%.

Importantly, neither the fans nor pumps levels for the HVAC system were adjusted, as insufficient information was available; additionally, the boiler pumps' energy use was not as significant as other end users. As such, Table 7.14 shows the simulated electricity and gas use after the second round of calibration. It is now apparent that the total simulated electricity use for the year (1,409.2 MWh) is close to the total simulated electricity use (1,408.8 MWh), with the same result being obtained for gas extremities (total simulated gas use 2,635.8 MWh against the total measured 2,666.1 MWh).

Figure 7.19 next shows the trend lines for both measured and simulated electricity energy use. There is a small improvement when compared to Figure 7.17, with approximately four months in which measured electricity use is slightly higher than the simulated electricity. However, on average both trend lines are closely matched. Further, Figure 7.20 shows the trend lines for both simulated and measured gas use, which, upon comparing to Figure 7.18, bears a better outcome according to their similarly patterned curve. Indeed, the statistical indices are subsequently used to test the second-round calibration level.

Table 7.14:
Comparison Between Measured Data and Simulated Data Following Second-round Calibration

	Electricity (MWh)		Gas (MWh)	
	measured	Simulated	measured	Simulated
January	116.7	129.3	162.5	173.1
February	118.8	116.1	165.3	163.6
March	118.8	124.6	201.9	201.7
April	113.6	113.4	202.8	214.4
May	118.8	116.9	233.9	241.9
June	113.9	111.8	250.6	255
July	122.3	114.3	281.9	265
August	126.1	116.1	278.1	255.3
September	109.9	111.9	234.4	235.8
October	126.4	117.6	241.7	224.7
November	113.1	115.7	216.1	205.8
December	110.5	121.4	196.9	199.4
Total	**1,408.8**	**1,409.2**	**2,666.1**	**2,635.8**

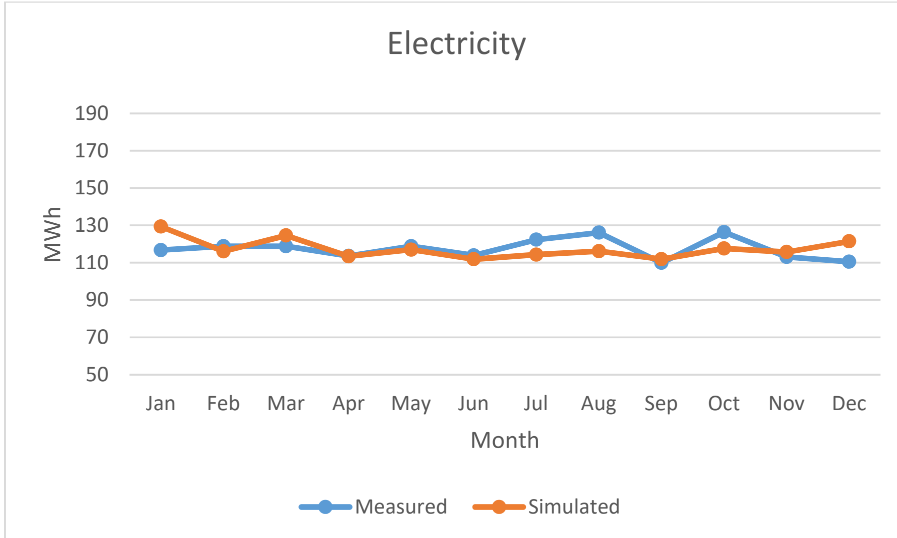


Figure 7.19. Comparison chart between measured and simulated electricity use (second-round calibration).

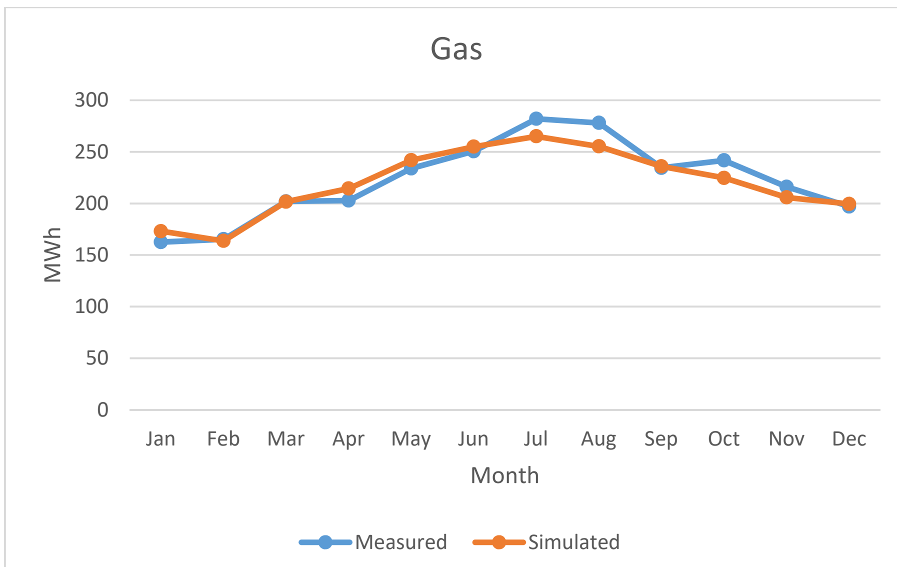


Figure 7.20. Comparison chart between measured simulated gas use (second-round calibration).

Table 7.15 indicates that the MBE and CV(RMSE) of the second-round calibrated simulation results are within the range required by ASHRAE, IPMVP and FEMP guidelines. This confirms that the simulation model has successfully calibrated.

Table 7.15:
Statistical Indices for Simulation Results Following Second-round Calibration

Statistical indices	Monthly calibration	
	Electricity	Gas
MBE	4.8%	4%
CV(RMSE)	5.9%	5%

The calibrated model can now be used in further analyses, such as parametric studies. It has been identified during the calibration process that a weather or season dependent variable is present which is the effect of evaporation occurring within the swimming pool hall. Aquatic centres are different to other types of buildings—in that significant evaporation continuously occurs within its swimming pool halls—the model evaporation rate must again be manually validated. As such, the evaporation heat loss and the amount of make-up water to replace evaporation, obtained from the simulated model, was compared to manual calculation.

7.4.2 Validating Evaporation

Evaporation is a complex phenomenon arising within the swimming pool halls of aquatic centres that can have a considerable effect on their energy performance and water use. Validating evaporation for the simulation model is also an important part of the calibration process, which was performed as such:

1. Evaporation heat loss and make-up water data were obtained from the EnergyPlus simulation model.
2. Manual calculations of evaporation were made using the ASHRAE formula.
3. The results helped compare monthly average evaporation heat loss and make-up water data.

Table 7.16 provides the monthly simulated evaporation heat loss and make-up water for all three sample pools. Expectedly, the small comparative difference in figures to the original simulation results confirms that the software indeed considers additional factors such as sensible heat gain from other variables (i.e., occupants and artificial lighting energy). For example, in observing that 254 kL of water is evaporated from the lap pool in a year and 170.4 MWh of heat is also lost from warm water due to evaporation, it appears this additional amount of energy must be used to keep the lap pool water at the desired temperature. As such, the next step of the validation process was to perform the manual calculation.

Table 7.16:
Calibrated Simulation Make-up Water and Evaporation Heat Loss

	Lap pool		Warm pool		Kids' pool	
	make-up water (kL)	Evaporation heat loss (MWh)	make-up water (kL)	Evaporation heat loss (MWh)	make-up water (kL)	Evaporation heat loss (MWh)
January	18.5	12.4	15.2	10.2	1.9	1.3
February	15.7	10.6	13.3	8.9	1.6	1.1
March	20.8	14	16.1	10.8	2.2	1.5
April	20.4	13.7	15.7	10.5	2.1	1.4
May	21.2	14.3	16.3	10.9	2.2	1.5
June	22.9	15.4	16.7	11.2	2.4	1.6
July	23.9	16.1	17.4	11.6	2.5	1.7
August	24.3	16.3	17.5	11.8	2.6	1.7
September	23.2	15.6	16.8	11.3	2.4	1.6
October	21.8	14.6	16.5	11.1	2.3	1.5
November	20.6	13.8	15.8	10.6	2.2	1.4
December	20.5	13.7	15.9	10.7	2.1	1.4
Total	**253.8**	**170.4**	**193.2**	**129.6**	**26.5**	**17.9**

As stated in Chapter 4, the EnergyPlus evaporation formula is derived from the ASHRAE method. Both the EnergyPlus evaporation and ASHRAE guidelines suggests an activity factor of '1' for a public pool. However, to make a fairer comparison, the activity factor when performing the manual calculation using ASHRAE's method should be reduced so that the unoccupied period (night-time) is also considered. The evaporation comparison was created only for the lap pool to better understand the difference between the manual calculation and the simulated results. Hence, the manual calculation for the evaporation rate and evaporation heat loss (lap pool) is as follows:

P_w = Water vapour saturation pressure (Engineering Toolbox 2015)

$P_w = e^{(77.345+0.0057T-725/T)}/T^{8.2}$

e = The constant 2.718

T = Dry-bulb temperature at the moist air

Pool-water temperature = 29 ^{o}C

$P^w = e^{(77.375+0.0057(273+29)-7235 / (273+29)} / (273 + 29)^{8.2} = 3.979$ kPa

P_a = Saturation vapour saturation at room dew point (Engineering Toolbox 2015)

Room temperature = 31 ^oC

Dew point at 60% relative humidity = 22.3 ^oC

$P_a = e^{(77.375+0.0057(273+22.3)-7235 / (273+22.3)}/(273 + 22.3)^{8.2} = 2.658$ kPa

ASHRAE (1995)

w_p = A/y (Pw – Pa)(0.089 + 0.0785V) x activity factor

w_p = Evaporation of water (kg/s)

A = Area of pool surface

y = Latent heat required to change water to vapour at surface water temperature = 2,257 (kJ/kg)

AF = Activity factor 0.5 was chosen to account for a half day; this becomes zero at night

W_p = 440/2,257 (3.979 – 2.658) (0.089 + 0.0782 x 0.01) x 0.5

= 0.00873 kg/s = 31.43 kg/hr

= 22,945 kg of water

Water evaporated each month (make-up water) = 22.9 kL

Evaporation heat loss = 51,786,865 kJ = 14.5 MWh

Table 7.17 shows the comparison of evaporation heat loss and the amount of make-up water between the simulated results and manual calculation. Since monthly data could be obtained from EnergyPlus, a monthly average of both the evaporation heat loss and the amount of make-up water was next calculated. It can be observed that both the figures obtained from the simulation model and the manual calculation are close. For evaporation heat loss, the simulation results state an average 14.2 MWh monthly loss compared to the 14.5 MWh variable obtained from manual calculation. The amount of make-up water for both situations is also close at 21.2 kL compared to 22.9 kL, respectively. Based on this validation process, it is apparent that the simulation model provides reasonable results in terms of evaporation when compared to manual calculation.

Table 7.17:
Evaporation Heat Loss Comparison (Lap Pool)

Lap pool	Simulated results	Manual calculation
Make-up water (kL) (monthly)	21.2 kL (average)	22.9 kL
Evaporation heat loss (MWh) (monthly)	14.2 MWh (average)	14.5 MWh

Additionally, the evaporation heat loss and make-up water volume were also compared using uniform activity level throughout the whole day (night and day). In other words, an activity factor of 1 was used in both EnergyPlus and ASHRAE calculation and this comparison is shown in Table 7.18 below.

Table 7.18:
Evaporation Heat Loss Comparison at Uniform Activity Level (Lap Pool)

Lap pool	Simulated results	Manual calculation
Make-up water (kL) (monthly)	43.4 kL (Average)	45.9 kL
Evaporation heat loss (MWh) (monthly)	28.2 MWh (Average)	28.8 MWh

Both the calibration and validation processes have verified and improved the accuracy of the simulation model in relation to the actual aquatic centres, thus, granting it a high level of certainty. As such, this newly validated model can now be used for parametric studies to provide further understanding about the energy performance and water use of aquatic centres. However, details on each element in the simulation still require further extrapolation before more analysis is done.

7.4.3 Discussion of Energy Simulation Results

As Research Question 5 queries the features that can influence both energy and water usage in aquatic centres, it has since clarified that simulation provides a possible solution. Nonetheless, it is plagued by multiple complexities due to the limited number of studies available on this type of building, the limited availability of software capable of simulating the evaporation phenomenon arising within swimming pool halls, and the general lack of sufficient information on relevant architectural and electromechanical data. Despite these drawbacks and following a number of iterations, a successful simulation model of an aquatic centre was still created. This study then provided a detailed procedure of how to model an aquatic centre that can be followed by any type or size of facility, thus, making energy- and water-use investigation easier. As such, this section will build upon that knowledge and present all the relevant energy data, including a breakdown of end-use energy consumption.

Table 7.19 lists the monthly energy use for air heating, cooling, pool-water heating, lighting, domestic hot water, and equipment and pumps. This table shows the final result after the simulation model has been successfully calibrated and validated. Figures 7.21 and 7.22 then provide the percentage of each end use as well as the energy sources. Evidently, the swimming pool hall consumes around 56% of the total energy use, as the majority of the centre's air heating is used in this space and to heat the pool water. The lighting energy use is also higher than some literature claim, but this is due to the energy use for the stadium, which has a large floor area. The percentages for domestic hot water, cooling, and equipment and pumps are likewise similar to the percentages displayed in Figure 7.16 (i.e., Sydney Water's end-use energy breakdown of a typical aquatic centre).

Table 7.19:
End Use Energy Use After Second-round Calibration

	Air heating (MWh)	Air cooling (MWh)	Pool-water heating (MWh)	Lighting (MWh)	Domestic hot water (MWh)	Equipment and pumps (MWh)
January	66.1	37.4	82.7	58.5	24.2	33.4
February	59.1	32.9	82.7	52.9	21.7	30.2
March	77.9	31.9	96.8	59.2	26.9	33.4
April	89.3	25.3	97.2	55.8	27.9	32.3
May	105.9	24.3	102.7	59.2	33.4	33.4
June	113.9	22.4	103.3	57.1	37.6	32.3
July	118.5	22.9	107.3	57.9	39.2	33.4
August	111.9	23.5	106.4	59.2	36.9	33.4
September	102.1	23.1	100.4	56.4	33.4	32.3
October	93.6	25.6	100.6	58.5	30.7	33.4
November	82.6	26.3	94.9	57.1	28.2	32.3
December	76.9	30.2	96.7	57.8	25.8	33.4
Total	**1,097.8**	**325.9**	**1,171.8**	**689.8**	**365.9**	**393.4**
Percentage	**27%**	**8%**	**29%**	**17%**	**9%**	**10%**

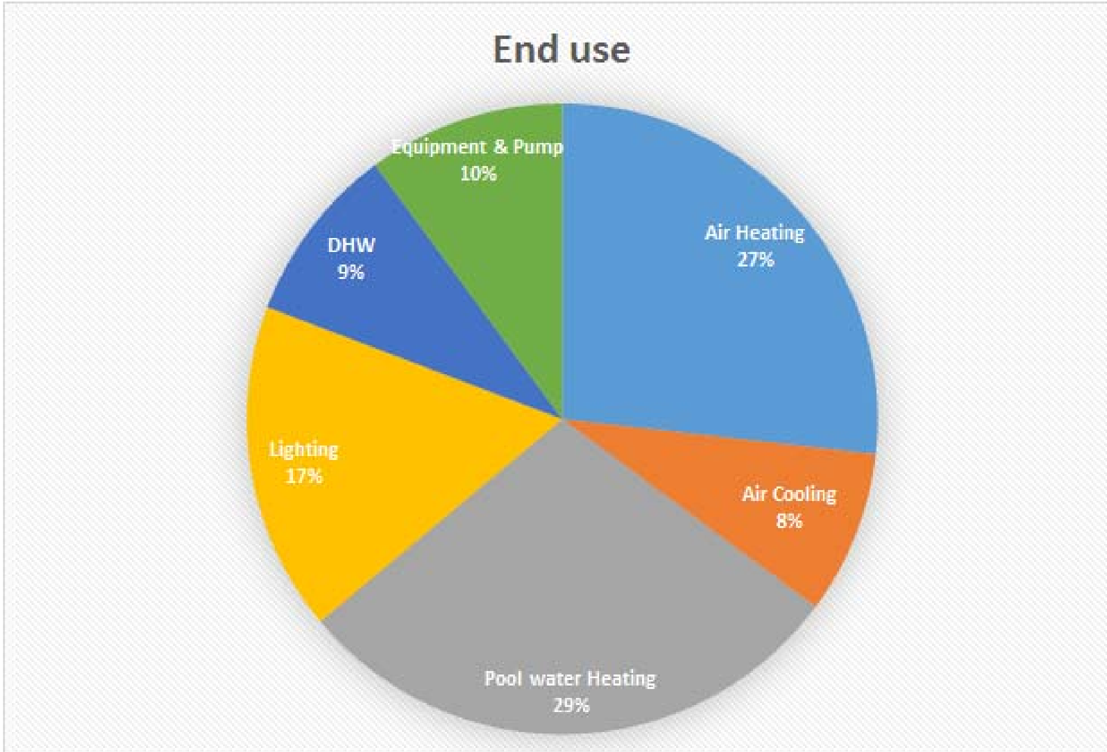


Figure 7.21. Breakdown energy end use of the simulation model.

Figure 7.22 shows the percentage of the energy-source breakdown. Upon reviewing the literature, total gas energy use is usually significantly higher than total electricity use due to pool-water heating and air heating, which both use gas as a PE source. Based on the data collected, the average proportion of gas and electricity usage for aquatic centres in Victoria is approximately 78% and 22%, respectively, while the proportion for the simulation model appears at 66% and 34%. This indicates a correct trend for the desired energy-source breakdown, but a slightly high total electricity use, which is likely due to stadium lighting. As shown in Figure 7.23, removing this factor changes the proportion of gas and electricity usage for the simulation model to 73% and 27%, as expected.

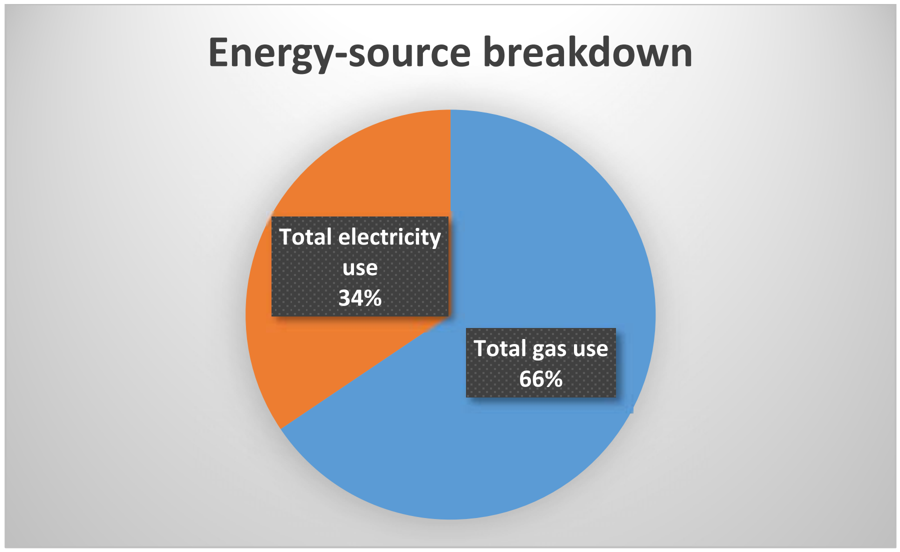


Figure 7.22. Energy-source (site energy) breakdown of the simulation model.

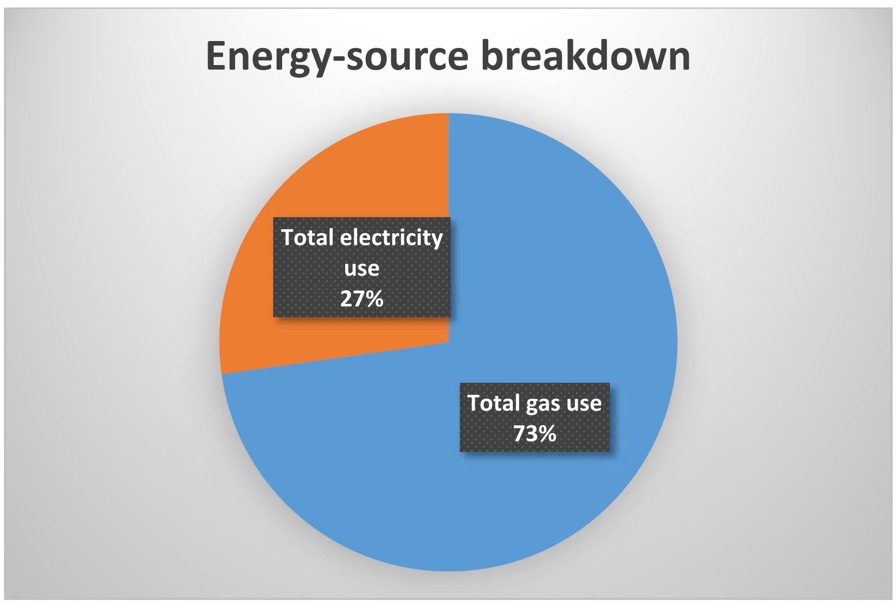


Figure 7.23. Energy-source (site energy) breakdown of the simulation model (without stadium lighting energy use).

Overall, the simulation model has produced results comparable to the literature. This model can now be used for further analysis (such as parametric studies) with several other variables. Section 7.4.4 will subsequently examine the water use of the sample aquatic centre based on this simulation.

7.4.4 Discussion of Water Simulation Results

Estimating the entire water use of an aquatic centre is harder to gauge than energy use, as no software is available to model an entire water cycle. Both cold- and hot-water use must also be considered, the former for toilet flushing, backwash and make-up water, and irrigation, and the latter for domestic hot-water consumption. Further, EnergyPlus will provide information on only two variables: the amount of make-up water caused by evaporation, and the amount of domestic hot water used. Table 7.20 shows the monthly water use of the simulation model for the make-up water and domestic hot water.

Table 7.20:
Simulated Make-up Water and Domestic Hot-water Volume

	Simulated make-up water (kL)	Simulated domestic hot water (kL)
January	35.6	348.8
February	30.6	315.1
March	39.1	350.2
April	38.2	334.9
May	39.7	350.7
June	42	338.3
July	43.8	346.8
August	44.4	350.6
September	42.4	336.3
October	40.6	348.8
November	38.6	338.8
December	38.5	346.3
Total	**473.5**	**4,105.7**

Evidently, Table 7.20 implies that no calibration processes involving water use occurred for the simulation model. This is because:

1. no software has been identified to model the entire water cycle of an aquatic centre
2. water bills are released quarterly, therefore, cancelling out the option of monthly calibration
3. calibrating procedures and guidelines are mainly related to energy use
4. water use has a high level of fluctuation (as it is mostly related to occupancy, which is not a fixed variable) and uncertainty, due to leaks, amount of splashing in pools and the amount of water used for irrigation
5. there is a lack of studies regarding estimating or simulating water usage in aquatic centres or for swimming pools

6. the only variable that could have been adjusted is domestic hot-water use but, unfortunately, such data was not available, as the sample centre lacked sub-meters.

However, the make-up water volumes have been already validated using both manual calculation and the ASHRAE formula. As such, this method produced simulated results for the make-up water volume that were close to the actual values. Domestic hot-water consumption produced by EnergyPlus was based on occupancy rate and scheduling entered as simulation inputs, which included utilities such as showers, hand basins and kitchen consumption throughout the sample aquatic centre. Estimating the total water use of the simulation model is also based on data obtained from the literature, occupancy data and swimming pool guidelines, which were subsequently added to Microsoft Excel.

Table 7.21 shows the estimated water use of the aquatic centre using simulated data and manual calculations based on occupancy rate, data collected and the researcher's assumptions. Make-up water and domestic hot-water quantities were obtained from EnergyPlus, while toilet flushing water usage is based on the efficiency of a toilet and the likely numbers of people using the toilets according to actual occupancy rate and frequency. Backwash water usage is based on the type of filters used, which determine the average volume of backwash water used in each cycle, while the average volume of backwash water is based on the literature and the frequency based on the data collected. The other water uses due to splashing (calculated based on the number of bathers obtained from the data collected), leaks and cold tap use (including irrigation) are estimates based on the researcher's assumptions and from past studies (Sydney Water 2011). Figure 7.24 shows the breakdown of the water use from Table 7.21 for the simulation model; evidently, the estimated and simulated water use is 10,258 kL and the measured water use is 10,051 kL.

Table 7.21:
Estimated Water Usage

End use	Details	Usage	Occupancy	Frequency	kL/day	kL/year
Make-up water (EnergyPlus)						474
Domestic hot water (EnergyPlus)						4,106
Toilet flushing		4.5 L	800 persons	1 flush/day	3.6	1,314
Backwashing	Pressure filter (lap Pool)	50 kL		3/month		1,800
	Pressure filter (warm pool)	30 kL		3/month		1,080
	Pressure filter (kids' pool)	20 kL		2/month		480
Others	Splashing	0.5 L	211,010 bathers	Yearly		105
	Leaks (estimated)					500
	Cold tap uses including irrigation (estimated)					400
Total						**10,258**

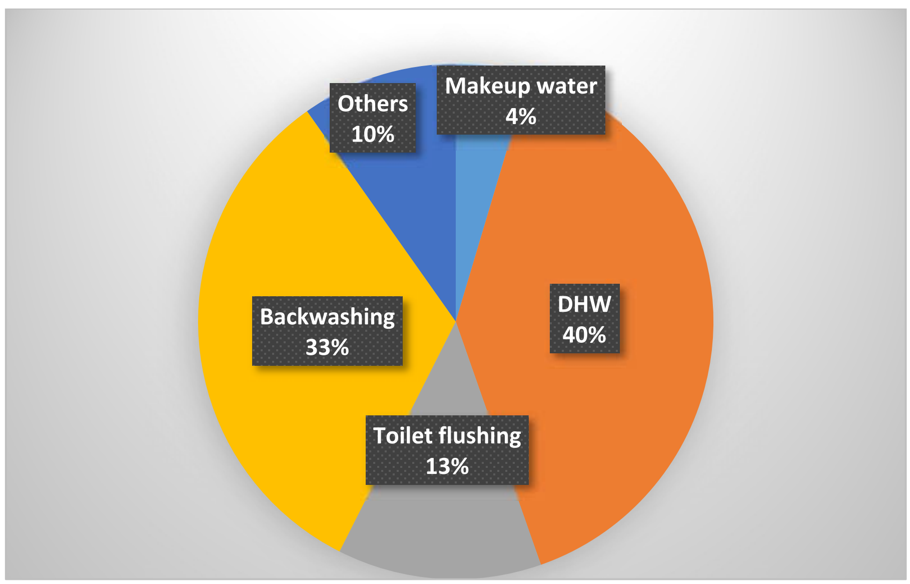


Figure 7.24. Breakdown of water end use for the sample aquatic centre.

The estimated water use for the selected aquatic centre is comprised of both simulated and calculated data. Assessing such data is harder to achieve when compared to energy use, but the analysis provided in this section has shown that it is possible. Upon demonstrating that energy- and water-use estimates for an aquatic centre are possible, Section 7.5 will next investigate through parametric study the determining features that make an aquatic centre more energy and water efficient.

7.5 Parametric Studies

Parametric studies have been undertaken to investigate how various features can improve an aquatic centre's energy and water efficiency. Earlier investigation did not provide clear indications as to what features achieved this feat. As such, a range of factors will, hence, be explored, including the effects of greenhouse gas emissions, as well as a range of architectural and electromechanical factors using building simulation. Cost analysis and life cycle analysis of the various features being investigated, are not within the scope of this research. However, Section 7.5.1 will first discuss how and if a parametric study of the selected aquatic centre can represent to other aquatic centres.

7.5.1 Comparing the Case Study Building with Other Samples

Selecting the aquatic centre as a case study for simulation was based on the availability of the required information (architectural and electromechanical) and on the cooperation of its manager to provide the necessary information; hence, it was not based on any specific selection criteria such as size, area or design. Some results obtained from the parametric studies may not have the same effect on the energy and water use of other aquatic centres due to architectural and electromechanical differences; however, the information obtained from the parametric studies can instead provide an understanding of how and to what extent specific features can affect the energy and water performance of such a building.

The aquatic centre has a gross floor area of 10,839 m^2, which is among the largest within both the collected sample and Australia, particularly as it includes a stadium with a gross floor area of 6,930 m^2. Excluding this space, the selected aquatic centre has a conditioned usable floor area of 3,232 m^2, which is within the range of the eight aquatic centres in the sample between 2,500 m^2 and 3,500 m^2.

In terms of amenities, it contains most of those also included at other aquatic centres, with three indoor swimming pools, a gymnasium, a cafe, a creche, program rooms and a stadium. Indeed, 52% of the surveyed aquatic centres have at least three indoor swimming pools and similar amenities (excluding a stadium) to the selected building. In terms of energy and water use, this aquatic centre is also classified as a medium energy user and a low water user.

Simulating others aquatic centres was not possible due to the lack of data required and the complexity of modelling such buildings, which can be time consuming. Nonetheless, Section 7.5.2 will discuss the results obtained from the parametric studies.

7.5.2 Pool-water Heating Systems (Boiler Type and Efficiency)

This part of the parametric study investigated the benefit of increasing the boiler efficiency for heating pool water by 5%, the effect of which on energy use is shown in Table 7.22. Another type of boiler that can be used is a condensing boiler, which is at least 25% more efficient to its non-condensing counterpart. This level of efficiency is achieved by using waste heat in the flue gas to preheat cold water entering the boiler, thus, capturing more heat from the outside rather than the inside of a room. As such, a condensing boiler captures 10–11% more heat and can reach up to 90% efficiency. Conversely, new non-condensing boilers can reach up to 78% efficiency, which is the percentage of heat that is actually usable.

Table 7.22:
Effects of Boiler Efficiency and Use of Condensing Boilers on Energy and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
Increasing boiler efficiency by 5%	3,954.7	2.3%	2,170.7	0.8%
Condensing boiler	3,751.7	7.3%	2,130.2	2.7%

7.5.3 Temperature Reductions

Both a pool-water's air and temperature within swimming pools and halls are usually high. The air temperature within the hall for the selected aquatic centre is maintained at 31 ^{o}C, while the water for both the lap pool and kids' pool are 29 ^{o}C and 31 ^{o}C for the warm water pool. Indeed, as high temperatures affect energy consumption, this set of simulation modules aimed to investigate different temperature combinations for both the air and pool water in the three sample pools.

Accordingly, a 1 °C reduction in both air and water temperatures may be possible while still remaining within the recommended guidelines. That is, ASHRAE (1999a) recommends air temperatures between 24–29 °C, and water temperatures between 24–29 °C for lap pools and 29–35 °C for both kids' and warm water pools. It is also recommended that the swimming pool hall air temperature is maintained at 1–2 °C above the water temperatures to reduce the evaporation rate and avoid chill effects on swimmers. Thus, a 1 °C reduction in both the swimming pool hall air and water temperature will hardly be noticed by either staff or bathers. Nonetheless, further reductions in each variable are simulated to examine the effects on energy use.

Another variation is to investigate the reduction of both the pool hall air temperature and pool-water temperatures during unoccupied periods when the centre is closed. The sample centre maintains the same temperatures throughout both periods. However, there exists the potential to significantly reduce both the pool hall and the pool temperatures at night and, thus, achieve significant energy reductions. Therefore, between 10 pm and 4 am (six hours), both the pool hall temperature and the pool-water temperature are reduced by 5 °C, but directly increased thereafter to allow sufficient time for both to reach the required levels before opening time. Accordingly, Table 7.23 shows the results of reducing these air and water temperatures.

Table 7.23:
Effects of Air and Water Temperature Reductions on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
Air temperature reduction (1 ºC) Water temperature reduction (1 ºC)	3,797.4	6.1%	2,138	2.3%
Air temperature reduction (1 ºC) Water temperature reduction (2 ºC)	3,669	9.6%	2,112.1	3.5%
Air temperature reduction (2 ºC) Water temperature reduction (2 ºC)	3,577	11.5%	2,096.7	4.2%
Night-time temperature reduction Air (5 ºC) Water (5 ºC)	3,651	9.5%	2,143	2.1%

7.5.4 LED Lighting

The selected aquatic centre uses several types of lighting systems throughout the building in addition to LEDs. Many areas including the stadium and swimming pool hall use halogen lights and metal halide lights, despite LEDs using far less wattage to run (3–4 times lower on average, depending on the application). The lighting density (W per m^2) in the stadium and its hall, the gym and the swimming pool hall have been reduced by 20%, which is a conservative figure for an LED upgrade. Its effect on the centre's energy consumption is only 3.5%, but is among the highest in relation to greenhouse gas emissions, according to the parametric studies. This is due to the high greenhouse gas emissions conversion factor for electricity in Victoria. As such, aquatic centres with less efficient baseline lighting or without LED technology would save more energy upon installation. Table 7.24 shows this subsequent reduction for total energy use.

Table 7.24:
Effects of LED Lighting on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
LED lighting	3,901.8	3.5%	1,990.1	9.1%

7.5.5 Pool Covers

Using pool covers has also been identified as an effective method to reduce evaporation rates (Sydney Water 2011). As such, a reduction in both energy and water use is typically noticed because the evaporative heat loss from swimming pools requires heating energy to maintain their temperature at the required level, while additional heating is nominated to warm the make-up water to replace that which is lost to evaporation. A subsequent reduction in water use is possible, as less water is evaporated from swimming pools; in turn, this reduces the amount of make-up water caused by evaporation. Accordingly, pool covers will be used on all swimming pools within the aquatic centres during the unoccupied periods when the aquatic centre is closed (between 10 pm and 5 am). The succeeding effects on energy use are shown in Table 7.25.

Table 7.25:
Effects of Using Pool Covers at Night on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
Pool covers	3,939	3%	2,167.5	1%

Table 7.26 provides more details on the effect of pool covers in relation to evaporative heat loss as well as make-up water volume. Although such covers incur a small impression on total energy consumption, their effect on both evaporative heat loss and evaporated water volume from the swimming pools is considerably greater at 25%.

Table 7.26:
Parametric Studies—Evaporative Heat Loss and Make-up Water

	Evaporative heat loss (MWh)	% Reduction	Make-up water (kL)	% Reduction
Existing condition	317.8		473	
Pool covers	237.5	25%	354	25%

7.5.6 Solar Pool-heating Systems

Based on the data collected, few aquatic centres used solar systems to heat their indoor swimming pools with the exclusion of one, which did so to heat its outdoor pools; as such, its energy use was among the lowest within the sample. For the study, EnergyPlus is used to model the effects of solar thermal energy on the total energy consumption for the selected aquatic centre. Modelling this system together with the indoor swimming pool is a complex task; for this reason, the solar system was only connected to the lap pool. As such, a brief description of the solar system created in the EnergyPlus is provided.

A schematic diagram of the solar pool-water heating system used in EnergyPlus (version 8.7) is demonstrated in Figure 7.25. There are two loops within the system: a collector loop and swimming pool loop. The former comprises a pump, a series of unglazed solar collectors and a storage tank, while the later comprises the swimming pool, storage tank and boiler or heat exchanger. The hot water produced by the collectors are stored in a 10 kL tank, and the system is operated and controlled by a differential thermostat. This will operate as long as it is within the tolerance set by the differential thermostat manager.

The collector pump will activate when the difference in the water temperature between the hot node and the cold node sensors are at least 3 °C, and will cease when the temperature difference is 1 °C. A high temperature turn-off manager is also used to stop the solar pump once the maximum water temperature of 82 °C is detected by a sensor located at the storage tank use outlet node. The storage tank is then linked to the swimming pool by the swimming pool loop, while a heat exchanger or boiler is located closest to the demand side of the swimming pool to ensure the water entering the swimming pool is at the required temperature, should insufficient hot water be produced by the solar water-heating system.

Two types of solar panels were tested: unglazed solar panels and glazed solar panels, with the total area of both collectors being approximately 704 m^2. Table 7.27 shows the effect on total energy use using unglazed and glazed solar panels to heat the swimming pool water. The results show that using these systems for pool water is effective but when investigating the energy specifically used to heat the swimming pools, the results offer more significant figures; essentially this is based on the fact that only one pool is connected to the solar-heating system. Nonetheless, there is a reduction of 25% (unglazed panels) and 55% (glazed panels) in the swimming pool's total water-heating energy.

Table 7.27:
Effects of Solar Pool-heating System on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
Unglazed solar panel	3,761.3	7%	2,145.5	2%
Glazed solar panel	3,423.7	15.4%	2,088.7	4.6%

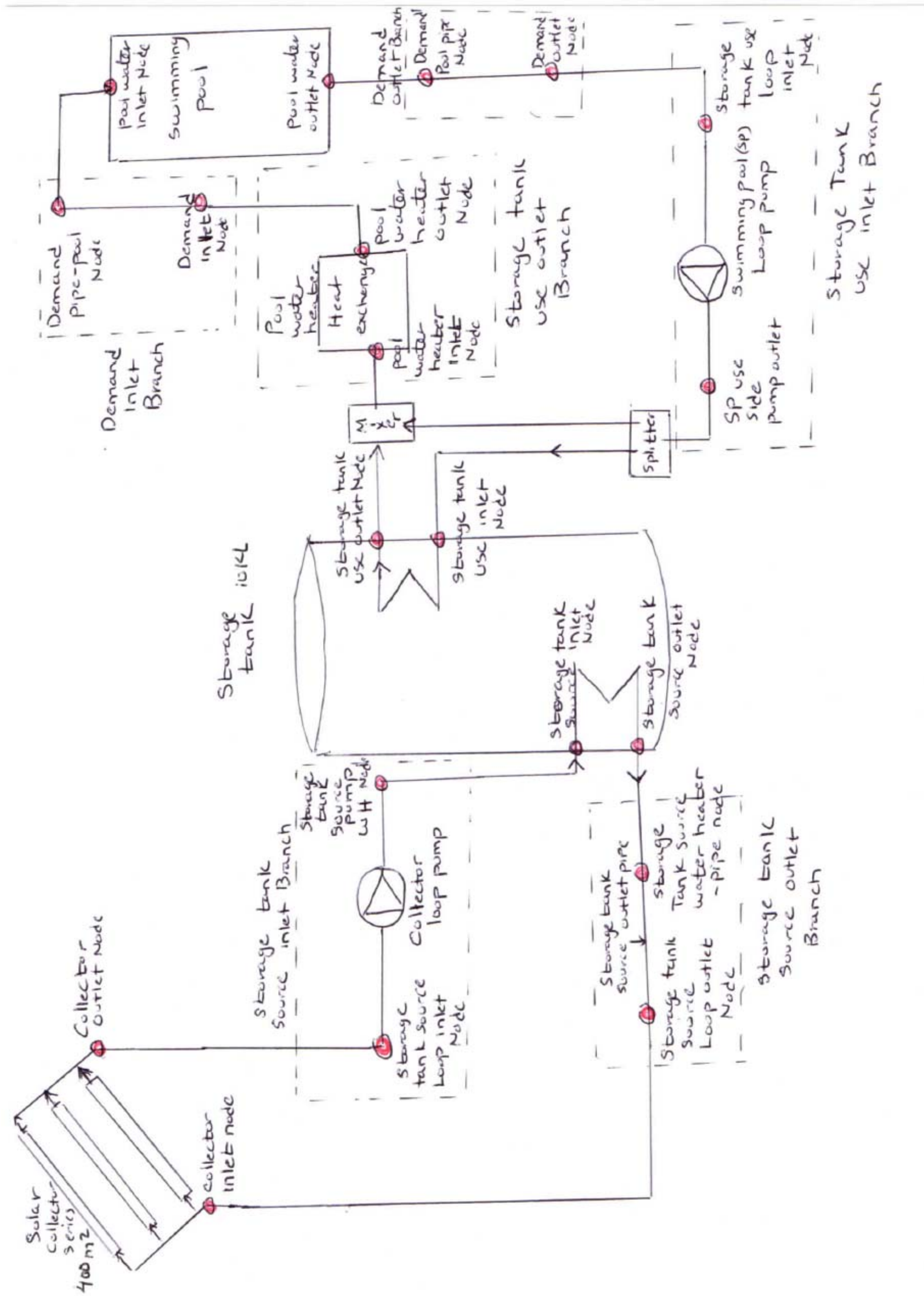


Figure 7.25: EnergyPlus solar-heating system, schematic design.

7.5.7 Solar Photovoltaic Systems

The simulation of a 100 kW solar PV system was undertaken to investigate its effect on the total energy use of the selected aquatic centre. Four aquatic centres within the sample have rooftop solar PV systems installed ranging from 40 kW to 100 kW. The majority of these aquatic centres are classified as medium energy users based on the energy benchmark undertaken; however, it is unclear whether their solar PV systems are beneficial. Based on the simulation results in Table 7.28, only a 3.5% reduction in total energy use was achieved by installing a 100 kW solar PV system, which is unparalleled by the comparatively higher 7.6% reduction in greenhouse gas emissions. When focusing on electricity use, an 11% reduction is achieved. The main constraint of installing such a large solar PV system is the availability of roof space to install all the solar panels. For a 100 kW system, and depending on the efficiency of the panels, around 360 panels and 650 m^2 of roof area are required. Indeed, the selected aquatic centre has a stadium large roof area, but this is not the case for all aquatic centres, which would otherwise struggle to install such a large system.

Table 7.28:
Effects of Solar PV Systems on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
100 kW solar PV system	3,901	3.5%	2,019	7.7%

7.5.8 Vertical-Axis Wind Turbine

Wind turbines have immense potential for integration in the built environment for power generation purposes. There has been a growing interest for vertical-axis wind turbines (VAWT) for power generation in built-up areas as they generally can run without much difficulty in turbulent wind environment and also in constant wind direction changes which are usually present in urban areas and on top of buildings (Sengupta, Biswas and Gupta 2017). The performance of wind turbines on the energy use of the aquatic centre was investigated. EnergyPlus has the capability to calculate the electrical power that a wind turbine system can produce. The model obtains the weather information from the weather data file in EnergyPlus and then determines the wind speed and air density at the specific height of the system. Four VAWTs (10 kW each) will be simultaneously modelled and it is assumed that they can be roof mounted on the stadium to reach an overall height of 10 metres. Table 7.29 shows the effect of the VAWTs on both total energy use and greenhouse gas emissions. The highest reduction in greenhouse gas emissions is observed amongst the features investigated.

Table 7.29:
Effects of Vertical-Axis Wind Turbines on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
VAWTs (4 x 10kW)	3,863.3	4.9%	1,974.5	9.8%

7.5.9 Insulation Upgrades

Although the selected aquatic centre did not have any data regarding the level of insulation within its external walls and roofs, low levels were included in the simulation model at R-2.0 and R-1.8, respectively. However, an upgrade was next applied to all external walls and roofs to better examine their effects on energy use; thus, they became R-2.7 and R-6.0, respectively. Table 7.30 shows the total energy of both the existing condition of the aquatic centre and the figures following the insulation upgrade. Evidently, a 6% reduction in total energy is achieved when applying higher levels of insulation to the external envelopes of the aquatic centre; in turn, this avoids almost 53.7 t of greenhouse gas emissions.

Table 7.30:
Estimated Effect of Insulation Upgrade on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
Insulation upgrade	3,807.4	5.9%	2,138.8	2.3%

Although the insulation upgrade can be cost effective but improve the energy efficiency of an aquatic centre, it is likewise difficult to increase in existing buildings due the restricted access to external walls and roof cavities. Nonetheless, maximising insulation levels above the National Construction Code (NCC) energy performance requirements (total R value of R-2.8 for external walls and R-3.5 for roofs) when constructing new aquatic centres can reduce their total energy use (NCC 2016).

Insulation upgrades should also be carefully installed due to issues with condensation, with some types of insulation performing better than others. For example, the closed cell structure of some foam insulation materials such as extruded polystyrene, phenolic, polyisocyanurate (PIR) and polyurethane (PUR) insulation are less susceptible to moisture (condensation) and water vapour ingress, thus, making them less prone to loss of insulative performance.

7.5.10 Materials and Solar Absorptance

Several aquatic centres have lightweight external walls and metal roofs, which are considered as having low thermal masses. This section will examine the effect of several materials such as high thermal mass materials (concrete and bricks) and those with high thermal resistance (autoclaved aerate concrete (ACC) blocks and expanded polystyrene (EPS) cladding) on the energy consumption of aquatic centres. The effect of low and high solar absorptance is also investigated.

The selected aquatic centre has both lightweight external walls (metal cladding) and high-density external walls (blockwork) as well as a metal roof. All the external walls and roofs are changed to different materials to determine their effect on energy use. Table 7.31 provides the results of using different materials for the external envelope of the aquatic centre, while Table 7.32 shows the difference in energy consumption between materials (external walls and roofs) with low and high solar absorptances.

Table 7.31:
Effects of Different Materials on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
Blockwork walls and concrete roof	4,012.2	0.8%	2,178.1	0.5%
100 mm concrete panel walls and concrete roof	4022.6	0.6%	2,180.5	0.4%
200 mm ACC block and concrete roof	4,002	1.1%	2,176.8	0.5%
100 mm EPS cladding and concrete roof	3,990.5	1.3%	2,174.9	0.6%

Table 7.32:
Effects of Low and High Solar Absorptance Materials on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction or increase	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction or increase
Existing condition solar absorptance; external walls (0.6); roofs (0.6)	4,044.9		2,188.7	
Low solar absorptance; external walls (0.1); roofs (0.1)	4,084.6	1% increase	2,184.1	0.2% decrease
High solar absorptance; external walls (0.9); roofs (0.9)	4,025.4	0.5% decrease	2,196.1	0.3% increase

Evidently, using materials with high solar absorptance caused a small decrease in total energy consumption compared to using materials with low solar absorptance. However, the opposite is obtained when investigating their effects on greenhouse gas emissions, as cooling energy is lower when using low rather than high solar absorptance materials. Notably, cooling energy uses electricity as an energy source, which has a much higher greenhouse emissions conversion factor in Victoria compared to gas.

7.5.11 Glazing Upgrade

The type of glazing used within a building can affect heat loss in winter and heat gain during summer. It was observed during site visits that many aquatic centres have large areas of glazing, especially in swimming pool halls. Since high air temperatures are usually maintained throughout these spaces, large areas of glazing could consequently increase the amount of heat loss. Therefore, using a high-performance glazing such as double glazing is preferred. The type of glazing system throughout the aquatic centre is aluminium frame single glazing.

As such, the glazing system in the simulated model was changed to double glazing to examine its effect on energy consumption. Yet, this examination did not extend to increasing or decreasing the ratio in the model, as such an exercise would be time consuming due to the complexity of modifying such shapes in EnergyPlus. The model would have to be adjusted in DesignBuilder and exported to EnergyPlus, with the entire swimming pool module (including its systems) also requiring total rebuilding. The results of the glazing upgrade are shown in Table 7.33.

Table 7.33:
Effects of Double Glazing on Energy Use and Greenhouse Gas Emissions

	Total energy (MWh)	% Energy reduction	Greenhouse gas emissions (tonne CO_{2e})	% Greenhouse gas emissions reduction
Existing condition	4,044.9		2,188.7	
Glazing upgrade	4,007.1	1%	2,179	0.4%

Evidently, the glazing upgrade only reduced the total energy use by 1%. The amount of external-wall-to-glazing ratio is used in this section to understand the proportion of glazing in reference to the external envelope of the aquatic centre, thus, denoting the overall ratio (excluding the stadium's external wall) as 4.2:1. However, forming a comparison of the glazing ratios between the case study and other aquatic centres within the sample is not possible because only two aquatic centres among the 22 sampled provided a full set of floor plans and elevations. In many cases, floor areas had to be measured onsite, which proved difficult, particularly for façades or glazing areas, due to the size of the aquatic centres. Conversely, the two with full sets of plans had wall-to-glazing ratios of 3:1 and 2.2:1.

Based on the simulation results, aquatic centres with a wall-to-glazing ratio of around 4.2:1 (23% of glazing) or lower can cause a small decrease in total energy use, but only if the type of glazing is changed from single to double glazing. However, this result may not carry over for another aquatic centre with a higher glazing ratio or different outdoor environment. For example, an aquatic centre with a wall-to-glazing ratio of 2.2:1 (45% glazing) can benefit more in terms of energy reduction from using double instead of single glazing.

7.5.12 Types of Filters

The type of filters used in aquatic centres will affect the amount of water used for backwashing. Several types can employ for use in swimming pools, but the selected centre uses a sand pressure system. However, opting instead for a vacuum system will reduce the volume of backwash water, as shown in Table 7.34.

Table 7.34:
Effects of Filter Type on Water Use

	Total water use (kL)	% Reduction
Existing condition	10,258	
Vacuum filter	8,218	20%

7.5.13 Rainwater Tanks

Rainwater is a valuable natural resource that can be utilised by notably high water consumers such as aquatic centres. These tanks can significantly reduce water consumption from a water main and from water bills depending on tank size, roof collection area and climate. Indeed, the typically large roof areas of such buildings can collect greater volumes of rainwater for re-use.

Of the 22 surveyed aquatic centres, nine already had rainwater tanks ranging from 25 kL to 100 kL capacity for toilet flushing, irrigation, make-up water (to refill swimming pools) or for backwashing. The following calculations using Microsoft Excel demonstrate the benefits and savings from using different rainwater tank sizes and re-using water for these same tasks. An analysis was performed based on the average rainfall data of 415 mm/year for the Melbourne region. The collected rainwater is re-used for toilet flushing (1,314 kL/year), irrigation (100 kL/year) and make-up water (474 kL/year), as based on the data in Table 7.20. Notably, irrigation is only performed during summer and at least three times a week. As such, Figure 7.26 shows the reliability curve and results from the rainwater tank analysis. These were based on a maximum rainwater tank size of 100 kL and a stadium roof area of 6,890 m^2.

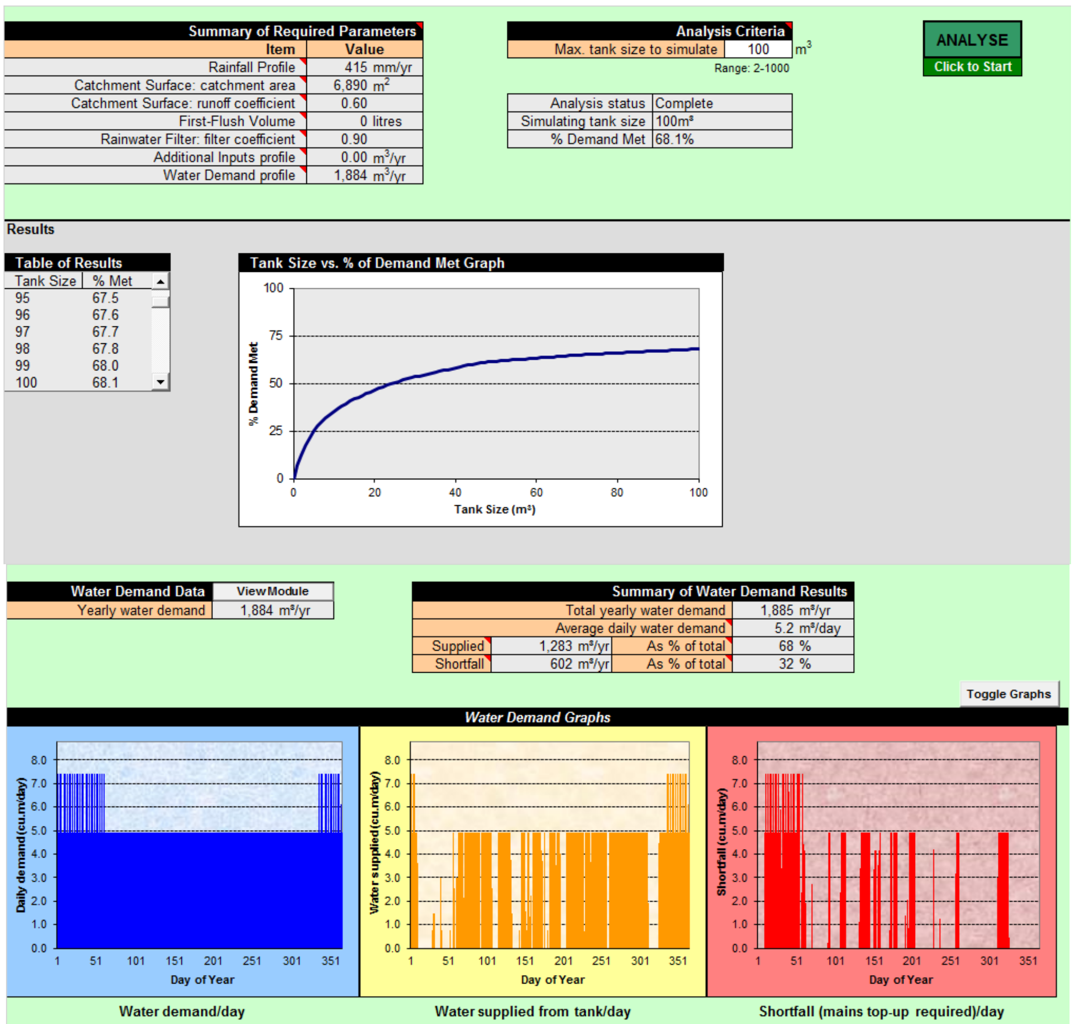


Figure 7.26. Reliability of rainwater tank supply.

Table 7.35 displays the use of several rainwater tank sizes on water consumption. The analysis shows that a 12.5% reduction in water use can be achieved with a 100 kL capacity tank; however, it is noted that a smaller tank can also achieve a similar reduction. Based on Figure 7.26, the curve from the 50 kL tank begins to flatten, thus, signifying that no significant water savings will be achieved from using such capacities.

Table 7.35:
Effects of Rainwater Tank on Water Use

	Total water use (kL)	% Reduction
Existing condition	10,258	
100 kL rainwater tank	8,975	12.5%
75 kL rainwater tank	9,034	11.9%
50 kL rainwater tank	9,099	11.3%
25 kL rainwater tank	9,308	9.3%

7.5.14 Summary Results of Parametric Studies

Table 7.36 summarises the results obtained from the parametric studies performed to examine the effect of several features on the total energy and water use of the selected aquatic centre. The selected features to perform this investigation were chosen based on the information obtained from the literature and on the capabilities of EnergyPlus. In turn, the results obtained can act as a guideline for other aquatic centres to facilitate their energy- or water-related decisions and help identify certain features of potential benefit. However, as this outcome is solely based on one selected aquatic centre, the results may differ for others due to architectural differences, size, and types and number of amenities. For example, an aquatic centre with a larger glazing-to-floor-area ratio may obtain better results from utilising double glazing compared to this case study. It is also noted that the parametric study is more focused on energy- rather than water-efficiency features due mainly to the restricted capability of EnergyPlus to model both the building's complete water cycle (cold- and hot-water consumption) and features such as the treatment of pool water. Additionally, several other energy features or systems—such as cogeneration CHP, heat-recovery systems for swimming pool halls and heat recovery from backwashing pool water—have not been simulated due again to EnergyPlus's limitations and the subsequent complexity of linking each to the swimming pool module.

Table 7.36:
Summary Results of Parametric Studies

Energy- and water-efficient features	% Energy reduction	% Water reduction	% Greenhouse gas emissions reduction
Solar pool-heating system; glazed collector	15.4%		4.6%
Condensing boiler	7.3%		2.7%
Solar pool-heating system; unglazed collector	7%		2%
Pool-water and pool hall air temperature reduction by 1 °C	6.1%		2.3%
Insulation upgrade	5.9%		2.3%
Vertical-axis wind turbine (4 x 10 kW)	4.9%		9.8%
100 kW solar PV system	3.5%		7.7%
LED lighting	3.5%		9.1%
Pool covers (night-time)	3%	1.2%	1%
Increasing boiler efficiency by 5%	2.3%		0.8%
High-density material upgrade; thermal mass external walls and roofs	1.1%		0.5%
Glazing upgrade (double glazing)	1%		0.4%
Vacuum filter		20%	
100 kL tank		12.5%	

7.6 Conclusion

This chapter has demonstrated that an aquatic centre can be modelled successfully, despite its noted complexity. As only little software identified can model indoor swimming pools, this further complicated an already difficult task. However, a new version of EnergyPlus (8.7) was instead chosen for its novel capacity to model an entire aquatic centre, including many indoor swimming pools within a pool hall. Yet, no studies have been identified to have done so just yet. Hence, new procedures and processes had to be created, as the EnergyPlus technical manual proved insufficient to perform the required task. The simulation model was created using two additional pieces of software: DesignBuilder was used to facilitate the construction of the three-dimensional model and to enter several inputs, and EnergyPlus was used to add the swimming pools and perform the simulations.

The proposed procedures and processes for building an aquatic centre simulation model proved effective, as a working simulation model was created and the required environment (including temperature, humidity and evaporation levels) within the swimming pool hall was achieved. The next step was to calibrate and validate the simulation model. Only two rounds of calibration were required for the statistical indices to be within the required threshold limits and attain total calibration. The trend lines of both gas and electricity consumption in the calibrated simulation model were very close to the actual figures; however, as evaporation remained a critical factor to the selected building type, further manual calculation was performed and compared to the simulated evaporation rates. Following some assumptions based on the formulas used by ASHRAE and EnergyPlus, the evaporation levels for both the simulation and the manual calculation were reasonably close. Despite an inability to calibrate and validate the water use of the simulation model (as the whole water cycle could not be modelled using EnergyPlus), Microsoft Excel was utilised to manually estimate its water use based on the results obtained from both the simulation (domestic hot-water usage and evaporation make-up water) and from the literature.

Using the procedures and processes listed in this chapter, many types of aquatic centres can be modelled through simulation and manual calculation to estimate and investigate both energy performance and water use statistics. Further analysis was performed using parametric studies to investigate the additional effects of several features, including architectural and electromechanical factors. Individually, each feature did not present significant effects on either energy use or greenhouse gas emissions, but when combining multiple, a significant reduction in both variables was achieved. As such, the overall reductions in the total energy use and greenhouse gas emissions upon incorporating several architectural and electromechanical features (e.g., double glazing, insulation upgrades, 1 ^{o}C air and water temperature reductions, pool covers, high-density materials such as blockwork walls and concrete roofs, glazed solar pool-water heating systems and LED lighting) are approximately 34% and 20%, respectively, which are significant.

The final results revealed that the most energy- and water-efficient features were respectively solar pool-heating systems (15%) and certain types of filters (20%) relating to backwash water usage. Similarly, the results obtained from the sensitivity analysis reflect the observations made from the sample data. Overall, the list of features used in the parametric study can be followed as a guide for the wider aquatics industries, despite varying results pertaining to architectural and electromechanical discrepancies.

Chapter 8: Conclusion

8.1 Introduction

The topics covered in this thesis are being acknowledged, discussed and investigated by many countries, governments, organisations and people alike. Excessive energy and water use have been shown to negatively affect the environment, and this has created a need for combative action in turn. As aquatic centres have been identified to use significant amounts of both resources, this helped form the basis for which to study a type of building that is both different to others (such as office buildings, apartment buildings, shopping centres and supermarkets) and is generally neglected in the research. However, this approach soon proved problematic due to inconsistencies in defining buildings with swimming facilities nationally and internationally, and a lack of information regarding both energy performance and water use. This created difficulties when researching and comparing data.

Despite these challenges, the energy and water use of aquatic centres in Victoria, Australia were examined in detail to better understand how this type of building operates. Three objectives were defined in an attempt to facilitate this study:

1. Develop a guideline for defining aquatic centres in Victoria for the purpose of energy and water benchmarking.
2. Benchmark the energy and water consumption of aquatic centres by analysing the data collected from existing facilities.
3. To investigate operational and building design features that will improve the energy and water performance of a sample aquatic centre by using building performance simulation.

Five research questions were then identified to successfully answer these queries:

1. How can aquatic centres be defined for the purpose of energy and water benchmarking?
2. What are the key performance indicators that can be used to benchmark the energy and water consumption of aquatic centres in Victoria?
3. What are the ranges of energy and water consumption for aquatic centres in Victoria?
4. How can the energy and water consumption of Victorian aquatic centres be benchmarked?
5. What are the main energy- and water-efficient features that can influence the energy and water use for an aquatic centre?

Section 8.2 will provide a summary of the main findings and conclusions drawn from the study. The contributions to the research field, main limitations of the study and recommendations for future research are also briefly discussed.

8.2 Main Findings and Conclusions

This study was conducted in three phases to provide clear and useful responses to the three objectives and research questions. As discovered, there are many inconsistencies in how buildings with swimming facilities (both nationally and internationally) have historically been defined, and this has caused difficulty when researching and comparing data and outcomes. These complications are directly related to the complexity of this building type itself. Evidently, some researches refer to aquatic centres more as a processing plant rather than a building due to its complex electromechanical systems to maintain certain levels required of the environment, especially within swimming pool halls. One critical difference when comparing aquatic centres to other buildings is the interaction between water and air occurring in the former, which is an important factor that requires careful control. The main findings and conclusions of which have subsequently been divided and discussed in Sections 8.2.1, 8.2.2 and 8.2.3.

8.2.1 Defining an Aquatic Centre

Defining an aquatic centre was important to first achieve in this study, as the current lack of clarity regarding what constitutes an aquatic centre consisted a major research issue. Understanding what types of amenities are included in these buildings is equally important, and, thus, discussing it early provided a clearer picture prior to tackling more in-depth investigations. Reviewing past studies next emphasised that researchers have not clearly justified and defined their aims; hence, a clear definition of an aquatic centre (based on investigations of those present in Victoria) was proposed. This was established according to the information collected from 110 aquatic centres across the state through a desktop analysis. The data collected from the internet was then used to establish several categories of aquatic centres based on the types and number of amenities they provide. As such, this study defined an aquatic centre as a community or public venue that provides at least one indoor swimming pool and three different types of amenities, such as a gymnasium, a sauna or spa, a cafe or a creche. Providing this description helped identify and differentiate factors that proved relevant or otherwise. For example, can a swimming pool within a school be classified within the same category as an aquatic centre, or can an outdoor swimming pool be classified as an aquatic centre? Once this definition was established, it proved far easier to draw comparisons with other studies and understand which held the most relevance.

However, evaluations between existing energy and water benchmarks for aquatic centres again provided confusion upon examining past studies, as the majority failed to clarify or justify how their definitions were derived. No comparison was made between the different types of swimming pool facilities and, in some cases, aquatic centres were included within the same building category such as small swimming pool halls. There was neither consensus among researchers on the type of performance indicators used when benchmarking energy and water consumption. As such, several indicators were used and this made comparison difficult. Proposing an otherwise clear definition in this study helped eliminate these uncertainties and questions pertaining to building type. In turn, this thesis can double as a guideline to better identify aquatic centres for future research and facilitate their classification or categorisation in both Australia and worldwide. In this sense, the investigation undertaken in this study successfully responds to the first research question and first objective.

Section 8.2.2 will next provide more details on both energy and water use. This data will help in developing appropriate benchmarks for such variables in aquatic centres.

8.2.2 Benchmarking Energy and Water Use in Aquatic Centres

Upon proposing a definition for an aquatic centre, it proved subsequently easier to review past studies. Benchmarking was identified as an appropriate method to understand the energy and water use in these buildings. Information on each factor for existing centres were collected using a questionnaire as well as through site visits and onsite measurements. Several aquatic centres in Victoria were contacted and data from 22 were collected, which accounts for approximately 20% of the state's centres. Although this seems a relatively small sample, the data collection was carefully done to ensure that only aquatic centres that accorded to the proposed definition were included.

Statistical investigations were performed using a two-step technique consisting of a correlation analysis to discover the variables with the strongest correlations to energy and water use, which was followed by a multiple linear regression analysis to identify the variables with the most significance to both factors in aquatic centres. The correlation analysis provided some useful indications on relevant variables to be used for benchmarking; however, more analyses (multiple linear regression) were required to pinpoint the most appropriate for energy and water consumption. In turn, the analysis found that conditioned usable floor area and number of visitors possess the strongest correlation and significance in relation to energy and water use in aquatic centres. Therefore, to calculate both usage intensities, energy and water consumption should be divided by the conditioned usable floor area and number of visitors, respectively. The EUIs for aquatic centres ranged between 648 kWh/m^2 and 2,283 kWh/m^2 (conditioned usable floor area), while the WUIs ranged between 11 L/visitor and 110 L/visitor, thus, answering the second, third and fourth research question. These results enabled the comparison of energy performance with other types of building, and concluded that no strong correlation exists between overall energy and water use in aquatic centres.

The second part of this analysis aimed to gain insights into specific features that increase energy and water efficiency. This was achieved by examining the data obtained from the detailed questionnaire and site visits. Features such as the use of solar pool-heating systems, solar PV systems as well as daylight and motion sensors for lighting appeared to have positive effects on overall energy savings within the sample. Likewise, recycled backwashing for swimming pool make-up water and rainwater harvesting had apparent water-use reductions. Conversely, several other features such as double glazing, variable speed pumps and pool covers did not show any apparent trends, and this is possibly due to significant disparities in the architectural and electromechanical design of different aquatic centres. Hence, this necessitated the use of simulation to further investigate such energy- and water-efficient features.

8.2.3 Simulating an Aquatic Centre

Simulating an aquatic centre was required to provide a comprehensive analysis of the features that determine whether an aquatic centre is comparatively energy or water efficient. This process has been described as a complex task due to such buildings' tricky interaction between water and air within swimming pool halls, which little software can attempt to simulate. The most important factor to consider when modelling an aquatic centre is the effect of evaporation on energy and water use. As such, EnergyPlus proved useful to model the building due to its indoor swimming pool module that was only recently added. Again, no studies using this method were found in the literature.

Detailed procedures and processes for simulating the aquatic centre using EnergyPlus were next created for this study. Modelling was performed in two parts: DesignBuilder was used to create the three-dimensional model of the aquatic centre and EnergyPlus helped perform the simulations. These two steps facilitated the process of quickly identifying errors, as the selected design was complex. Nonetheless, this model was selected based on the availability of specific data pertaining to its architectural and electromechanical systems (used for inputs), and at least 12 months of utility bills for subsequent calibration.

Once the model was built and the simulation output was examined, calibration was performed to ensure the model reflected the actual usage of the selected aquatic centre. A manual calibration method based on an iterative approach was then applied, with several variables such as boiler efficiency, lighting levels, occupancy adjustments and equipment loads adjusted thereafter. The model was considered calibrated once the statistical indices were within the threshold limits specified by ASHRAE, IPMVP and FEMP. This was considered after two rounds of calibration.

Following this process, it was next important to verify the evaporation outputs produced by the simulation model, with manual calibration performed using the ASHRAE evaporation method. It was noted that EnergyPlus offers the choice to adjust the activity factor of the swimming pool by creating and adjusting a corresponding schedule (hence, allowing different activities during the day and the night), while the ASHRAE method did not. Disregarding the different levels of activity present in the centre (especially during unoccupied periods) resulted in an overestimated evaporation level. Thus, to form a comparison between EnergyPlus and ASHRAE methods, the activity factor in the latter was reduced to make the results comparable.

For water use, monthly calibration was not possible, as consumption bills were available only every three months. In addition, no simulation software was identified to successfully model an entire water cycle. As EnergyPlus produces uses for both domestic hot-water and evaporation make-up water, the Microsoft Excel information and data obtained from the questionnaire (occupancy) still made it possible to establish a reasonable estimate of the centre's water consumption.

Creating a validated simulation model enabled further analysis, which provided more details on the effects of several architectural and electromechanical variables on energy and water consumption. A summary of the subsequent sensitivity analysis performed is provided in Table 7.36. As such, solar pool-heating systems were identified as one of the most effective features for energy efficiency, followed by the use of a condensing boiler. Solar heating also evidenced a possible device to have lowered energy use for the aquatic centres within the sample. However, reducing air temperature in both pool water and pool halls proved the most cost effective and efficient measure, in that a minor 1 °C reduction still produced a significant decrease in total energy use.

Developing a calibrated simulation model and parametric simulations helped answer the fifth research question regarding the main energy and water features that influence a building's consumption levels. EnergyPlus and manual calculation were too proven as the most suitable methods for estimating water use in aquatic centres, with the simulation results likewise providing insight into the apparent difficulty to identify energy-efficient features from the data collected. Evidently, each feature listed in Table 7.35 only resulted in a small percentage reduction in total energy use, which may not be viewed as sufficient by the industry. Therefore, for an aquatic centre, a combination of several energy-efficient features should be investigated or implemented if a significant total reduction is needed. These may include architectural and electromechanical factors—including double glazing, insulation upgrades, a 1 °C air and water temperature reduction, pool covers, high-density materials such as blockwork walls and concrete roofs, glazed solar pool-water heating systems and LED lighting—to produce an estimated 34% total energy decrease and a 20% reduction in greenhouse gas emissions.

Overall, the study has provided sufficient answers to all the research questions. The findings will not only be useful to academia but also to the wider aquatic industry. As such, Section 8.3 discusses how these findings provide significant knowledge to the field.

8.3 Research Contribution

This study was based on a specific type of building that has not been sufficiently investigated in the past compared to other building types. An aquatic centre was identified as an intensely complex building with unique internal conditions (e.g., evaporation) not usually encountered by other buildings, and these must be controlled constantly and efficiently. One of the main issues this study addressed was the lack of consistency regarding a clear definition of an aquatic centre. Most past research on swimming pool facilities failed to do so or likewise define or justify how they derived their definition. This created inconsistencies and uncertainties in the field, and comparing studies became problematic—especially upon examining the existing energy and water benchmarks of aquatic centres.

This study is among the first to propose a clear definition of an aquatic centre prior to performing further investigation. This description can be used in Australia and worldwide, as such buildings generally contain similar types of amenities. It can also be useful to the wider aquatics industry, as swimming pool facilities can now refer to this definition to easily distinguish whether they are considered as such and if the investigations performed are likewise applicable.

A set of energy and water benchmarks for aquatic centres was then proposed, which, due to most sharing similar internal conditions, can also be used globally. Together, the proposed definition, guidelines, and energy and water benchmarks streamline the process for aquatic centres in Australia and around the world to compare their energy and water consumption.

This study is also among the few to examine both energy and water use in aquatic centres. Although it revealed a weak correlation between both factors, this important energy and water nexus has finally been investigated thoroughly. Nonetheless, it became clear that specific standards, guidelines and requirements regarding temperatures and relative humidity levels (which bear significant effects on evaporation, energy use and water use alike) within swimming pool halls exist; however, many facilities fail to follow these principles. Indeed, this could be due to a general lack of understanding and knowledge from aquatic centre operators.

Another contribution to the aquatic centre industry derives from the investigations performed using building simulation. This study is the first to simulate an aquatic centre using EnergyPlus with an indoor swimming pool module. As no previous work has applied this version of the software as such, new procedures and processes had to be purposely created to successfully model the sample building. Naturally, a detailed guide on how to do so using EnergyPlus was subsequently provided, not only to facilitate the design of future centres but also for investigating additional energy- and water-efficient features in existing aquatic centres. In turn, this study simultaneously identified several coding errors in an earlier version (8.3) of EnergyPlus's swimming pool module, which were relayed to the software's technical teams and later rectified in version 8.7.

This investigation also provided a successfully calibrated and validated model of an aquatic centre for parametric study, the results of which are worthwhile for both academics and aquatic industries to identify potentially beneficial variables of use. Overall, the study has made significant contributions to the knowledge on energy and water performance of aquatic centres.

8.4 Study Limitations

This study was mainly restricted by its sample size. Several aquatic centres were contacted but data from only 22 could be recorded. Additionally, some of the required information such as floor area specification were missing from the questionnaire and had to be recorded during site visits. Another limitation derived from restricting the geographic location of this study to Victoria, as obtaining data from aquatic centres in other states proved difficult. Indeed, Australia is a large country with several states and several weather types ranging from mild winters in the south, to tropical climates up north. With all the aquatic centres within the sample consequently situated in Victoria, this restricted the data to account only for mild winters and occasional hot weather during the summer season. Therefore, aquatic centres in other states will have to account for different weather conditions before utilising the results.

Further, building energy simulations could only be performed for one aquatic centre, as the required data to do so could not be obtained from others within the sample. This feat may not prove sufficient to represent all aquatic centres, such as those with outdoor swimming pools. Additionally, many of the energy- and water-efficient features used in the parametric study will neither have the same effect when simulated for other aquatic centres. For example, another building might have a large glazing-to-wall ratio and might discover a greater benefit from using high-performance glazing instead of upgrading their insulation.

Several limitations also appear in the capabilities of EnergyPlus. Many systems facilitating heat recovery to preheat make-up pool water as well as treat swimming pools cannot yet be simulated. Typically, heat-recovery systems in a modern aquatic centre are deployed to recover energy from the renovated water in a swimming pool and then preheat the make-up water. This system is formed by a plate heat exchanger working with a counter-flow configuration to maximise the efficiency of energy transfer. However, the indoor swimming pool model included in EnergyPlus neither provides the possibility to evaluate the preheating provided by this system to the make-up water, nor to model an outdoor swimming pool itself, which proved problematic.

As such, no software was identified to perform the simulation of water consumption in an aquatic centre. Neither can include specific water demands such as backwashing water, water used during pool treatments and water used to replace leaks or instances of splashing.

8.5 Recommendations for Further Research

Although this study has made significant contributions to the research field, more are required to provide a greater understanding. With such a small sample of 22 aquatic centres, further studies with comparatively larger models could be undertaken to provide more insights to the proposed energy and water benchmarks. Extending this investigation to other states will likewise provide more information on how different climate zones can affect the energy and water use in aquatic centres around Australia. In addition, it is recommended that aquatic centres with and without outdoor swimming pools are investigated separately, should a larger sample become available. However, this task will be complex, as some outdoor facilities are only open during the summer seasons, while others are available year round, with some being heated, while others are not.

In addition, more aquatic centres and buildings with indoor pools (such as hotels and schools) could be modelled using the processes and procedures created in this study to further investigate the effects on energy- and water-efficient features. More specific systems could also be modelled, including heat-recovery systems that use air from swimming pool halls, as well as cogeneration systems. This will help not only understand their effects on energy consumption, but also investigate their influences on greenhouse gas emissions.

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Appendix 1: Questionnaire

RMIT UNIVERSITY

Energy and Water (Aquatic centre)

Name and address of the aquatic centre: ____

____

Name of contact person: ____

Position: __________________________________

Tel. No.: __________________________________

Email address: ____

Instruction: Please complete the questionnaire by answering all the questions and when information is not available or unknown, please indicate N/A.

Aquatic Centre Energy and Water use:

Fuel Type	Electricity (kWh)	Gas (GJ)	Water (kL)	Others (Please Specify)
Jan				
Feb				
Mar				
Apr				
May				
Jun				
Jul				
Aug				
Sep				
Oct				
Nov				
Dec				
Total				

Note: Please enter the most current energy and water data for at least a year only if copies of bills are not available. If available please send copies of the bills as an attachment instead.

Alternative energy

Any solar energy system? No

Yes (please specify) Solar Photovoltaic system ☐ Solar Hot water System ☐

Size of system: ______________________

Any CHP (Co-gen) system? No

Yes (please specify) Type: ______________________________

Size of system: ______________________

Building Management system

Is there a Building Management System (BMS) in the building? Yes ☐ or No ☐

Building Physical Characteristics

Building construction (if known): - External walls: _____________________________

Roof: Concrete roof ☐ Or Metal deck (colourbond) ☐

Glazing: Single glazing ☐ Or Double glazing ☐

Note: Please provide a scaled floor plan of the aquatic centre if available or enter the total area of the centre below.

Function areas

Function types	Tick if available	Floor area (m^2)	Operating Hours (hr/day)	Comments
Reception				
Indoor swimming pool				
Outdoor swimming pool				
Gym				
Spa and sauna				
Sport hall				
Childcare centre				
Café/ F & B area				
Change rooms and toilets				
Others				
Total				

Swimming pools

	Tick if available	No of pools	Types of pools (lap, kids, etc.)	Size (25m, 50m etc.)	Volume of pool (Kl)	Comments
Indoor swimming pool						
Outdoor swimming pool						

Building Operating Characteristic

Aquatic centre weekly opening hours: __________hrs

Closed periods (if any): ____ days

Total number of visitors per year: ____________

Total number of bathers per year: ____________

Occupancy rate (if available)											
Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec

Building Indoor Environment

Indoor thermal settings: Pool hall temperature __________ (Degree C)

Relative humidity: ______ (%)

Swimming pool types (indoor, kids, outdoor etc.)	Pool temperature setting (Degree C)

Building Services

Building HVAC System

Area	Type of HVAC	Size (KW)	Efficiency (COP/EER)	Operating hours (Hrs/daily)	Comments
Swimming pool hall					
Reception					
Gym					
Changing room and toilet					
Café					
Sport hall					

Note: If information is not available, please enter N/A. For HVAC system, enter the following if known: Split System, Central/ Package Air-con unit, VRV, heat pump or others

Any heat recovery system? _______ if yes, please specify: ____________________________________

Lighting system

Types of lighting used (if known) - LED, compact fluorescent, halogen etc.: ____________________

Any sensor installed (occupancy / daylight sensors): _________ If yes please specify: ______________

Water

Types of treatment

Pool water treatment (chlorine, sodium, calcium, ozone, salt, UV etc.): _________________________

Filtration

Types of filters (gravity, pressure, pre-coat, vacuum): __________________

No of filters: _____

Automatic or manual backwashing? ______________ when: _______________ Duration: _______Hrs

Amount of water to clean filters (if known): ______ Kl

Circulation pump

Types of pumps (variable or fixed): _____________

No of pumps: ___________

Operating hours per day: ______ Hrs Comments: ____________________________

Amenities

WELS rating:

Showers: _______ star

Toilets: _______ star

Taps: ______ star

Urinals: _____ star

Water heating

Pool water

Type of pool water heating system: _____________________________________

Type of fuel used for pool heating (gas, electricity etc.): ______________________

Details about pool water heating system (if known)-Size, efficiency etc.: ____________________

Any preheating of pool water (if known)? _____ If Yes Please specify: ___________________

Domestic hot water

Type of domestic hot water system: ___________________________

Details about domestic hot water system (if know)-Size, efficiency etc.: ____________________

Alternative water sources and recycling

Any alternative water sources used: ___________ if yes Please specify: ________________

Any rain water tanks: ________ If yes nominate tank size: _____ Kl Use: ______________________

Is backwashing water recycled? _______ if yes provide details: ________________________

General

Are pool covers installed? _________

Has any energy and water audit been conducted previously? _______ if yes please specify when________

Comments:____
____
____
____
____
____
____
____
____