MINISTÉRIO DA EDUCAÇÃO
UNIVERSIDADE FEDERAL DO RIO GRANDE DO SUL
PROGRAMA DE PÓS-GRADUAÇÃO EM ENGENHARIA MECÂNICA

FREE COOLING POTENTIAL FOR DATA CENTERS IN BRAZIL

por

Eduardo Alves Amado

Dissertação para obtenção do Título de
Mestre em Engenharia

Porto Alegre, Abril de 2019

FREE COOLING POTENTIAL FOR DATA CENTERS IN BRAZIL

por

Eduardo Alves Amado
Engenheiro Mecânico

Dissertação submetida ao Corpo Docente do Programa de Pós-Graduação em Engenharia Mecânica, PROMEC, da Escola de Engenharia da Universidade Federal do Rio Grande do Sul, como parte dos requisitos necessários para a obtenção do Título de

Mestre em Engenharia

Área de Concentração: Energia

Orientador: Prof. Dr. Paulo Smith Schneider
Co-Orientador: Prof. Dr. Cirilo Seppi Bresolin

Aprovada por:

Prof. Dr. Roberto Lamberts .... PPGEC / UFSC

Prof. Dr. Mario Henrique Macagnan .... PPGEM / UNISINOS

Prof.[a] Dra. Letícia Jenisch Rodrigues .... PROMEC / UFRGS

Prof. Dr. Fernando Marcelo Pereira
Coordenador do PROMEC

Porto Alegre, 30 de Abril de 2019

AGRADECIMENTOS

Agradeço primeiramente à Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES) pelo suporte financeiro para a elaboração desta dissertação.

Agradeço também aos professores Paulo Schneider e Cirilo Bresolin pela orientação neste trabalho. Suas sugestões e indicações foram muito importantes para o desenvolvimento deste estudo até a sua conclusão.

Gostaria de agradecer também à colegas e amigos que me auxiliaram durante a elaboração desta dissertação, seja por meio de *feedbacks*, sugestões, conselhos ou apoio. Com destaque para Conrado Ermel, Tiago Haubert, Gabriel Trujillo e Leonardo Amado.

Por fim, agradeço à minha família, em especial à minha mãe Maria Loreci Alves, cujo apoio foi imprescíndivel não apenas no período de desenvolvimento deste trabalho, mas também durante toda a minha vida.

RESUMO

O consumo de energia de data centers cresce à taxas alarmantes em todo o mundo, ao passo que sistemas de refrigeração são responsáveis por cerca de 40% da demanda elétrica destas edificações. Neste contexto, o resfriamento natural (free cooling) surge como uma solução eficaz a fim de reduzir o consumo de energia nestas instalações. Este trabalho propõe critérios para avaliar o potencial de resfriamento natural para data centers no Brasil, considerando economizadores à ar e à água, baseando-se em revisões da literatura e nos limites térmicos de operação propostos pelas normas da ASHRAE. Os critérios propostos foram aplicados à quatorze importantes cidades brasileiras, representando todas as regiões do país, por meio do uso de arquivos do Ano Climático de Referência destas cidades. Os resultados mostraram que cidades como Curitiba, São Paulo, Porto Alegre e Brasília possuem potencial para operar tanto com economizadores à ar como à água por mais de 3000 horas em um ano, mesmo considerando limites térmicos conservadores para a operação de um data center. Cidades das regiões Norte e Nordeste do país somente apresentaram potencial para operar em resfriamento natural quando considerados limites de operação mais flexíveis. Resultados apontaram que economizadores indiretos possuem um potencial maior no Brasil, considerando os atuais limites recomendados pela ASHRAE, devido ao alto nível de umidade das cidades estudadas. Por fim, um panorama geral foi fornecido sobre os principais tipos de economizadores à ar e à água para data centers, apresentando vantagens e desvantagens sobre suas aplicações e seus desempenhos.

Palavras-chave: Data center; Resfriamento natural; Economizadores à ar; Economizadores à água; Potencial de resfriamento natural em cidades brasileiras.

ABSTRACT

Data centers energy consumption has been increasing in alarming rates all around the world, and the refrigeration system is responsible for about 40% of the building electricity demand. In this context, free cooling appears as an effective solution to achieve energy savings in these facilities. The present work proposed criteria to assess the free cooling potential for data centers in Brazil considering airside and waterside economizers based on literature review and on ASHRAE thermal guidelines operating limits. The proposed criteria were applied to fourteen Brazilian key cities, which represented all of the country regions, with the aid of the cities Test Reference Year weather data. Results showed that cities such as Curitiba, São Paulo, Porto Alegre and Brasília have potential to operate in both airside and waterside economizers mode for more than 3000 hours in a year, even considering conservative data center thermal operating limits. Cities from the North and Northeast region of the country only presented potential to operate in free cooling while considering more flexible operating limits. It was shown that indirect economizers have a higher potential in Brazil, considering the current data center operating limits recommended by ASHRAE, due to the cities high humidity levels. Finally, an overview of the main types of airside and waterside economizers was provided, presenting advantages and disadvantages regarding their application and performance.

Keywords: Data center; Free cooling; Airside economizer; Waterside economizer; Free cooling potential in brazilian cities.

INDEX

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

ACWE	Air Cooled Waterside Economizer
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CRAC	Computer Room Air Conditioner
CRAH	Computer Room Air Handler
CTWE	Cooling Tower Waterside Economizer
DAE	Direct Airside Economizer
DC	Data Center
DWCE	Direct Water Cooled Waterside Economizer
DX	Direct Expansion
ESD	Electronic Discharge
FC	Free Cooling
HX	Heat Exchanger
IAE	Indirect Airside Economizer
IT	Information Technology
PWSE	Parallel Waterside Economizer
Rec	Recommended
SWSE	Series Waterside Economizer
TC	Technical Committee
TES	Thermal Energy Storage
TRY	Test Reference Year
WCT	Wet Cooling Tower

LIST OF SYMBOLS

Latin Symbols

Ap_{HX}	Approach of the Heat Exchanger, °C
Ap_{WCT}	Approach of the Wet Cooling Tower, °C
cp_a	Air Specific Heat, J/(kg k)
cp_w	Water Specific Heat, J/(kg K)
C_{min}	Minimum Heat Capacity, J/K
DBT	Dry-Bulb Temperature, °C
$DBT_{in,max}$	Maximum Acceptable Supply Dry-Bulb Temperature, °C
DBT_{out}	Outdoor Dry-Bulb Temperature, °C
DPT	Dew-point Temperature, °C
$DPT_{in,max}$	Maximum Acceptable Supply Dew-point Temperature, °C
DPT_{out}	Outdoor Dew-point Temperature, °C
$\dot{m}_a$	Indoor Air Circuit Mass Flow Rate, kg/s
$\dot{m}_w$	Water Circuit Mass Flow Rate, kg/s
q	Heat transfer rate, W
PUE	Power Usage Effectiveness, -
q_{HX}	Rate of Heat exchanged in the Heat Exchanger, W
q_{WCT}	Rate of Heat exchanged in the Wet Cooling Tower, W
q_{max}	Maximum Rate of Heat that could be exchanged in the Heat Exchanger, W
Rg	Range of the Cooling Tower, °C
RH	Relative Humidity, %
$T_{a,c}$	Indoor Air Circuit Cold Temperature, °C
$T_{a,h}$	Indoor Air Circuit Hot Temperature, °C
$T_{w,c}$	Water Circuit Cold Temperature, °C
$T_{w,h}$	Water Circuit Hot Temperature, °C
WBT	Wet-Bulb Temperature, °C
WBT_{out}	Outdoor Wet-Bulb Temperature, °C
$WBT_{out,max}$	Maximum Acceptable Wet-Bulb Temperature, °C

Greek Symbols

γ	Sum of the Approaches of the system , °C
ΔT_a	Temperature Difference in the Indoor Air Circuit, °C
ΔT_w	Temperature Difference in the Water Circuit, °C
ϵ	Global Effectiveness of the Heat Exchangers , -

1 THESIS BACKGROUND

1.1 Motivation

Data centers (DCs) are dedicated facilities whose primary function is to house computer servers and provide data services. In these facilities, thermal dissipation can reach heat densities up to 100 times higher than the ones from regular office rooms [Capozzoli et al., 2014; Oró et al., 2015a]. Reliability and availability are paramount for DCs since many companies rely heavily on a proper and uninterrupted data center operation all year round [Capozzoli et al., 2014; Johnson and Marker, 2009].

Digital information has been experiencing massive growth in the last decade, and data centers are the core infrastructure to support this trend [Rong et al., 2016]. Many countries are having rapid expansions in both the number and size of these facilities to meet their demands for internet, cloud computing services [Ni and Bai, 2017] and, more recently, to cryptocurrency mining [Rareshide, 2019]. Hence, DC financial and energetic impacts have been drawing a lot of attention worldwide.

The DC market has been increasing at accelerated rates. According to Statista, 2019b, spending on DC systems worldwide has grown from US$ 140 billion in 2012 to US$ 202 billion in 2018, and it is expected to reach US$ 210 billion in 2019. Within the DC market, stands out the colocation sector. A colocation is a special data center facility that rents infrastructure for customers to host their servers and other computing hardware [Rouse et al., 2019]. This sector has been growing even faster than the average DC market. The colocation market should reach revenue of US$ 48 billion in 2021 [Statista, 2019a].

The colocation market spread has been contributing to the segmentation of DC facilities worldwide [Shende, 2015]. Partly driven by this, the Latin America DC market generated a turnover of US$ 2.87 billion in 2017, and Brazil was responsible for 47.6% of this amount, which is expected to reach US$ 4.37 billion until 2021 [EXAME, 2018]. Some local environmental characteristics are desired to compete at a world scale, such as cheap electricity cost, cold climate and low-cost real estate. However, these characteristics are worthless unless applied to high-level energy performance systems.

With respect to the energetic consequences of data centers, it is fair to say that their energy consumption has been increasing in alarming rates all around the world. Between 2000 and 2005 this value has doubled, from 2005 to 2010 it increased another 56%, even though the world was facing an economic crisis [Zhang et al., 2014]. DCs were responsible for about 1.5% of worldwide electricity consumption in 2011, and an annual increase of 15-20% is expected in the near future [Amoabeng and Choi, 2016].

Furthermore, there is also a major concern regarding data centers CO_2 emissions. According to Amoabeng and Choi, 2016; Avgerinou et al., 2017, it is estimated that 2% of the global CO_2 is a result of energy usage in DCs. This value is expected to increase at a 6% annual rate, and account for 12% of worldwide emissions by 2020. In this context, the DC energy performance has also become an important factor.

As a result of all these factors, the trend in the IT and DC industries is to seek a high-level of reliability and availability followed by a reduction in energy consumption. As Figure 1.1 shows, the main responsible for energy consumption in data centers are the servers and the refrigeration system, each of them accounting for about 40% of the entire facility consumption [Rong et al., 2016].

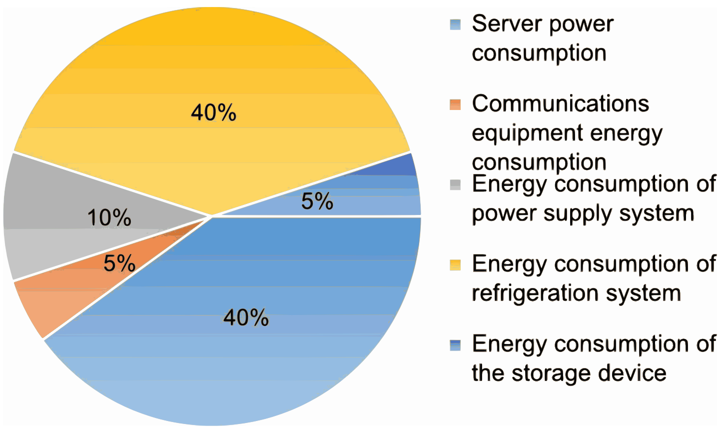


Figure 1.1 – Energy consumption distribution of Data Centers [Rong et al., 2016].

From this perspective, The Green Grid, 2007 have proposed the Power Usage Effectiveness (PUE) index, which is acknowledged as the most accepted metric to describe

DC energy efficiency. PUE is defined as the ratio of the total amount of energy used by an entire data center facility to the energy demanded only by the computing equipment as shown in Equation 1.1.

$$PUE = \frac{Total\ \ Facility\ \ Energy}{IT\ \ Equipment\ \ Energy} \tag{1.1}$$

PUE is always a value higher than 1. $PUE = 1$ represents the hypothetical situation that the energy consumption from all non-computing devices of a data center facility; such as lighting, power supply, communication and cooling systems; would be zero. Table 1.1 presents two different rating systems for this metric [Amoabeng and Choi, 2016].

Table 1.1 – PUE ratings [Adapted from The Green Grid, 2007; EPA, 2019].

PUE	Green Grid rating system	PUE	EPA rating system
2.5	Inefficient	1.9	Current Trends
2.0	Average	1.7	Improved Operation
1.5	Efficient	1.3	Best Practice
1.2	Very Efficient	1.2	State of the Art

Therefore, one can state that a high-level energy performance in a DC is equivalent to reach low PUE values, ideally close to 1.2. Considering Figure 1.1 and Equation 1.1, it is possible to conclude that reducing the energy consumption of the cooling system is the key factor to achieve a low PUE value and improve a data center facility in both: energetic and financial aspects.

1.2 Cooling systems in data centers

IT equipment demand continuous heat rejection in order to respect their temperature and humidity operating thresholds, which makes cooling systems necessary for a reliable operation of a DC facility. On the other hand, DC cooling systems represent about 40% of the entire facility energy consumption (Figure 1.1), turning these systems the main target for energy efficiency strategies.

Mechanical cooling systems based on vapor compression cycles are conventionally used in DCs. They can operate with fluid direct expansion (DX) or chilled water as shown in Figure 1.2. These units are named as computer room air conditioner (CRAC) and computer room air handler (CRAH). Both systems monitor and maintain the temperature, air distribution and humidity in a DC within desired limits [Nadjahi et al., 2018].

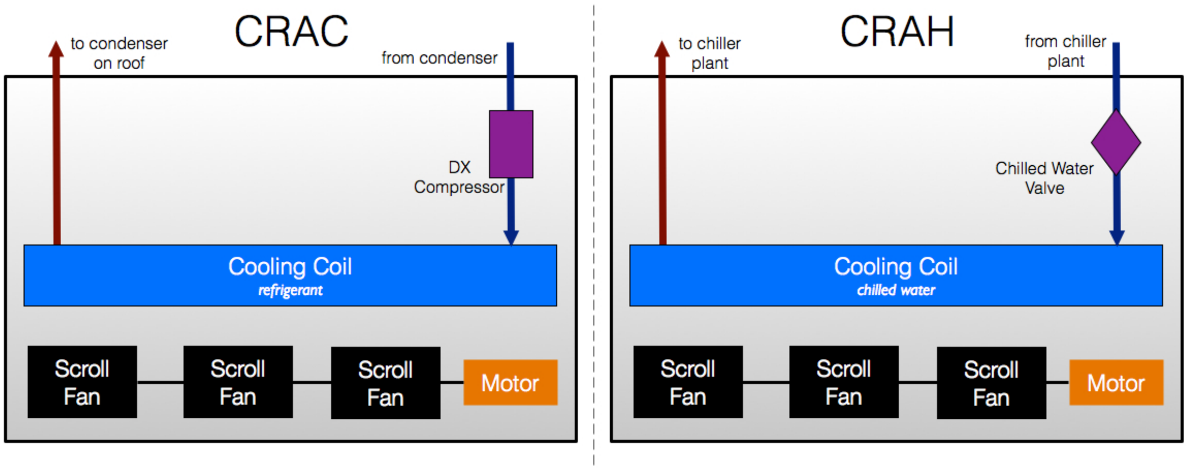


Figure 1.2 – Comparison between systems based on CRAC and CRAH units [DC Huddle, 2019].

CRAC units demand low investment and maintenance and are often used in small DCs, limited to 200 kW of IT power. CRAH units are more suited to big DCs, with more than 200 kW of IT power [Amoabeng and Choi, 2016]. Both CRAC and CRAH are mechanical cooling systems designed to operate all year round, which makes the refrigerant compressor consumes substantial amounts of energy.

1.3 Energy efficiency in data centers

Much research has been done lately on technologies to reduce the cooling systems energy consumption in data centers. In this regard, The American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Technical Committee (TC) 9.9 has been identifying, proposing, funding and publishing research projects about data center operation and, mainly, its cooling system performance and energy efficiency techniques [ASHRAE, 2019]. Their research, often made in association with IT equipment manufacturers, results on standards and guidelines for good practices. Some of the most important thermal and airflow management techniques recommended by ASHRAE TC 9.9 are presented in this section.

1.3.1 Airflow management

Airflow distribution inside a DC is essential to allow for an adequate heat dissipation around the servers. In this context, two non-exclusive configurations stand out: the raised floor and the hot and cold aisles [Amoabeng and Choi, 2016; Nadjahi et al., 2018].

The raised floor is a construction model in which a higher floor is constructed slightly above the original facility concrete slab floor creating an open space called plenum. Inlet cold air provided either from the CRAC or CRAH unit flows through the raised floor plenum vents to the IT equipment rack to remove the heat. Hot air is then returned through the facility ceiling [Amoabeng and Choi, 2016].

Hot and cold aisles configuration is often used alongside the raised floor layout as presented in Figure 1.3. Cold air is supplied in the raised floor plenum and flows to the data center through perforated tiles. This cold air is then aspired by racks on the front side, absorbs the heat generated by the IT equipment and, then, is expelled at the rear of each rack [Nadjahi et al., 2018].

Both layouts provide advantages such as reducing equipment fan speeds (and consequently its energy consumption), and extending the IT equipment life cycle. However, air mixing from hot and cold aisles due to their high-level of stratification is an issue. Some solutions for this problem have been proposed, such as the cold aisle containment and the hot aisle containment as shown in Figure 1.4 [Nadjahi et al., 2018].

Modeling and optimization of these layouts and the airflow management in a data center are object of intense research for several years in both: academia and industry. Numerical modeling, reduced-order models and experimental studies are among the tools

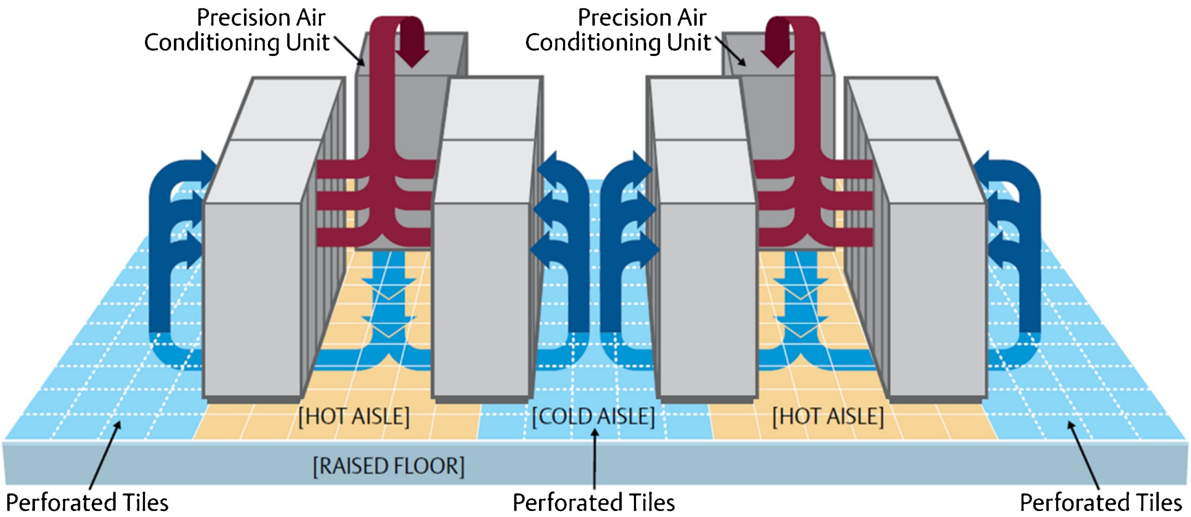


Figure 1.3 – Hot and cold aisles configuration with a raised floor [Nadjahi et al., 2018].

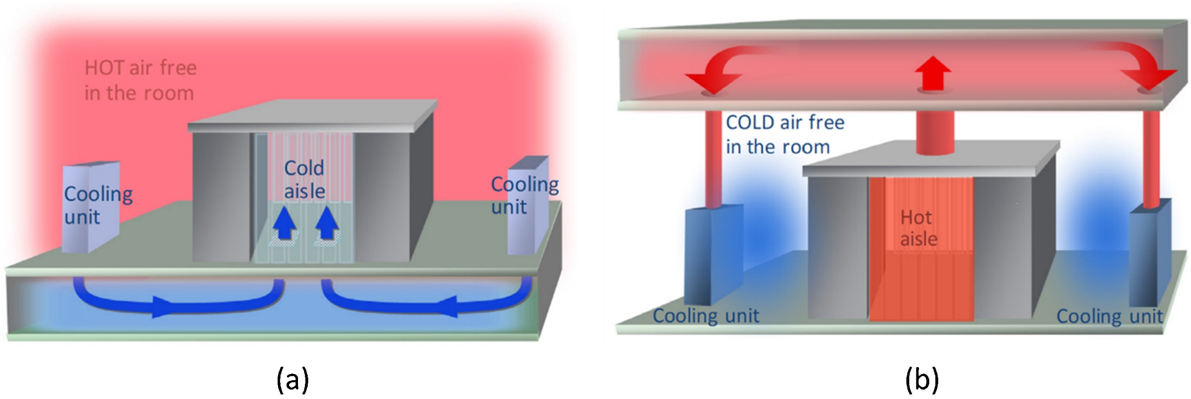


Figure 1.4 – Use of containment in data centers (a) cold aisle containment (b) hot aisle containment [Nadjahi et al., 2018].

that can be used for that purpose [Bhalerao et al., 2016; Hong, 2008; Phan and Lin, 2014; Rambo and Joshi, 2007; Kang et al., 2001; Wemhoff and Frank, 2010; Zavřel et al., 2015].

1.3.2 Cooling efficiency techniques

Liquid cooling, thermal energy storage (TES) systems and the free cooling stand out as techniques to improve the DC cooling efficiency.

Liquid cooling consists in to bring water-based cooling fluid into direct contact with high heat generating electronic components improving the heat transfer efficiency [Amoabeng and Choi, 2016]. The advantage of this technique is the reduction of the thermal resistances between heat source and cold source allowing higher inlet temperatures to the coolant [Zhang et al., 2018]. The liquid cooling is classified as direct when attaching cold plate heat exchangers at the chip level, and it is considered indirect when a liquid-cooled door is used providing rack-level cooling [Nadjahi et al., 2018].

The use of a thermal energy storage system is considered an effective strategy to reduce the cooling energy consumption in data centers, especially when used in combination with free cooling. The TES system can store cold fluid from the environment when the conditions are favorable and provide it when needed. It also improves the cooling system reliability [Amoabeng and Choi, 2016]. TES systems in data center commonly use water as the thermal storage material [Oró et al., 2015a].

The use of free cooling strategies is, nowadays, one of the most used cooling efficiency techniques for data centers [Oró et al., 2015a]. It can be implemented alongside almost all of the other techniques presented in this section. This technique becomes more effective when the facility has a good layout and airflow distribution [ASHRAE TC 9.9, 2016]. According to The Green Grid, 2012, it is estimated that the use of free cooling results in saving an average of 20% of money, energy and carbon emissions caused by cooling when compared to DCs that do not use this technique. The following section describes free cooling in detail.

1.4 Free cooling

Free cooling is a principle defined as the use of natural weather to cool an indoor environment [Oró et al., 2015a]. When the outdoor temperature is sufficiently low compared to the indoor operating temperature, it is possible to take advantage of this and cool the data center indoor environment without mechanical cooling [Amoabeng and Choi, 2016]. This compressor-less operation is commonly known as economizer cycle [Zhang et al., 2014].

Niemann et al., 2011 pointed out that an economizer is not an object, but a mode of operation. The economizer modes differ from each other regarding mainly the way the heat transfer is done. According to Oró et al., 2015b; Nadjahi et al., 2018, they can be roughly divided into airside and waterside categories. The main types of economizer modes of these categories are shown in Figure 1.5.

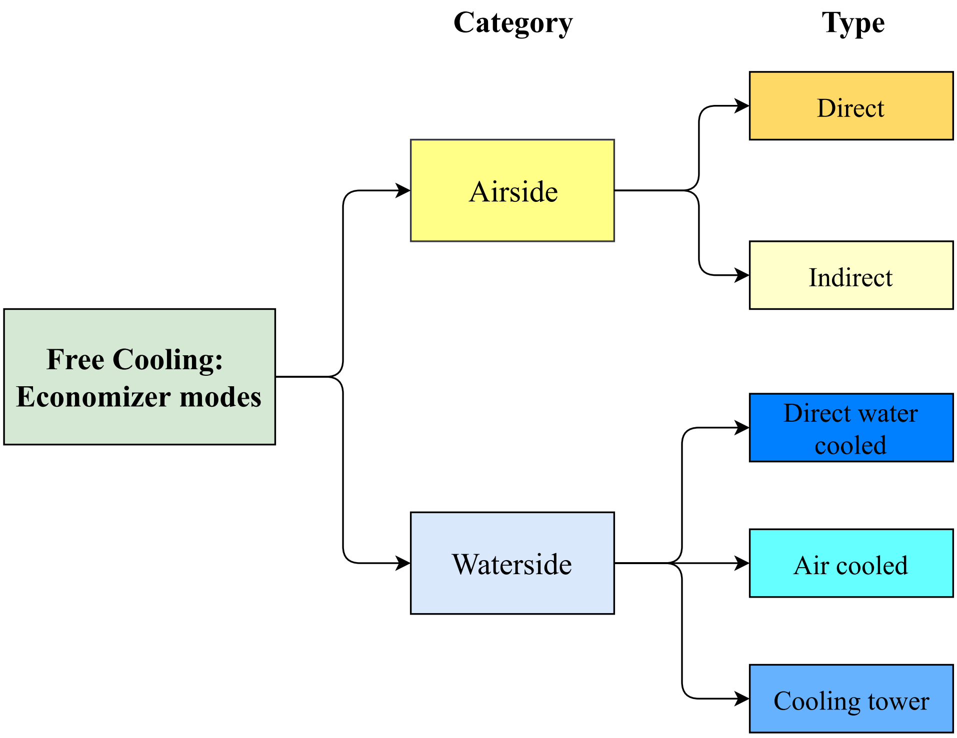


Figure 1.5 – Classification of the main types of economizer modes according to Amoabeng and Choi, 2016; Zhang et al., 2014.

Economizer types from the airside category cool the DC indoor environment air using the outdoor air directly or indirectly with the aid of heat exchangers [ASHRAE TC 9.9, 2016; Niemann et al., 2011], whereas waterside economizers use the outdoor weather to cool some or all of the return water in a chilled water loop [Lui, 2010]. All of the economizers types highlighted in Figure 1.5 are capable to reduce or eliminate the need for mechanical cooling when the outdoor condition is favorable.

Free cooling can be used either on full economizer, i.e., without the compressor; or in partial economizer as an auxiliary step to reduce the cooling load. Free cooling still relies on auxiliary power to drive system pumps and fans even working on full economizer mode [Niemann et al., 2011]. However, air conditioning compressors are the highest energy demanding device of a cooling system. Thus, significant energy savings can be achieved whenever they are turned off [Amoabeng and Choi, 2016].

1.4.1 Free cooling potential

Free cooling is considered an effective solution for reducing the energy consumption of cooling systems in data center when its operation is viable for a high number of hours in a year. Thus, the free cooling potential is defined as the number of hours in a year that the DC can be cooled without compressor work [Oró et al., 2015a; Malkamäki and Ovaska, 2012; Siriwardana et al., 2013]. The free cooling potential varies significantly depending on local climate [Amoabeng and Choi, 2016].

In this context, free cooling potential assessments are studies that evaluate the potential of a given city, region or country to cool environments without mechanical cooling. This concept is also applied to human comfort, as reported by Bulut and Aktacir, 2011, who compared dry-bulb temperatures retrieved from weather data of Istanbul (Turkey) with different temperatures for residential comfort limits aiming to evaluate the domestic free cooling potential in that city.

DC free cooling potential assessments were performed by Oró et al., 2015a; Malkamäki and Ovaska, 2012; Siriwardana et al., 2013; The Green Grid, 2009, 2012; among others. However, there is a lack of these studies in Brazil and Latin America. Besides, these studies are often made overly result-oriented, considering only the direct airside type, for particular cases and under strict conditions that may easily change in the future.

1.5 Thesis Objectives

Acknowledging the urge of energy savings in data centers, free cooling potential studies have an important role in the development of this technique and, consequently, in the increase of energy efficiency of these facilities. Motivated by the rising trend for energy efficiency in data centers, this work aims to develop criteria to estimate the DC free cooling potential of Brazilian cities.

It is intended to assess the potential considering the two main categories of free cooling: airside and waterside economizers. The criteria proposed in this work should be general and flexible to keep its relevance in the future and to be suitable for different DCs and regions in the country.

As specific objectives, the established criteria should be applied in Brazilian key cities to assess their free cooling potential.

1.6 Thesis Outline

This thesis is organized as described in the flowchart of Figure 1.6.

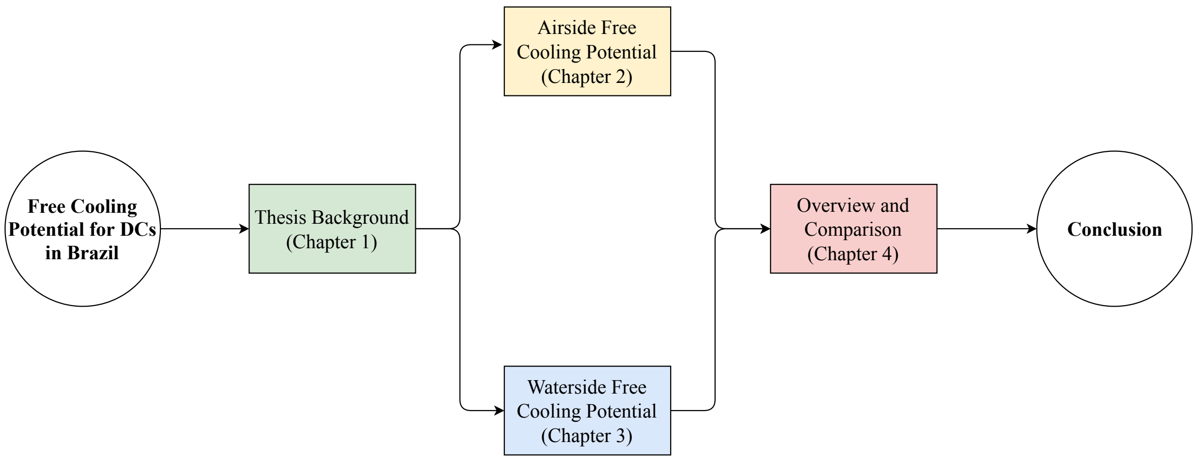


Figure 1.6 – Thesis outline flowchart.

- Chapter 1 provides background information about data centers, their energy consumption and trends for the future. It presents information about conventional cooling systems and the most common energy efficiency techniques seen in the DC industry nowadays. Concepts about free cooling and its potential assessments are also presented. Finally, the objectives of the thesis are stated in Section 1.5.
- Chapter 2 provides detailed information about airside free cooling types for data centers. It proposes criteria to estimate the airside free cooling potential in Brazil

and, then, evaluate this number for 14 Brazilian key cities using their weather data.

- Chapter 3 provides detailed information about waterside free cooling types for data centers. It develops a methodology to establish criteria to estimate the waterside free cooling potential. Then, it applies these criteria to estimate this potential for 14 Brazilian key cities.
- Chapter 4 provides an overview of the five main types of economizers in the airside and waterside categories. A comparison is made qualitatively and quantitatively with the aid of literature research and the results obtained in Chapters 2 and 3.

A bibliometric analysis of the references used in this study is presented in Appendix A.

2 AIRSIDE FREE COOLING POTENTIAL ESTIMATION FOR DATA CENTERS IN BRAZIL[1]

2.1 Introduction

Airside free cooling is an energy saving technique which makes use of the outdoor air to cool data centers (DCs) indoor environment. DCs indoor and outdoor air conditions are constantly monitored with the aid of sensors [Zhang et al., 2014]. When the outdoor condition is appropriate, the cooling system works in the so-called economizer or, in this case, airside economizer mode [Niemann et al., 2011]. In this mode of operation, outdoor air can either be drawn directly to cool the indoor environment or be used indirectly, with the help of heat exchangers or thermal wheels [ASHRAE TC 9.9, 2016; Niemann et al., 2011].

Airside free cooling is considered an effective solution for reducing the energy consumption of cooling systems in data center when its operation is viable for a high number of hours in a year, which is defined as free cooling potential [Oró et al., 2015a; Malkamäki and Ovaska, 2012; Siriwardana et al., 2013]. The airside free cooling potential varies significantly depending on local climate [Amoabeng and Choi, 2016].

DC free cooling potential assessments commonly focus on general direct airside economizers. Siriwardana et al., 2013 investigated the potential of airside economizers in DCs housed in 20 Australian cities, using weather data from 2000 to 2011. The cities had their hourly dry-bulb temperature being compared with 15°C, which was set by the authors as the maximum allowed temperature for the DC supplied air intake. The results showed that Melbourne presented the highest free cooling potential from the cities assessed allowing for direct airside economizers to be used for more than 5000 h per year.

Similarly, The Green Grid, 2009 published the "Airside Free Cooling Maps" (Figure 2.1), evaluating the potential of direct airside economizers for DCs in Europe, North America and Japan. These maps were updated in 2012 [The Green Grid, 2012] to take

[1]The content of this chapter was presented in the ENCIT 2018-17$_{th}$ Brazilian Congress of Thermal Sciences and Engineering-November 25$_{th}$-28$_{th}$, 2018, under ID-0167

into account newer and more relaxed operating ranges limits [ASHRAE TC 9.9, 2011].

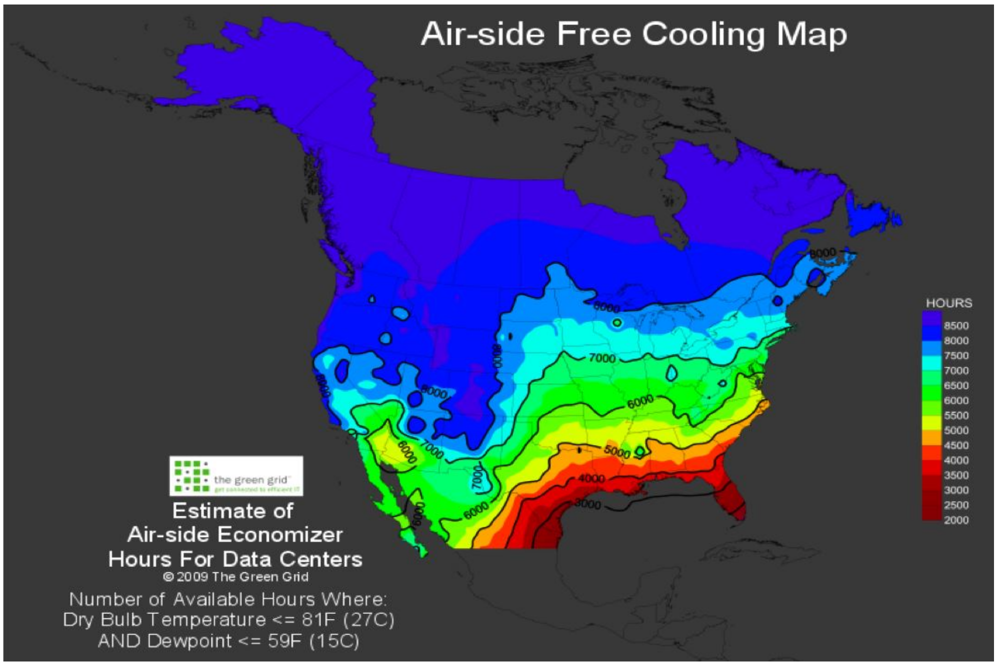


Figure 2.1 – North America airside free cooling map made by The Green Grid, 2009.

These maps were made by comparing bin data collected from the WeatherBank with maximum limits of dry-bulb and dew-point temperatures for data centers. The Green Grid Airside Free Cooling Maps have become an important reference for DC operators and researchers in this field, as it allows for a first estimate of the free cooling performance in different regions.

In Brazil, works from Belizário, 2018; Driemeyer, 2016 modeled and assessed free cooling systems as case studies, but there is still a lack of general free cooling potential assessments in the country. The work presented in this chapter aimed to propose criteria to estimate the free cooling potential of direct type airside economizers in Brazil. These criteria were applied to 14 Brazilian key cities.

2.2 Airside economizer types

Zhang et al., 2014 classified airside economizers in direct and indirect types, while ASHRAE TC 9.9, 2016; Niemann et al., 2011 differentiate architectures inside the indirect economizers such as heat exchanger and thermal wheel systems. For simplification, this work uses the classification described by Zhang et al., 2014.

2.2.1 Direct airside economizer

In order to work in direct airside (or fresh air) economizers, DCs require control systems with dampers and fans to change the operation of the facility from a compressor-based cooling to a free cooling mode which brings fresh air to cool the IT equipment. Outdoor air must be filtered prior to its admission into the DC [Zhang et al., 2014].

Typically, the outdoor air is drawn to the indoor environment without any air conditioning or humidity control [ASHRAE TC 9.9, 2016]. Humidification or dehumidification systems can be used to extend the economizer operation. However, a detailed study should be carried out to verify the feasibility of these processes, because they can increase the DC energy consumption if excessively used, as shown by Lee and Chen, 2013.

Figure 2.2 presents a typical direct airside economizer system. It is worth noticing that some of the hot exhaust air could be mixed back with the cold outdoor air aiming to maintain the humidity parameters of the supply air within the specified ranges [Niemann et al., 2011].

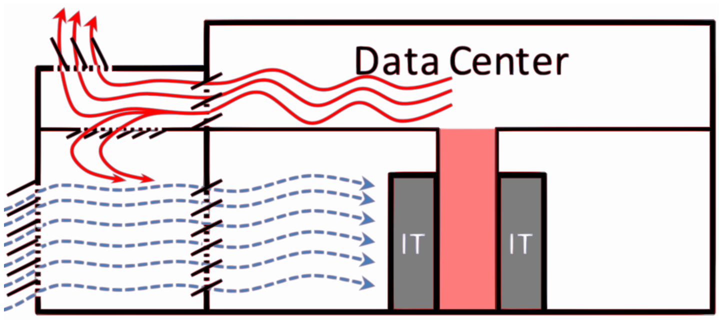


Figure 2.2 – Typical direct airside economizer system [Niemann et al., 2011].

Although direct airside free cooling has the advantage to be a less complex system which does not require pump, cooling towers or heat exchangers, there are some concerns about this type of economizer that should be addressed [Zhang et al., 2014]. Much research has been done regarding the problems that could be caused to IT equipment due to the indoor temperature and humidity disturbance, unwanted particulates and gaseous contaminants which are consequences of the direct airside free cooling [Gao et al., 2015; Hydeman and Swenson, 2010; Intel, 2012; Wan et al., 2013]. These concerns are being addressed by IT manufacturers who are constantly improving their products aiming to increase the temperature and humidity operating ranges and, consequently, provide equipment which are more suitable to be cooled by free cooling.

2.2.2 Indirect airside economizer

Indirect airside economizers use air to air heat exchangers to transfer indoor heat to the outside aiming to reduce the disturbance in the DC environment [Zhang et al., 2014] as shown in Figure 2.3.

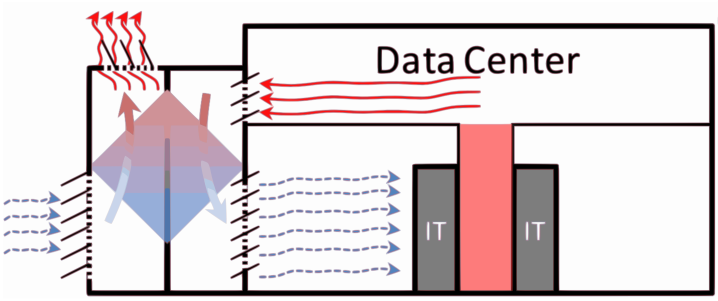


Figure 2.3 – Typical indirect airside economizer system [Niemann et al., 2011].

The additional heat transfer step causes a reduction in the effectiveness of the system, usually allowing for less free cooling hours when compared to direct airside economizers. On the other hand, it brings the advantages of preserving the indoor air quality, saving the need for additional air filtering and being less dependent on the outdoor humidity [ASHRAE TC 9.9, 2016; Zhang et al., 2014]. Besides, it can even provide more free cooling hours than a direct type for DCs located in regions with constant high humidity levels.

The performance of direct type economizers depends only on the regional climate and indoor operating conditions, while the indirect type performance relies also on parameters related to the heat exchanger. Thus, direct airside free cooling potential assessments are more general and straightforward, making this kind of assessment a better starting point for DCs free cooling potential studies.

2.3 Methodology

The methodology of this chapter is summarized in the flowchart of Figure 2.4.

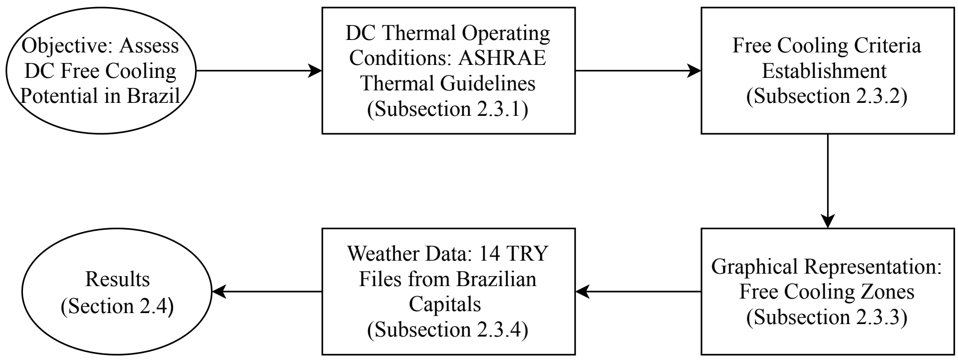


Figure 2.4 – Methodology for the assessment of DCs direct airside free cooling potential in Brazil.

ASHRAE thermal guidelines [ASHRAE TC 9.9, 2015] were considered to identify DC operating conditions (Subsection 2.3.1). Further research was performed to select the most relevant parameters to establish the free cooling criteria, namely: upper dry-bulb temperature limit and upper dew-point temperature limit (Subsection 2.3.2). A graphical representation was proposed in Subsection 2.3.3 to illustrate the free cooling zones on a psychrometric chart. Finally, in Subsection 2.3.4, weather data from 14 Brazilian capitals were used to assess their hourly behavior over a year and compare it with the established free cooling criteria.

2.3.1 DC thermal operating conditions

The most recent ASHRAE thermal guidelines [ASHRAE TC 9.9, 2015] were selected to be the reference of the required conditions to achieve a reliable operation in a DC. Ranges of dry-bulb temperature (DBT), relative humidity (RH) and dew-point temperature (DPT) were featured for different classes of IT equipment in this guideline as shown in Table 2.1.

Table 2.1 – Recommended and Allowable ranges for DC operation [Adapted from ASHRAE TC 9.9, 2015].

Range	DBT (°C)	DPT (°C)	RH (%)
Recommended	18 to 27	-09 to 15	8 to 60
Allowable A1	15 to 32	-12 to 17	8 to 80
Allowable A2	10 to 35	-12 to 21	8 to 80
Allowable A3	05 to 40	-12 to 24	8 to 85
Allowable A4	05 to 45	-12 to 24	8 to 90

The Recommended range is defined as a reference, as it is the safest one and also the most accepted by DC operators [Lee and Chen, 2013]. The other four are called Allowable ranges, with different limits according to the IT equipment class. [ASHRAE TC 9.9, 2008]. An equipment class is a definition for IT manufacturers design their products.

When it was first created, the Recommended range was intended to be the most reliable, acceptable and reasonable power-efficient operation zone, but it was never meant to be the absolute limits of operation [ASHRAE TC 9.9, 2011]. As a result of the growing need for energy efficiency, and consequently the interest to utilize economizers as much as possible during a year, the Allowable ranges were proposed, reinforcing the idea that it is acceptable to operate outside the Recommended range for short periods of time without affecting the overall reliability of the IT equipment [ASHRAE TC 9.9, 2011]. It is worth noticing that the newer the equipment is, its allowable thermal operating zone tend to be more relaxed and, hence, it should suit a broader class such as A3 or A4, while the older ones are more suited to operate within the A1 and A2 classes.

ASHRAE TC 9.9, 2015 states that the DBT, RH and DPT parameters should be measured in the IT equipment cold face, i.e., roughly at the supplied air intake. The operating envelopes (Figure 2.5[2]) were made using the thresholds of Table 2.1. They illustrate the conditions of the supplied air intake that allows a DC to operate within the ASHRAE suggested ranges.

According to ASHRAE TC 9.9, 2011, these operating envelopes should only be considered for facilities that have already achieved a good architecture design and airflow management. The reliability of the DC is not secured, even in the Recommended range, if some basic aspects of the data center design were not respected.

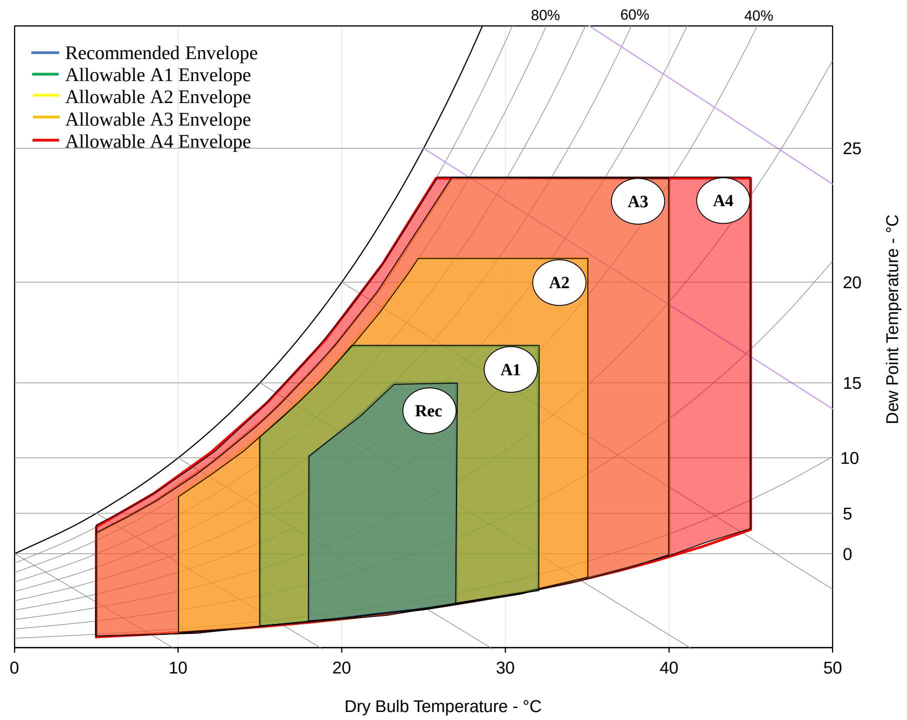


Figure 2.5 – Recommended and Allowable operating envelopes on a psychrometric chart.

2.3.2 Free cooling criteria

The Recommended and Allowable envelopes shown in Figure 2.5 are intended to describe operating limits of DCs while using mechanical cooling. The free cooling

[2]All the psychrometric charts figures presented in this Thesis were made using Microsoft Excel software with the aid of the Psych plugin [WCEC, 2013].

potential of a location is measured by a prior assessment which verifies if the local weather condition allows natural air usage for a reliable IT equipment cooling. In that procedure, some of the envelope boundaries may not be required. An in-depth survey in the literature was carried out in this subsection in order to understand which limits could be discarded while establishing the direct airside free cooling criteria.

Dry-bulb temperature

The upper DBT limit is the most important parameter for IT equipment operation and should be taken into account in this evaluation, as most of the failure mechanisms of electronic components are intensified by increasing their operational temperature [ASHRAE TC 9.9, 2016]. The maximum operating temperature limit that an IT equipment should reach at the chip level is about 85°C [Amoabeng and Choi, 2016; Marcinichen et al., 2012]. The heat removal in a data center must guarantee that this limit is not surpassed.

The lower boundary of DBT in the ASHRAE suggested ranges is intended to prevent a very inefficient energetic operation under mechanical cooling, as stated in the ASHRAE TC 9.9, 2011. That boundary was discarded in the present work as it does not impact the free cooling potential assessment.

Lower humidity boundaries

The RH and DPT parameters are metrics to measure the relative and absolute humidity of the DC environment respectively. Their lower limits were introduced by ASHRAE TC 9.9 to avoid the risk of electronic discharges (ESD) in the IT equipment [Oró et al., 2015a]. ASHRAE TC 9.9, 2015 reduced the lower RH limit from 25% [ASHRAE TC 9.9, 2011] to 8% after studies [Gao et al., 2015; Hydeman and Swenson, 2010; Wan et al., 2013] had verified that this reduction would not increase at high rates the ESD probability.

In Brazil, there are almost no occurrences of RH and DPT values below 8% and -9°C respectively [Kontoyanis, 2018]. Thus, it was decided to discard the lower RH

and DPT limits while assessing the free cooling potential.

Higher humidity boundaries

High humidity levels can cause water vapor to condensate on IT equipment, putting at risk their reliability [Oró et al., 2015a]. However, the RH parameter is difficult to be controlled inside a DC facility as it depends on both the absolute humidity content and the dry-bulb temperature [Kristoff, 2019]. Nevertheless, its control can be performed by blending hot exhaust air to the inlet air as shown in Section 2.2.

DPT is a more stable parameter, as it is linked to the air absolute humidity, which does not change significantly throughout the DC environment [Kristoff, 2019]. Therefore, the upper DPT limit was taken into account while the upper RH limit was discarded in the present assessment.

Establishing the free cooling criteria

Based on these assumptions, only two parameters among those presented in the operating ranges suggested by ASHRAE were considered to evaluate the free cooling potential of Brazilian cities: upper dry-bulb temperature limit ($DBT_{in,max}$) and upper dew-point temperature limit ($DPT_{in,max}$). Thus, the free cooling is considered possible for the hourly step accounted by the double condition imposed in Equation 2.1,

$$DBT_{out} \leq DBT_{in,max} \;\&\; DPT_{out} \leq DPT_{in,max} \therefore \text{Free cooling is possible.} \tag{2.1}$$

for the hourly outdoor dry-bulb DBT_{out} and dew-point DPT_{out} temperatures in respect to the desired limits for $DBT_{in,max}$ and $DPT_{in,max}$.

It was assumed that the air temperature remains unchanged along its intake through the cold face of IT equipment. Any possible deviation can be taken into account by using a more conservative value of $DBT_{in,max}$.

It is worth noticing that this methodology does not exclusively rely on Table 2.1 values, as these limits may be relaxed in the future. However, these limits were taken into account to evaluate this assessment.

2.3.3 Graphical representation

A graphical representation was made to illustrate the criteria established in Subsection 2.3.2 on a psychrometric chart. Figure 2.6 presents the free cooling zone considering the free cooling criteria applied to the Recommended range limits for $DBT_{in,max}$ and $DPT_{in,max}$.

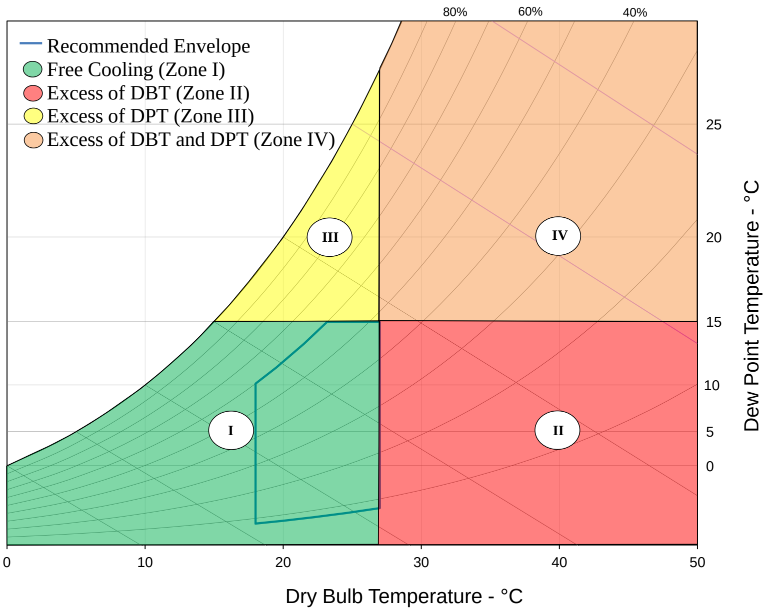
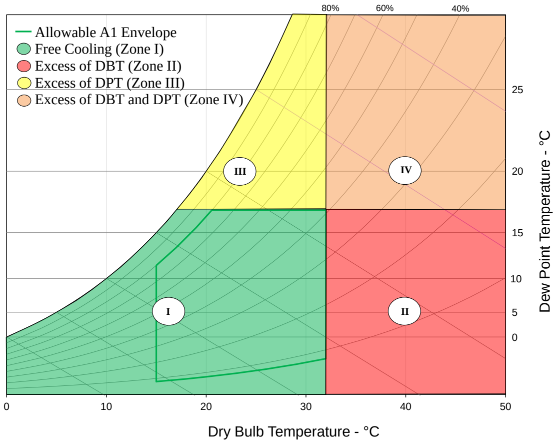


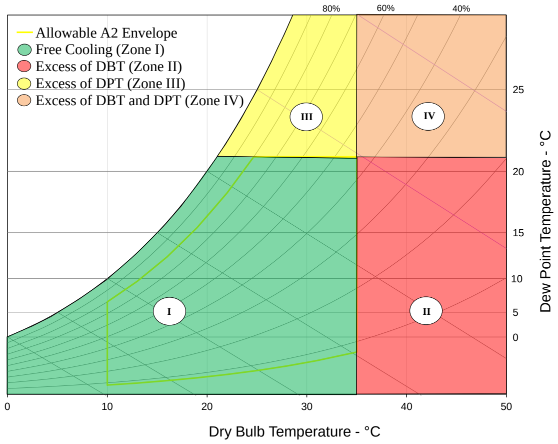
Figure 2.6 – Free cooling zone considering the Recommended range limits on a psychrometric chart.

The green color represents the zone where free cooling is achievable (Zone I), the red color means that the free cooling is not possible due to the high DBT level (Zone II), the yellow color represents that free cooling is not possible due to the high DPT level (Zone III), and the orange zone is where free cooling is not viable due to both: DBT and DPT parameters (Zone IV).

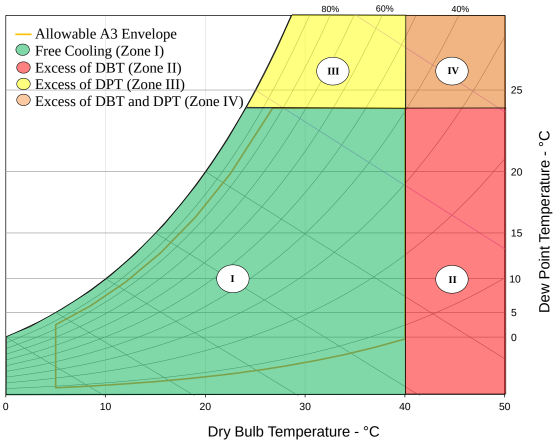
Free cooling zones for Allowable ranges limits A1, A2, A3 and A4 were similarly plotted on a psychrometric chart as shown in Figure 2.7. DBT and DPT limits from all ranges were taken into consideration aiming to provide greater flexibility to the free cooling assessment.



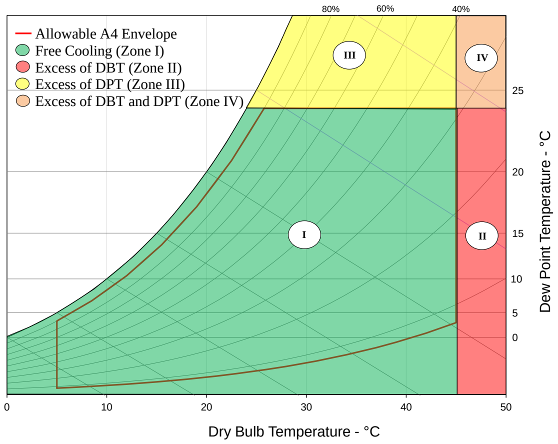
(a) A1 range



(b) A2 range



(c) A3 range



(d) A4 range

Figure 2.7 – Free cooling zones considering Allowable ranges limits.

2.3.4 Weather data

Dry-bulb and dew-point temperatures were employed to identify the number of hours that each city could potentially operate on free cooling along a year period (8760 hours). Fourteen capital cities were selected for the assessment based on the availability of Test Reference Year (TRY) weather data. All country regions were covered (South, Southeast, Midwest, Northeast and North), as presented in Table 2.2. Microsoft Excel software was used to compare the criteria established with the cities weather data.

Table 2.2 – Capital cities assessed by country region. Weather data obtained from LabEEE, 2018.

Region	City (State) assessed
South	Porto Alegre (RS), Florianópolis (SC), Curitiba (PR)
Southeast	São Paulo (SP), Rio de Janeiro (RJ), Vitória (ES)
Midwest	Brasília (DF)
Northeast	Salvador (BA), Maceió (AL), Recife (PE), Natal (RN), Fortaleza (CE), São Luís (MA)
North	Belém (PA)

2.4 Results

Table 2.3 summarizes the airside free cooling potential assessment results for the 14 Brazilian capitals listed in Table 2.2. Limits from all ranges (Recommended and Allowable A1, A2, A3, A4) were considered. Reddish tones represent lower free cooling potential, while bluish tones represent higher potential.

Table 2.3 – Free cooling potential in 14 Brazilian capitals.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	3783	5309	7927	8735	8735
Florianópolis	SC	27°36'S	1925	3760	7004	8470	8470
Curitiba	PR	25°26'S	5575	7299	8726	8760	8760
São Paulo	SP	23°33'S	4259	6418	8665	8760	8760
Rio de Janeiro	RJ	22°54'S	255	1134	5481	8555	8555
Vitória	ES	20°19'S	447	1417	5304	8494	8494
Brasília	DF	15°47'S	3028	5079	8745	8760	8760
Salvador	BA	12°58'S	17	261	5061	8729	8729
Maceió	AL	9°40'S	8	130	5795	8759	8759
Recife	PE	8°03'S	0	4	2521	8694	8694
Natal	RN	5°48'S	0	6	3048	8697	8697
Fortaleza	CE	3°43'S	0	1	221	6657	6657
São Luís	MA	2°32'S	0	1	168	8141	8141
Belém	PA	1°27'S	0	2	387	7888	7888

Curitiba displayed the best performance among all cities, being capable to operate inside Zone I (Figure 2.6) for 5575 hours considering the Recommended range limits. Capital cities such as São Paulo, Porto Alegre and Brasília presented free cooling potential for more than 3000 hours considering the Recommended range. Most of the North and Northeast cities displayed a negligible number of free cooling hours for both Recommended and A1 range limits.

Overall better results were achieved when considering more flexible ranges (A2, A3 and A4). Curitiba, São Paulo and Brasília can operate in free cooling considering A2 range for almost the entire year (8000+ hours), and all cities aside from Fortaleza are able to operate inside Zone I for 7800+ hours in a year when A3 or A4 ranges were considered.

By looking exclusively to the free cooling hours, one cannot identify whether the excess of DBT or the excess of DPT were responsible to prevent more free cooling hours. It was decided to further analyze some of these cities, now looking for the reasons why it is not possible to have extra free cooling hours there. The capital cities chosen for this analysis were: Curitiba due to its overall good results, São Paulo due to its economic relevance for the country and Fortaleza as a representative city of the Northeast region. The hourly weather occurrences were plotted on a psychrometric chart with the indicated zones (as in Figure 2.6) to achieve a better understanding of the cities climate and its relation with the free cooling potential.

2.4.1 Curitiba detailed results

Figure 2.8 shows the hourly weather occurrences for Curitiba considering the Recommended range limits to define the four zones. The hourly weather occurrences in this city were mainly in Zone I (free cooling) and Zone III (free cooling not achieved by an excess of DPT). Zone II (excess of DBT) had only a few occurrences in the entire year, which indicates that DBT is not the critical parameter for free cooling potential in Curitiba. The detailed quantitative results are presented in Table 2.4, considering all ranges.

Curitiba has potential to operate 63.64% of the hours in a year inside Zone I con-

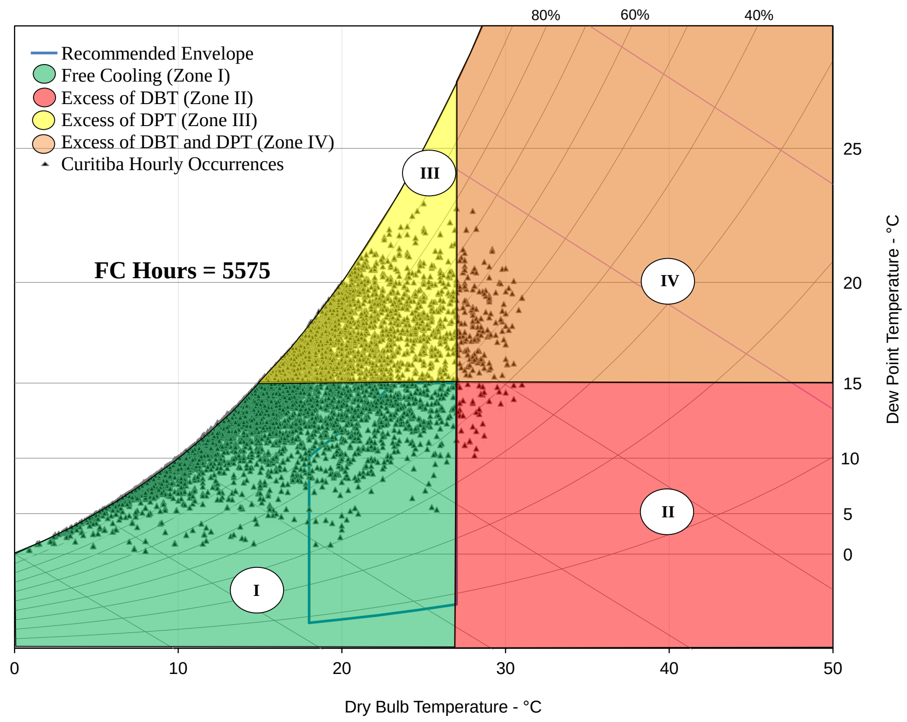


Figure 2.8 – Curitiba hourly weather occurrences in a year.

Table 2.4 – Detailed results of free cooling potential in Curitiba.

Range	Zone I (%)	Zone II (%)	Zone III (%)	Zone IV (%)
Recommended	63.64%	0.45%	34.07%	1.83%
A1	83.32%	0.00%	16.68%	0.00%
A2	99.61%	0.00%	0.39%	0.00%
A3	100.00%	0.00%	0.00%	0.00%
A4	100.00%	0.00%	0.00%	0.00%

sidering the Recommended range. There are no hours above the dry-bulb temperature limit of the Allowable class A1 due to the city cool climate. The main issue in Curitiba is the DPT level, which prevents the free cooling application within the A1 range for 16.68% of the year (1461 hours). In a more flexible limit, such as A2, it is possible to operate in free cooling for almost the entire year (99.61%). Moreover, considering A3 and A4 ranges all occurrences were in Zone I.

2.4.2 São Paulo detailed results

Figure 2.9 shows the hourly weather occurrences for São Paulo considering the Recommended range limits to define the four zones. Results were less promising than the ones for Curitiba, with a higher amount of weather occurrences outside Zone I. Most of the occurrences were placed in Zone I and Zone III, which indicates that the DPT is the critical parameter for the free cooling assessment in this city. The detailed quantitative results are presented in Table 2.5, considering all ranges.

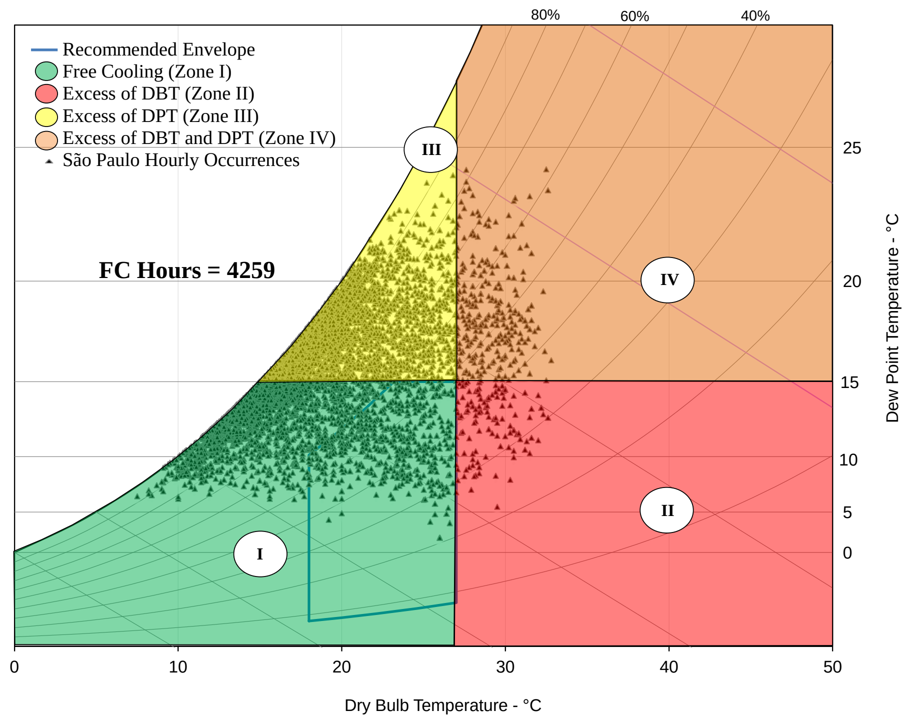


Figure 2.9 – São Paulo hourly weather occurrences in a year.

Table 2.5 results confirmed that DBT does not represent a problem at all for free cooling in São Paulo, since only 1.52% of the occurrences were within Zone II considering the Recommended threshold. There were no occurrences of DBT above the A2 range limit. São Paulo displayed a free cooling potential of 73.26% of the year considering the A1 range limit, 98.92% considering A2 limits, and for the entire year considering A3 and A4 ranges.

Table 2.5 – Detailed results of free cooling potential in São Paulo.

Range	Zone I (%)	Zone II (%)	Zone III (%)	Zone IV (%)
Recommended	48.62%	1.52%	46.47%	3.39%
A1	73.26%	0.08%	26.63%	0.03%
A2	98.92%	0.00%	1.08%	0.00%
A3	100.00%	0.00%	0.00%	0.00%
A4	100.00%	0.00%	0.00%	0.00%

2.4.3 Fortaleza detailed results

Figure 2.10 shows the hourly weather occurrences for Fortaleza considering the Recommended range limits to define the four zones. Fortaleza displayed the worst performance among the three cities further analyzed in this section. There is no hour in the year that fits inside Zone I or II due to its constant high *DPT* level. The detailed behavior of this city considering all ranges limits is presented on Table 2.6.

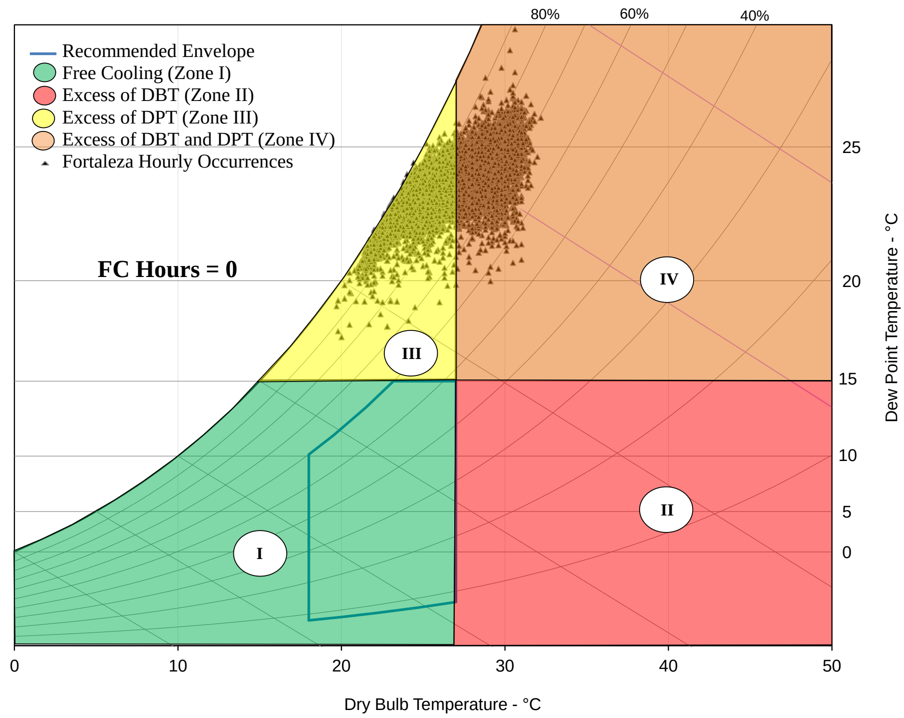


Figure 2.10 – Fortaleza hourly weather occurrences in a year.

Table 2.6 – Detailed results of free cooling potential in Fortaleza.

Range	Zone I (%)	Zone II (%)	Zone III (%)	Zone IV (%)
Recommended	0.00%	0.00%	61.88%	38.12%
A1	0.01%	0.00%	99.98%	0.01%
A2	2.52%	0.00%	97.48%	0.00%
A3	75.99%	0.00%	24.01%	0.00%
A4	75.99%	0.00%	24.01%	0.00%

Table 2.6 shows that Fortaleza only achieved potential to free cooling while considering A3 and A4 ranges limits (75.99%). *DPT* was the critical parameter preventing extra free cooling hours, since there was not even a single occurrence within Zone II, and from A1 range onwards there were almost no weather occurrences in Zone IV.

2.4.4 Parameter analysis

The *DPT* was the critical parameter preventing extra free cooling hours for the three further analyzed cities. The free cooling hours prevented exclusively by the *DBT* parameter were almost negligible for these cities. An expanded assessment based only on the *DPT* criterion was performed to the 14 capital cities to investigate whether the *DBT* criterion was really required (Table 2.7).

Results presented in Table 2.7 corroborate with the idea that *DPT* is indeed the critical parameter to the free cooling potential assessment in Brazil. The *DBT* criterion was only relevant while assessing the Recommended range limits and for a few cities such as Brasília and São Paulo, which displayed changes of 9.94% and 3.12% respectively. Maceió had a variation of 62.50% in its free cooling hours, but the absolute number is negligible since it raised from 8 to 13 hours. All cities displayed slightly increases or even no changes at all while considering the limits of the Allowable ranges, which indicates that the direct airside free cooling assessment could be performed based only on the *DPT* criterion without causing major changes in the free cooling potential hours of the 14 Brazilian cities.

Table 2.7 – Free cooling hours while assessing only the dew-point temperature criterion and its percentage growth in relation to the assessment considering the two criteria.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	3836 (+1.40%)	5323 (+0.26%)	7939 (+0.15%)	8735 (=)	8735 (=)
Florianópolis	SC	27°36'S	1929 (+0.21%)	3760 (=)	7004 (=)	8470 (=)	8470 (=)
Curitiba	PR	25°26'S	5615 (+0.72%)	7299 (=)	8726 (=)	8760 (=)	8760 (=)
São Paulo	SP	23°33'S	4392 (+3.12%)	6425 (+0.11%)	8665 (=)	8760 (=)	8760 (=)
Rio de Janeiro	RJ	22°54'S	259 (+1.57%)	1134 (=)	5487 (+0.11%)	8555 (=)	8555 (=)
Vitória	ES	20°19'S	447 (=)	1417 (=)	5304 (=)	8494 (=)	8494 (=)
Brasília	DF	15°47'S	3329 (+9.94%)	5086 (+0.14%)	8745 (=)	8760 (=)	8760 (=)
Salvador	BA	12°58'S	17 (=)	261 (=)	5061 (=)	8729 (=)	8729 (=)
Maceió	AL	9°40'S	13 (+62.50%)	130 (=)	5795 (=)	8759 (=)	8759 (=)
Recife	PE	8°13'S	0 (=)	4 (=)	2521 (=)	8694 (=)	8694 (=)
Natal	RN	5°48'S	0 (=)	6 (=)	3048 (=)	8697 (=)	8697 (=)
Fortaleza	CE	3°43'S	0 (=)	1 (=)	221 (=)	6657 (=)	6657 (=)
São Luís	MA	2°32'S	0 (=)	1 (=)	168 (=)	8141 (=)	8141 (=)
Belém	PA	1°27'S	0 (=)	2 (=)	387 (=)	7888 (=)	7888 (=)

2.5 Conclusion

In this chapter, criteria to assess direct airside free cooling potential in data centers have been developed considering two parameters: upper dry-bulb temperature ($DBT_{out,max}$) and upper dew-point temperature ($DPT_{out,max}$). These criteria were presented algebraically and graphically. Then, the criteria were applied to assess the free cooling potential of 14 Brazilian capitals using TRY weather data and considering the ASHRAE thermal guidelines limits.

The results showed that cities such as Curitiba, São Paulo, Porto Alegre and Brasília have the potential to use free cooling in their data centers for over than 3000 hours in a year considering the most conservative operating limits (Recommended range). Curitiba presented the best overall performance among the analyzed cities, being able to operate 5575 hours without mechanical cooling in that range.

All North and Northeast cities did not show viability to the direct airside free cooling when considering the most conservative ranges. However, almost all cities could operate with more than 7800 hours of compressor-less cooling while assessing more flexible limits, such as the ones from A3 and A4 classes.

A further analysis was performed to detail the results from Curitiba, São Paulo and Fortaleza, which indicated that the critical parameter to assess direct airside free cooling potential was the dew-point temperature (DPT). This suspicion was confirmed by a parameter analysis which showed that the dry-bulb temperature (DBT) criterion was only relevant for a few cities under the Recommended range. The assessment could be performed based only on the DPT parameter without causing major changes in the final result, at least when considering the Allowable range limits.

Better free cooling potential results are expected to be achieved with an indirect type of economizer, since the results of this chapter indicated that the high level of humidity in the outdoor air was the main issue preventing extra free cooling hours for Brazilian weather conditions.

3 WATERSIDE FREE COOLING POTENTIAL ESTIMATION FOR DATA CENTERS IN BRAZIL

3.1 Introduction

Waterside free cooling is an energy saving technique which consists in operate a facility in the waterside economizer mode. In this mode of operation, the outdoor weather is used to cool some or all of the return water in a chilled water loop, substantially reducing or even eliminating the need for mechanical cooling [Lui, 2010]. The main difference in relation to the airside category is that any of the waterside economizer types cool the DC indoor environment using water and always in an indirect way.

Free cooling is considered an effective solution for reducing the energy consumption of cooling systems in data center when its operation is viable for a high number of hours in a year, which is defined as free cooling potential [Oró et al., 2015a; Malkamäki and Ovaska, 2012; Siriwardana et al., 2013]. The free cooling potential varies significantly depending on local climate [Amoabeng and Choi, 2016].

Most of the free cooling potential assessments in the literature consider only economizers from the airside category because their potential estimation is more straightforward, while inside the waterside category there are more variables in the problem to be taken into account, making this assessment more difficult to be done. Works regarding waterside economizers often prefer to perform a system analysis for a specific data center (such as Afonso and Moreira, 2017; Agrawal et al., 2016; Beaty et al., 2018; Belizário, 2018; Cho et al., 2017; Ling et al., 2018 have done) rather than a general potential assessment.

Beaty et al., 2019 presented an assessment of the waterside free cooling potential assessment for several North American cities, by considering different values for the supply air temperature, ranging from 14°C to 24°C. The approach between the outdoor wet-bulb temperature and the chilled water supply was assumed as 3.9°C and the temperature difference between the chilled water supply and the supply air temperature was assumed as 5.6°C. The author evaluated the hour percentage in a year which a DC under those conditions could operate under waterside free cooling, based on the local weather data. Denver displayed the highest potential among the assessed cities, with 53% of free cooling potential for the worst scenario.

A similar way to simplify the cooling tower system was adopted by Belizário, 2018 in his economic case study of a data center in São Paulo (Brazil). He set the cooling tower approach as 4°C and fixed the chilled water supply temperature as 23°C. However, the number of hours in a year in which free cooling was possible was not directly assessed in his work.

The work presented in this chapter aimed to establish criteria to free cooling potential for data centers considering a cooling tower economizer system. The assessment of waterside free cooling potential intended to be as general and flexible as possible, avoiding specific detailing that would reduce its relevance and applicability for different kinds of DC. The developed criteria were focused on 14 Brazilian key cities.

3.2 Waterside economizer types

Waterside economizers were classified by Zhang et al., 2014 as direct water cooled system; air cooled system and cooling tower system, presented as follows.

3.2.1 Direct water cooled type

In a direct water cooled system, natural cold water is used to cool the data center indoor air without any other steps of heat transfer. This application is limited by the dependency either on purchasing water or on natural cold water availability, meaning that the DC must be located close to water sources [Zhang et al., 2014]. Nevertheless, direct water cooled economizer is an efficient operating mode, able to maintain the facility temperature close to the average environment temperature for 24 h a day. Figure 3.1 presents a schematic of this economizer system.

Direct water cooled can be a good option for DCs that overcome those limitations. These systems seem promising in Brazil, due to the country large coastline, and the proximity of its key cities to the ocean. However, cooling water drawn from nat-

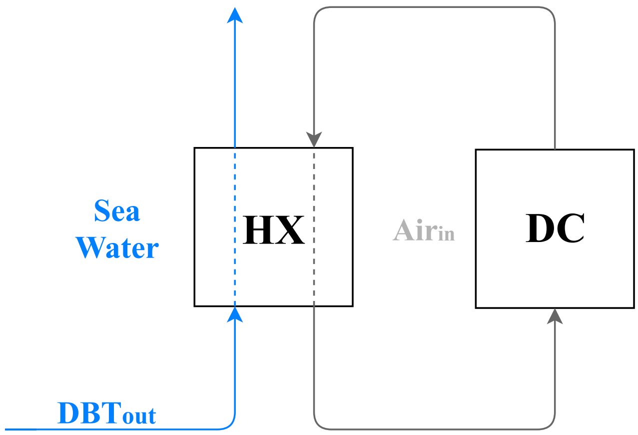


Figure 3.1 – A schematic of a direct water cooled system [Adapted from Clidaras et al., 2009].

ural sources may impact the local ecosystem due to the increased temperature of the discharged water. Besides, water purchased from utilities for this purpose became very expensive because of increased water supply and disposal costs [ASHRAE, 2016]. In short, direct water cooled systems is considered an attractive alternative if their issues regarding the operational cost and environmental impact can be handled.

3.2.2 Air cooled type

Air cooled systems are based on sensible heat exchangers to cool down the circulating water whenever the outdoor air dry-bulb temperature is favorable. When the outdoor air is not capable to handle the entire heat load, the required mechanical cooling is provided by the chiller. Figure 3.2 presents a schematic of this economizer system.

Waterside economizers of air cooled type are a simpler solution than the direct water cooled ones and avoid the environmental impact caused by the consumption of natural water. On the other hand, its effectiveness is lower [ASHRAE, 2016], promoting fewer free cooling hours.

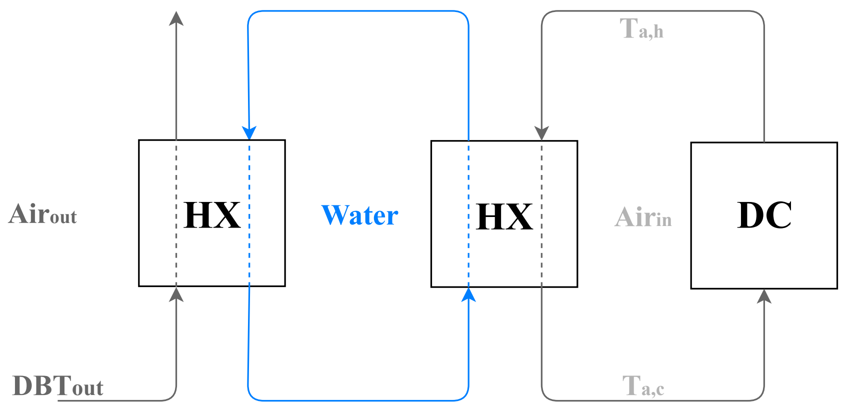


Figure 3.2 – Schematic of an air cooled waterside economizer system [Adapted from Zhang et al., 2014].

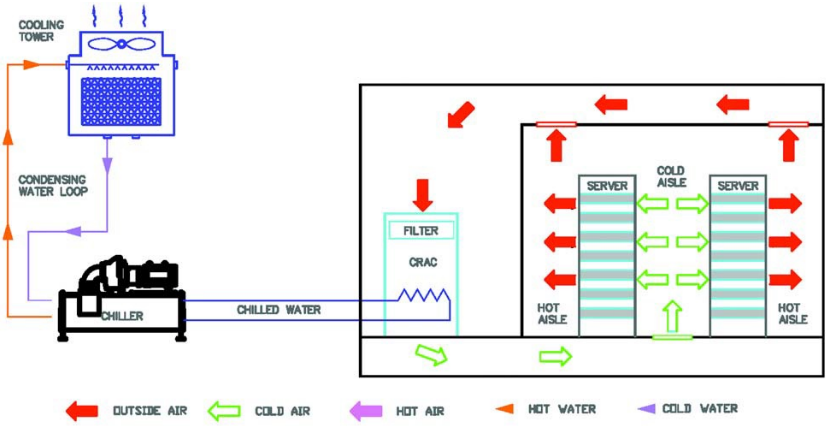
3.2.3 Cooling tower type

A cooling tower water circuit is used to cool the indoor circulating water in this type of economizer as shown in Figure 3.3.

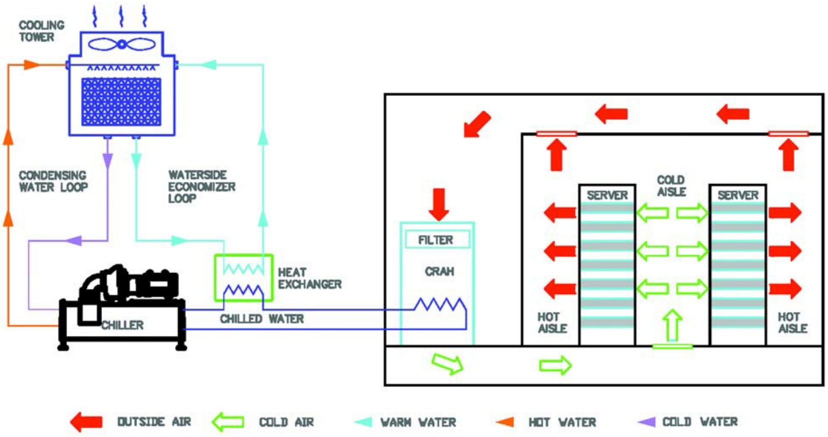
At least two water loops are needed, one for the cooling tower and other to cool the DC indoor environment. This type of free cooling can be built from a conventional cooling system by adding a chiller bypass via heat exchanger economizer mode [Zhang et al., 2014]. The DC indoor heat is transferred from the chilled water loop into the cooling tower water loop to be dissipated into the atmosphere, usually aided by plate and frame heat exchangers. As a result, the DC cooling demand is partially or entirely satisfied without the use of mechanical cooling [Lui, 2010].

The configuration referred to as parallel waterside economizer (PWSE) [Lui, 2010] or, more commonly, as non-integrated [Beaty et al., 2018; Stein, 2009], presented on Figure 3.4, consists on installing a heat exchanger in parallel with the chiller. This means that it is either possible to cool the entire heat load in the economizer mode, or none of that.

The system is referred to as series waterside economizer (SWSE) [Lui, 2010] or integrated [Beaty et al., 2018; Stein, 2009] whenever the heat exchanger is installed in tandem with respect to the chiller as shown in Figure 3.5. This configuration is capable



(a) Conventional cooling system with cooling tower.

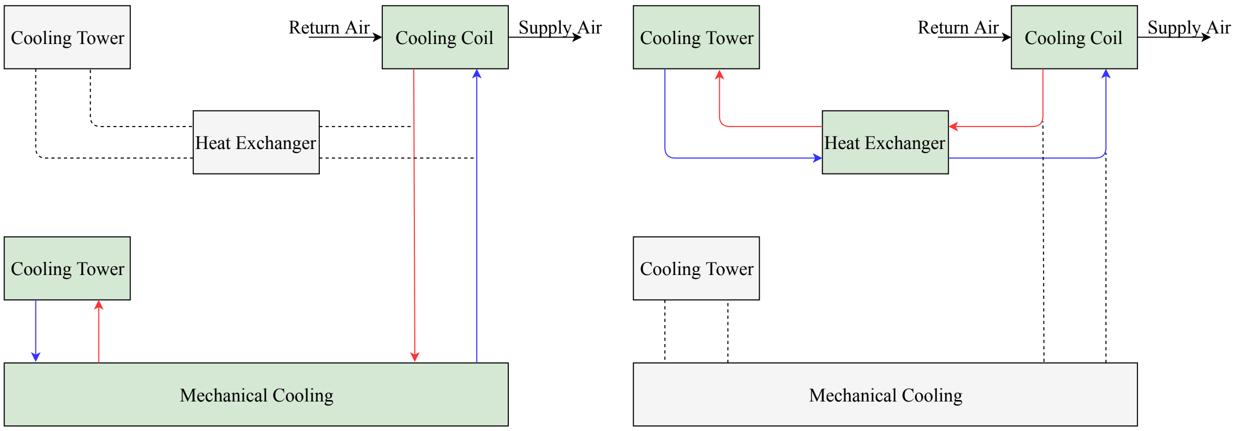


(b) Waterside economizer of cooling tower type.

Figure 3.3 – Comparison between a conventional cooling system and its adaptation to the waterside economizer mode [Lui, 2010].

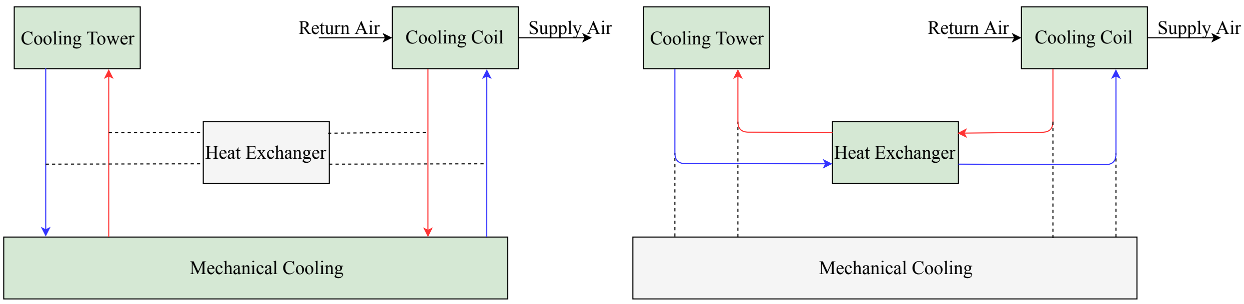
to provide full or partial waterside economizing. During partial economizing mode, the cooling tower is operated in conjunction with the chiller, pre-cooling the building, returning chilled water before it enters the chiller and, thus, reducing the cooling load.

Cooling tower type economizers are the most widely used in the waterside category because they overcome most of the problems of the other types. The water consumption rate of this system is only about 5% of a once-through system, making it more viable to operate with purchased water. Furthermore, the amount of heated water discharged is very small, so the environmental harm is greatly reduced if compared with

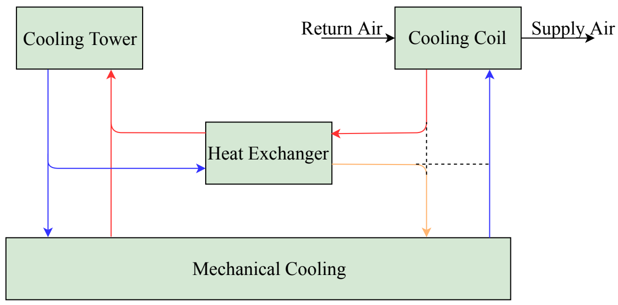


(a) Mechanical cooling operation (b) Full economizer mode

Figure 3.4 – Non-integrated (or PWSE) waterside economizer of cooling tower type [Adapted from Beaty et al., 2018].



(a) Mechanical cooling operation (b) Full economizer mode



(c) Partial economizer mode

Figure 3.5 – Integrated or SWSE cooling tower architecture [Adapted from Beaty et al., 2018].

the direct water cooled system [ASHRAE, 2016].

The present work selected the cooling tower economizer type to assess the waterside free cooling potential of Brazilian cities. It was decided to consider the non-integrated configuration of this type (displayed in Figure 3.4) due to its simplicity.

3.3 Waterside economizer in detail

Figure 3.6 presents a schematic description of the waterside economizer type chosen to assess DC free cooling potential.

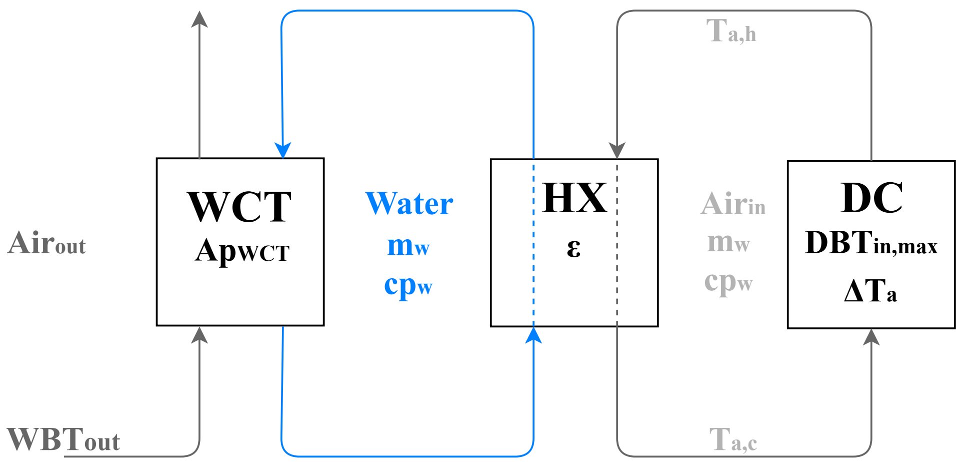


Figure 3.6 – Cooling tower waterside economizer system modeled.

The heat removed from DC indoor spaces depends on the maximum supply air dry-bulb temperature $DBT_{in,max}$ and its temperature difference between the supply and return air ΔT_a. The indoor air heat is transferred to a water loop with the aid of heat exchangers (HX), modeled by its effectiveness ϵ. Heat rejection to the environment is performed at a wet cooling tower (WCT), which process is regulated by the outdoor air wet-bulb temperature WBT_{out} and depends on its approach Ap_{WCT}. Figure 3.7 brings a schematic view of a wet cooling tower.

Hot water at $T_{w,h}$ is admitted at the tower top level and passes through a combination of convective exchange with the outside air, mechanically driven in counterflow and water evaporation [ASHRAE, 2016]. Make-up water is continuously added to com-

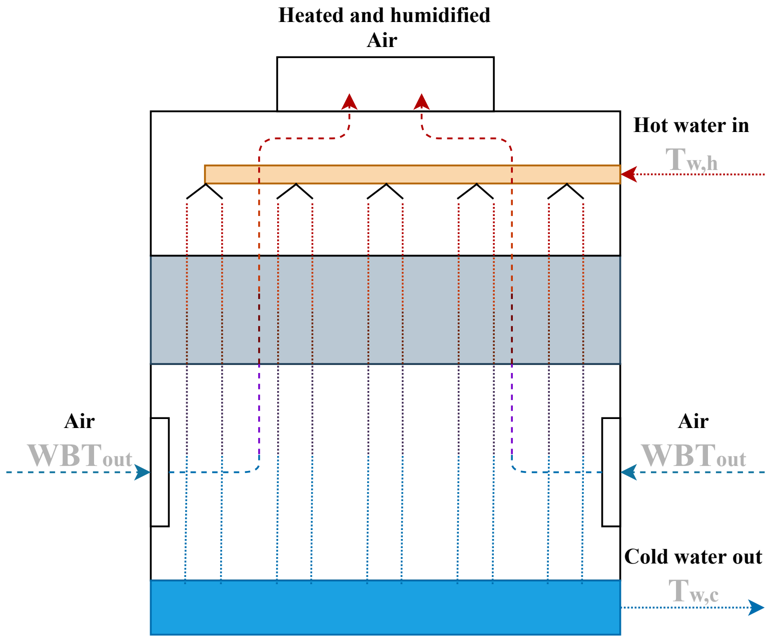


Figure 3.7 – A schematic of a direct contact cooling tower [Adapted from ASHRAE, 2016].

pensate for lost water from evaporation and drag.

Figure 3.8 displays the evolution of the temperature of the cooling tower working fluids, water and air, along the tower vertical length.

The approach Ap_{WCT} and range Rg are two important parameters to assess cooling tower performance. Approach is defined as the difference between the cooling tower outlet cold water T_w, c and the outdoor wet-bulb temperature WBT_{out} and the range is defined as the temperature difference between the inlet hot water $T_{w,h}$ and the cold water leaving the cooling tower T_w, c [ASHRAE, 2016].

An ideal infinite wet cooling tower operates with $Ap_{WCT} = 0$, which would led to a $T_{w,c}$ equal to WBT_{out}. In reality, it is not usual to guarantee any approach less than 2.8°C in the cooling tower industry, as the Ap_{WCT} reduction from this point onwards would require huge increases in the cooling tower size [Beaty et al., 2018; SPX, 2019].

The Ap_{WCT} also depends on the outdoor condition. According to Beaty et al., 2018, a typical open-circuit cooling tower which has a 3.9°C approach when the WBT_{out} is equal to 25.5°C will have $Ap_{WCT} = 10.6$°C when $WBT_{out} = 1.7$°C considering the

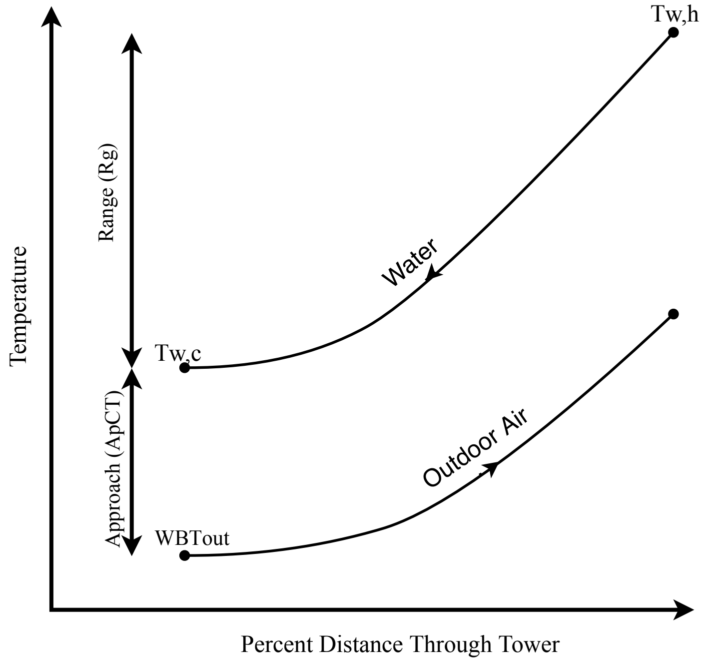


Figure 3.8 – Cooling tower range and approach definitions [Adapted from ASHRAE, 2016].

same range and flow rate. That is, a 23.9°C decrease in the WBT_{out} resulted in an increase of 6.7°C in the cooling tower approach. This information should be taken into account while setting the Ap_{WCT} to assess cooling tower economizer types.

3.4 Methodology

The waterside free cooling potential assessment started by assuming simplifying hypothesis in Subsection 3.4.1 to relate the outdoor air condition (WBT_{out}) to system parameters, such as the Ap_{WCT} and the $DBT_{in,max}$. A mathematical framework was carried out in Subsection 3.4.2 to derive an expression to evaluate the maximum value of WBT_{out} which allows a data center to operate in free cooling. The free cooling criteria were proposed from that expression. Then, a graphical procedure was proposed in Subsection 3.4.3 to plot the free cooling zone on a psychrometric chart. After that, it was possible to compare the free cooling criteria with the weather data of each of the studied cities (Subsection 3.4.4) and, finally, obtain their free cooling potential.

3.4.1 Model assumptions

Typically, cooling tower waterside economizers are built with at least two water loops, but simpler modeling was assumed in the present work, by merging these loops into a single one and taking this into account in the ϵ value. The heat exchangers were taken as adiabatic, allowing to assume that the cooling tower rejects the total amount of dissipated heat from the IT equipment. Both indoor air and water loops were modeled as tight and leakage free systems, with no need for fluid make-up. The evaporative cooling process relied on the Ap_{WCT} value only.

The $DBT_{in,max}$ is the main parameter to be monitored whenever indirect waterside economizers are used. The ASHRAE thermal guidelines limits presented on Table 3.1 were used as a reference to evaluate this parameter.

Table 3.1 – Dry-bulb temperature limits $DBT_{in,max}$ considering all of the ASHRAE suggested ranges [Adapted from ASHRAE TC 9.9, 2015].

Range	Recommended	Allowable A1	Allowable A2	Allowable A3	Allowable A4
$DBT_{in,max}$ (°C)	27	32	35	40	45

Furthermore, it was considered a non-integrated configuration (Figure 3.4) of the cooling tower type economizer. It is worth noticing that higher free cooling potential could be achieved if the partial economizer operation had also been considered.

3.4.2 Mathematical framework

Mass and energy balances were performed in the waterside system presented in Figure 3.3 aiming to find an expression to the maximum outdoor wet-bulb temperature $WBT_{out,max}$ which allows for a system to operate in full waterside free cooling mode.

An expression to relate WBT_{out} to the cold water temperature $T_{w,c}$ is presented in Equation 3.1 with the aid of the wet cooling tower approach, followed by the water loop temperature difference ΔT_w in Equation 3.2.

$$T_{w,c} = WBT_{out} + Ap_{WCT} \tag{3.1}$$

$$\Delta T_w = T_{w,h} - T_{w,c} \tag{3.2}$$

Equations 3.3 and 3.4 describe, respectively, the temperature difference in the indoor air circuit ΔT_a and the heat exchanged from the indoor air to the water q_{HX} in the heat exchanger (HX).

$$\Delta T_a = T_{a,h} - T_{a,c} \tag{3.3}$$

$$q_{HX} = \dot{m}_a cp_a \Delta T_a \tag{3.4}$$

Considering that the heat rejected from the water in the cooling tower q_{WCT} is equal to q_{HX}, they can be referred only as q.

The HX effectiveness ϵ is defined by Equation 3.5 and it accounts for the fraction between q and the maximum heat that could be exchanged in the heat exchanger q_{max}.

$$\epsilon = \frac{q}{q_{max}} = \frac{\dot{m}_a cp_a \Delta T_a}{\dot{m}_a cp_a (T_{a,h} - T_{w,c})} \tag{3.5}$$

Equation 3.6 is derived directly from Equation 3.5.

$$T_{w,c} = T_{a,h} - \frac{\Delta T_a}{\epsilon} \tag{3.6}$$

Combining Equation 3.1 and Equation 3.6, it is possible to find an expression for WBT_{out}:

$$WBT_{out} = T_{a,h} - \frac{\Delta T_a}{\epsilon} - Ap_{WCT} \tag{3.7}$$

with $T_{a,h}$ given by:

$$T_{a,h} = T_{a,c} + \Delta T_a \tag{3.8}$$

Equation 3.7 can be rewritten in terms of $T_{a,c}$ with the aid of Equation 3.8, resulting in Equation 3.9:

$$WBT_{out} = T_{a,c} + \Delta T_a \left(1 - \frac{1}{\epsilon}\right) - Ap_{WCT} \tag{3.9}$$

which is the relation between the outdoor wet-bulb temperature and the system parameters. When $T_{a,c}$ assumes the maximum acceptable value to cool the data center indoor environment $DBT_{in,max}$, WBT_{out} assumes its maximum value as well: $WBT_{out,max}$, while assuming constant ΔT_a, ϵ and Ap_{WCT}. Thus, Equation 3.9 is reduced to Equation 3.10.

$$T_{a,c} = DBT_{in,max} \therefore WBT_{out} = WBT_{out,max}$$

$$WBT_{out,max} = DBT_{in,max} + \Delta T_a \left(1 - \frac{1}{\epsilon}\right) - Ap_{WCT} \tag{3.10}$$

Alternatively, if one does not intend to use ΔT_a and ϵ parameters, it is possible to relate the term $DBT_{in,max} + \Delta T_a \left(1 - \frac{1}{\epsilon}\right)$ of Equation 3.10 to heat exchangers approach Ap_{HX} as shown in Equation 3.11. The following steps demonstrate that Ap_{HX} could be defined in a similar way adopted to Ap_{WCT} (Equation 3.12).

$$Ap_{HX} = \Delta T_a \left(\frac{1}{\epsilon} - 1\right) \tag{3.11}$$

$$Ap_{HX} = \Delta T_a \left(\frac{1}{\frac{\Delta T_a}{T_{a,h} - T_{w,c}}} - 1\right)$$

$$Ap_{HX} = (T_{a,h} - T_{w,c}) - \Delta T_a$$

$$Ap_{HX} = (T_{a,h} - T_{w,c}) - (T_{a,h} - T_{a,c})$$

$$Ap_{HX} = T_{a,c} - T_{w,c} \tag{3.12}$$

An alternative expression for $WBT_{out,max}$ can be obtained by combining Equation 3.11 with Equation 3.10.

$$WBT_{out,max} = DBT_{in,max} - Ap_{HX} - Ap_{WCT} \tag{3.13}$$

Finally, both Equations 3.10 and 3.13 are expressions to find the maximum outdoor wet-bulb temperature which guarantees $DBT_{in,max}$ as the indoor supply air temperature considering that all DC restrictive parameters had been set. Therefore, free cooling is considered possible whenever the outdoor wet-bulb temperature is less than or equal to this maximum calculated value (Equation 3.14).

$$WBT_{out} \leq WBT_{out,max} \therefore \text{Free cooling is possible.} \tag{3.14}$$

Cooling tower and heat exchanger approaches

In Equation 3.13, the heat transfer process characteristics were inserted in the parameters Ap_{WCT} and Ap_{HX}. This means that it is necessary to measure, calculate or estimate these two parameters previously when applying the criteria. For example, the Equation 3.11 is already a suggested procedure to calculate Ap_{HX} as a function of ϵ and ΔT_a parameters.

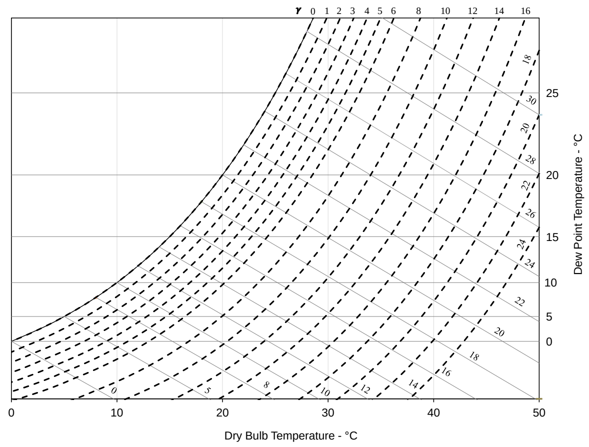
Besides that, the free cooling potential assessment assumes these two parameters as fixed values. However, in reality, they are subject to slight changes alongside the year depending on the outdoor weather condition. As shown in Subsection 3.3, a 23.9°C decrease in the WBT_{out} would result in a 6.7°C increase in the Ap_{WCT} for a typical cooling tower. Therefore, it is recommended to set the approaches values considering approximately the situation in which $WBT_{out} = WBT_{out,max}$ to achieve a better estimate of the free cooling potential.

3.4.3 Graphical procedure

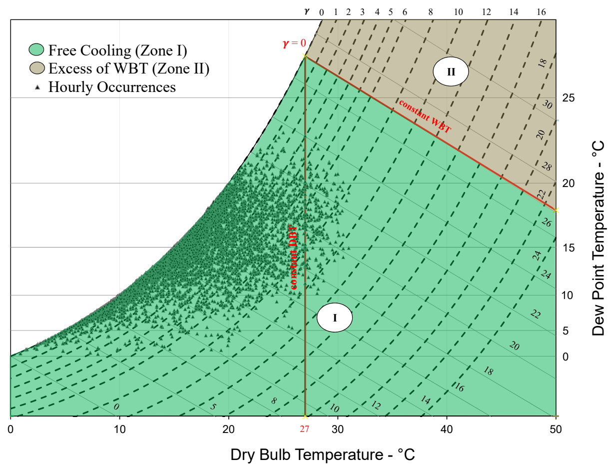
A graphical procedure was made to define the free cooling zone on a psychrometric chart. The customized psychrometric chart presented in Figure 3.9 (a)[1] displays the "γ isolines". With γ being defined as the sum of approaches from the cooling tower and heat exchangers as shown in Equation 3.15. A full-size version of the chart presented in Figure 3.9 (a) is available in Appendix B.

$$\gamma \equiv Ap_{HX} + Ap_{WCT} \tag{3.15}$$

[1] All the psychrometric charts figures presented in this Thesis were made using Microsoft Excel software with the aid of the Psych plugin [WCEC, 2013].



(a) Customized psychrometric chart with the γ isolines.



(b) Example of a free cooling zone created with $DBT_{in,max} = 27^{o}$C and $\gamma = 0^{o}$C.

Figure 3.9 – Graphical representation of the waterside free cooling potential criteria.

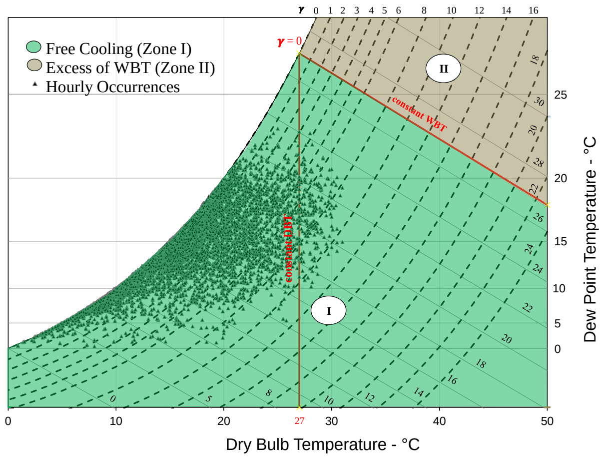
$$WBT_{out,max} = DBT_{in,max} - \gamma \tag{3.16}$$

For given values of $DBT_{in,max}$ and γ, one can trace a constant DBT line from the $DBT_{in,max}$ until it reaches the set γ value and then mark this point. The WBT of this point is the $WBT_{out,max}$. Thus, the free cooling zone can be defined as the entire zone below a constant WBT line which contains that point as shown in Figure 3.9 (b).

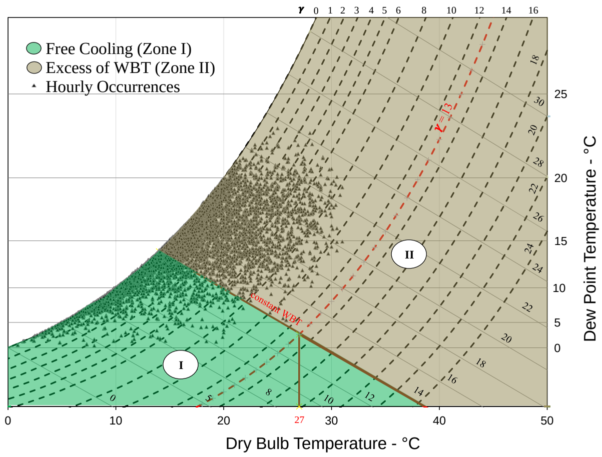
This procedure is useful to create free cooling zones and compare them with weather data graphically. Figure 3.10 presents applications of this graphical procedure to create different free cooling zones, relying on different system parameters, but considering the same weather data occurrences.

3.4.4 Weather data

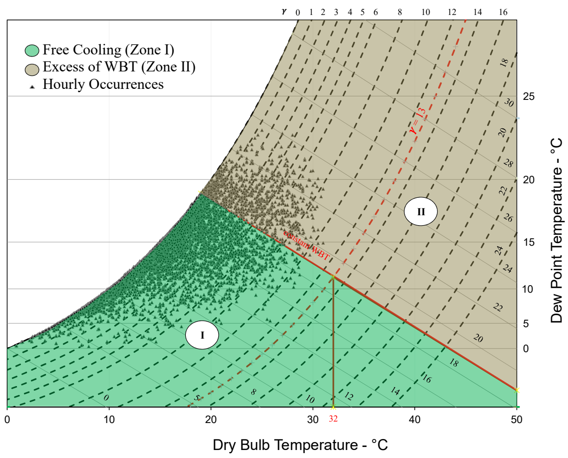
Hourly wet-bulb temperatures WBT were required to calculate the number of hours that a given DC can operate on waterside free cooling along a year-long period (8760 hours). Fourteen Brazilian capitals with available Test Reference Year TRY files were selected (Table 3.2). All the country regions were portrayed.



(a) $DBT_{in,max} = 27^{o}$C and $\gamma = 0^{o}$C.



(b) $DBT_{in,max} = 27^{o}$C and $\gamma = 13^{o}$C.



(c) $DBT_{in,max} = 32^{o}$C and $\gamma = 13^{o}$C.

Figure 3.10 – Application examples of the graphical procedure to establish the free cooling zones considering different system parameters but the same weather data.

Table 3.2 – Capital cities assessed by country region. Weather data obtained from LabEEE, 2018.

Region	City (State) assessed
South	Porto Alegre (RS), Florianópolis (SC), Curitiba (PR)
Southeast	São Paulo (SP), Rio de Janeiro (RJ), Vitória (ES)
Midwest	Brasília (DF)
Northeast	Salvador (BA), Maceió (AL), Recife (PE), Natal (RN), Fortaleza (CE), São Luís (MA)
North	Belém (PA)

3.5 Results

The free cooling potential results for 14 Brazilian capitals are presented in Table 3.3 for an average scenario considering $\gamma = 10°C$. As reference values, Beaty et al., 2019 and Belizário, 2018 used, respectively, an equivalent value to $\gamma = 9,5°C$ and $\gamma = 8°C$ in their work. Results for additional scenarios ranging from an optimistic $\gamma = 5°C$ to a conservative $\gamma = 15°C$ are available Appendix C. All of the ASHRAE thermal guidelines operating ranges limits (Table 3.1) were taken into consideration to set the $DBT_{in,max}$ values in this assessment.

Table 3.3 – Free cooling potential hours in 14 Brazilian capitals considering the average scenario ($\gamma = 10°C$).

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	4291	7700	8613	8760	8760
Florianópolis	SC	27°36'S	2600	7077	8389	8752	8760
Curitiba	PR	25°26'S	6301	8664	8760	8760	8760
São Paulo	SP	23°33'S	5117	8569	8754	8760	8760
Rio de Janeiro	RJ	22°54'S	578	5238	8242	8760	8760
Vitória	ES	20°19'S	832	5215	8261	8760	8760
Brasília	DF	15°47'S	3032	8660	8760	8760	8760
Salvador	BA	12°58'S	79	4113	8553	8760	8760
Maceió	AL	9°40'S	34	5051	8700	8760	8760
Recife	PE	8°03'S	0	1726	8613	8760	8760
Natal	RN	5°48'S	0	2302	8380	8760	8760
Fortaleza	CE	3°43'S	0	309	5939	8760	8760
São Luís	MA	2°32'S	0	132	6922	8760	8760
Belém	PA	1°27'S	0	609	6875	8760	8760

Curitiba displayed the best performance among all cities, as it was identified 6301 hours per year of free cooling potential considering the Recommended range limit. Capital cities such as São Paulo, Porto Alegre and Brasília came right after, with more than 3000 hours in a year on the same range limit.

Most of the North and Northeast regions of the country displayed a negligible potential to free cooling considering Recommended and A1 limit, with exception of Salvador and Maceió which achieved more than 4000 hours in the A1 limit. Overall better results were found when considering more flexible limits.

All the 14 assessed cities displayed at least 5900 free cooling hours with the waterside economizer mode when considering the A2 range limits, and that number can reach at least 8300 hours (almost the entire year) if Fortaleza, São Luís and Belém were excluded from the assessment. Free cooling is possible for the entire year for all the 14 cities whenever A3 or A4 limits were considered.

This assessment was performed over an average of $\gamma = 10$°C. Results are very sensitive to changes on γ, and WBT cumulative frequency distributions can aid to assess the free cooling potential of a given city considering variations of γ. The following subsections perform this procedure for Curitiba, São Paulo and Fortaleza. The WBT cumulative frequency distributions for the other eleven cities are available in the Appendix D.

3.5.1 Curitiba further results

Figure 3.11 shows the cumulative frequency distribution of WBT in Curitiba throughout a year.

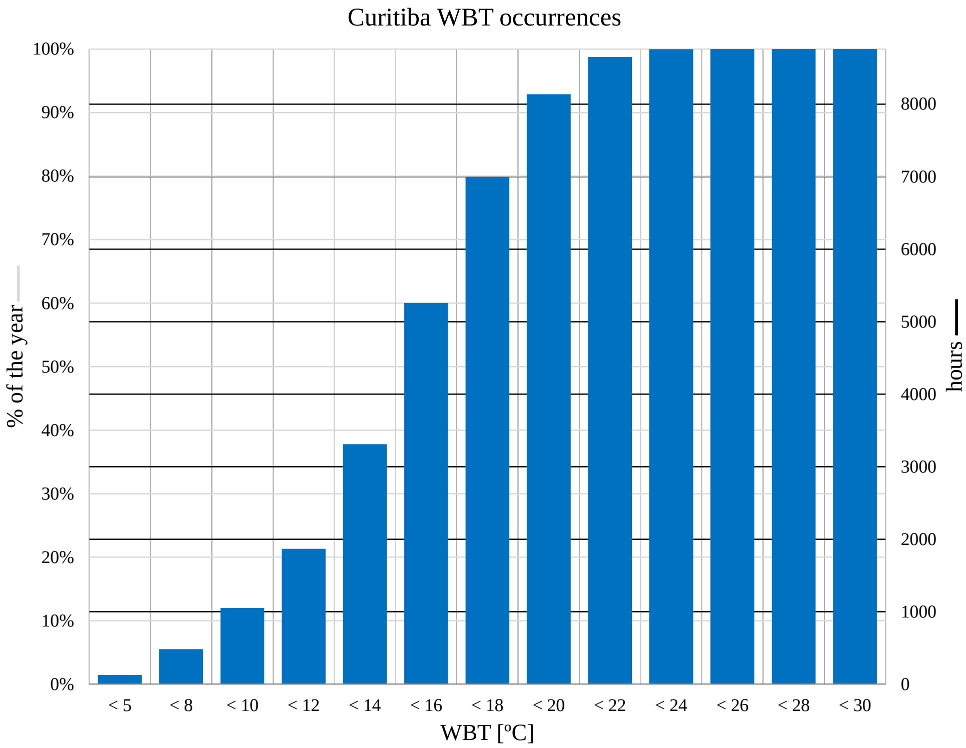
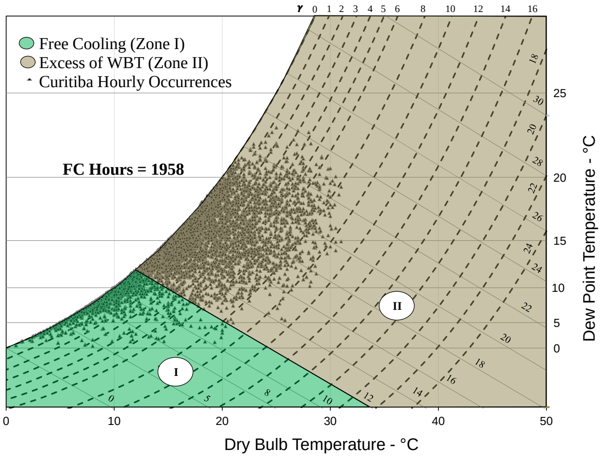


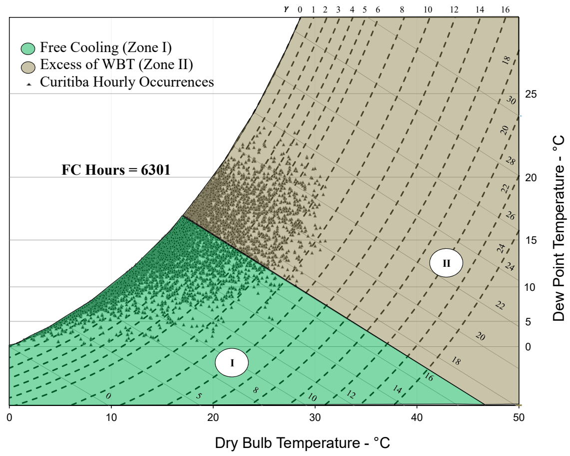
Figure 3.11 – Curitiba WBT cumulative frequency distribution.

With that information, it is possible to estimate the waterside free cooling potential in this city for different values of γ. As an example, the optimistic scenario with $\gamma = 5$°C and the ASHRAE Recommended limit for $DBT_{in,max} = 27$°C, led to a $WBT_{out,max} = 22$°C according to Equation 3.16. Back to Figure 3.11, the free cooling potential in Curitiba correspond to almost the entire year long for that scenario. The same can be performed to the conservative scenario with $\gamma = 15$°C and $WBT_{out,max} = 12$°C. According to Figure 3.11 the free cooling potential in Curitiba under these conditions is approximately 2000 hours.

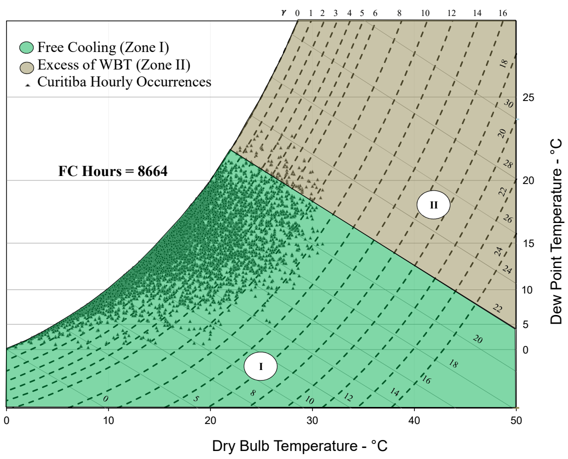
It is also possible to evaluate the free cooling potential behavior with variations on the maximum supply air temperature $DBT_{in,max}$ or even combined variations of γ and $DBT_{in,max}$, as the x axis on Figure 3.11 is related to $WBT_{out,max}$ which depends on γ and $DBT_{in,max}$. Any combination of $DBT_{in,max}$ and γ which results in a $WBT_{out,max} \geq 14$°C would allow for at least 3000 h of free cooling potential in a year. The Figure 3.12 represent graphically those examples.



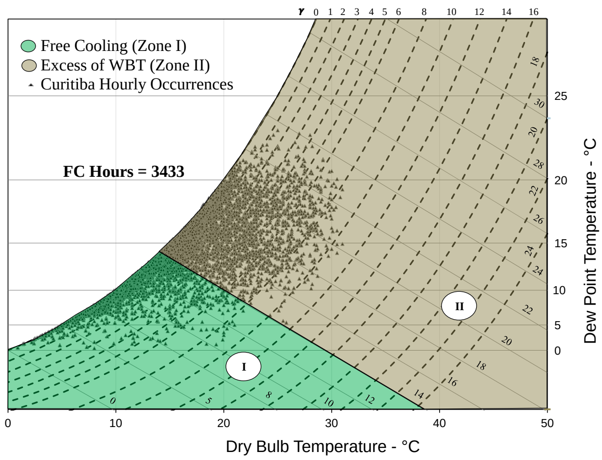
(a) $DBT_{in,max} = 27°\text{C}$ and $\gamma = 15°\text{C}$.



(b) $DBT_{in,max} = 27°\text{C}$ and $\gamma = 10°\text{C}$ or $DBT_{in,max} = 32°\text{C}$ and $\gamma = 15°\text{C}$.



(c) $DBT_{in,max} = 27°\text{C}$ and $\gamma = 5°\text{C}$ or $DBT_{in,max} = 35°\text{C}$ and $\gamma = 13°\text{C}$.



(d) $WBT_{out,max} = 14°\text{C}$, the lowest integer value which provides at least 3000 hours of free cooling.

Figure 3.12 – Curitiba hourly weather occurrences plotted on a psychrometric chart with the free cooling zone defined for different scenarios of $DBT_{in,max}$ and γ.

3.5.2 São Paulo further results

Figure 3.13 shows the cumulative frequency distribution of WBT in São Paulo throughout a year.

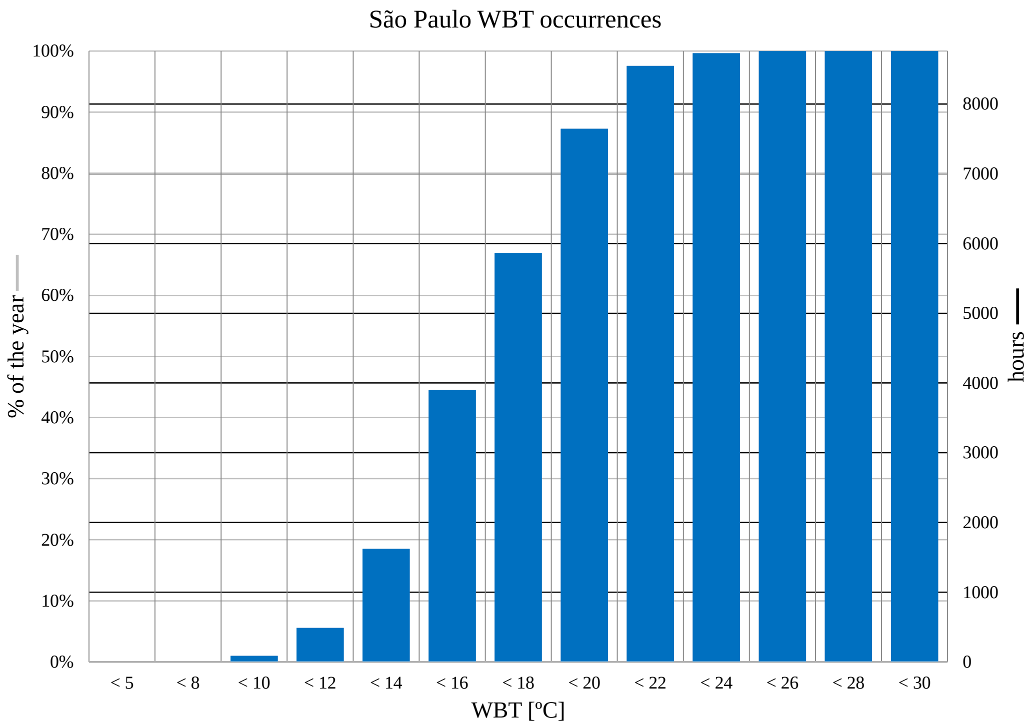
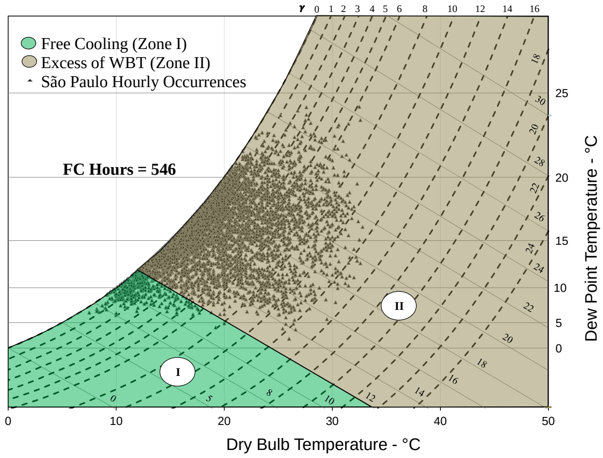
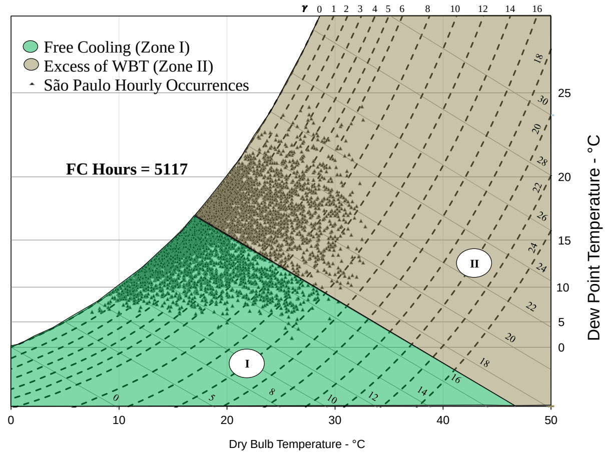


Figure 3.13 – São Paulo WBT cumulative frequency distribution.

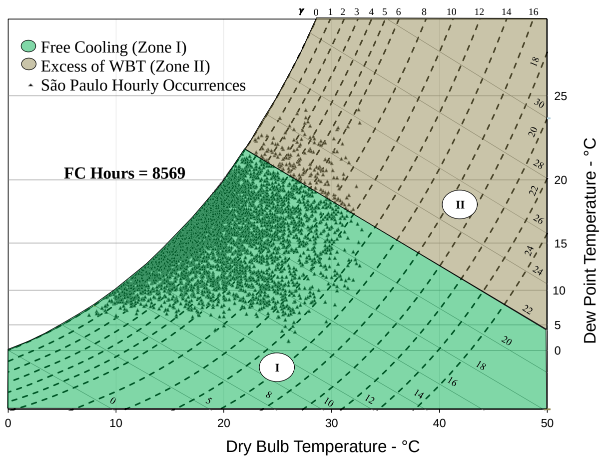
By looking to Figure 3.13 it is possible to affirm that the free cooling potential in this city considering the optimistic scenario and the Recommended limit is approximately 8500 hours, whereas it drops to only 500 hours for the conservative scenario. Additionally, any combination of γ and $DBT_{in,max}$ which results in $WBT_{out,max} \geq 16$°C allows for at least 3000 hours of free cooling in São Paulo. Figure 3.14 presents those examples of free cooling results graphically.



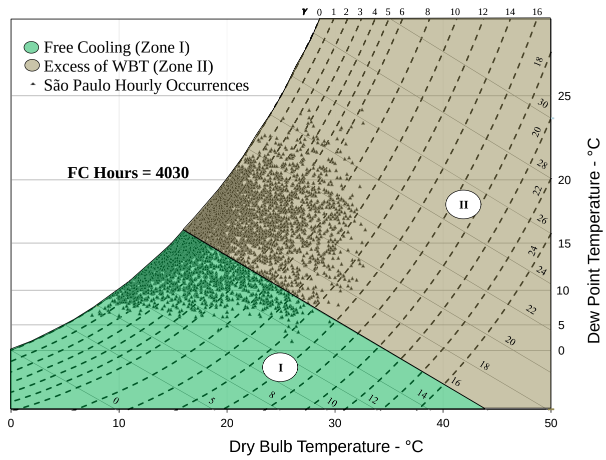
(a) $DBT_{in,max} = 27^{o}$C and $\gamma = 15^{o}$C.



(b) $DBT_{in,max} = 27^{o}$C and $\gamma = 10^{o}$C or $DBT_{in,max} = 32^{o}$C and $\gamma = 15^{o}$C.



(c) $DBT_{in,max} = 27^{o}$C and $\gamma = 5^{o}$C or $DBT_{in,max} = 35^{o}$C and $\gamma = 13^{o}$C.



(d) $WBT_{out,max} = 16^{o}$C, the lowest integer value which provides at least 3000 hours of free cooling.

Figure 3.14 – São Paulo hourly weather occurrences plotted on a psychrometric chart with the free cooling zone defined for different scenarios of $DBT_{in,max}$ and γ.

3.5.3 Fortaleza further results

Figure 3.15 shows the cumulative frequency distribution of WBT in Fortaleza throughout a year in the same way of what was done in Curitiba and São Paulo.

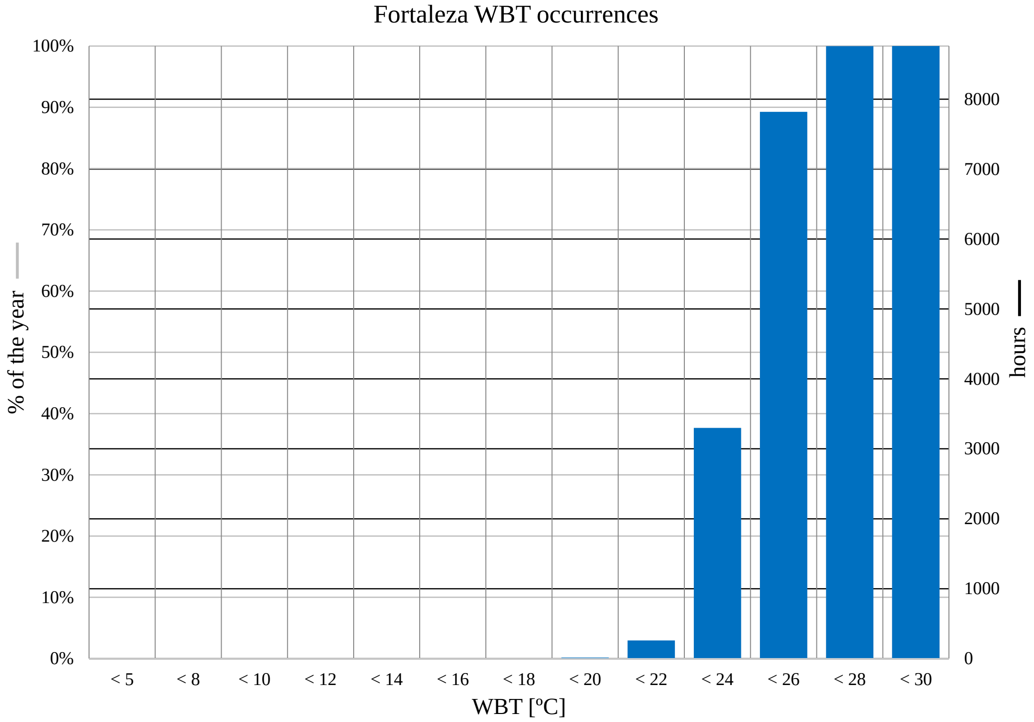
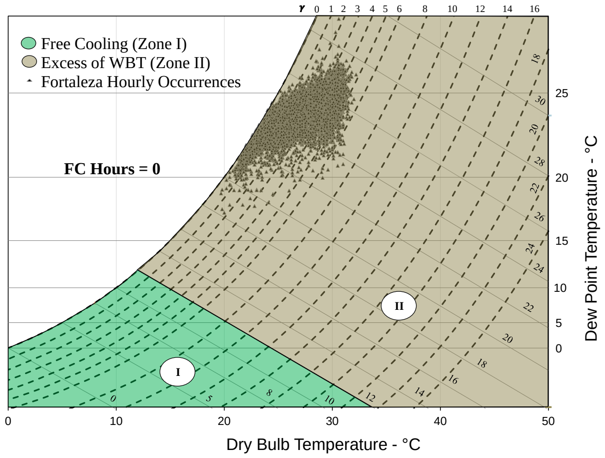


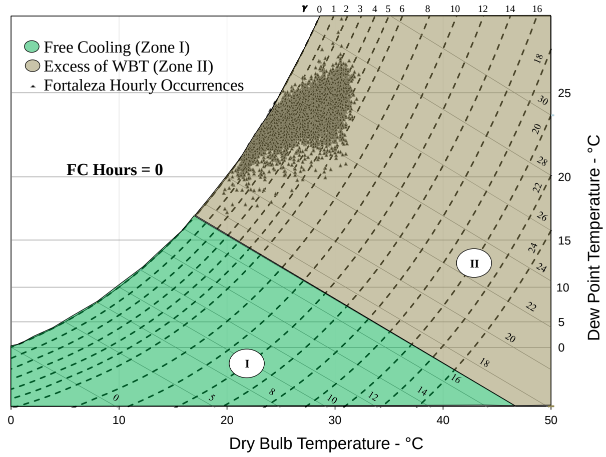
Figure 3.15 – Fortaleza WBT cumulative frequency distribution.

The free cooling potential in Fortaleza is significantly lower than the other two further analyzed cities. Considering the optimistic scenario with $\gamma = 5$°C and the Recommended limit $DBT_{in,max} = 27$°C the free cooling potential is lower than 500 hours, and in the conservative scenario it is null.

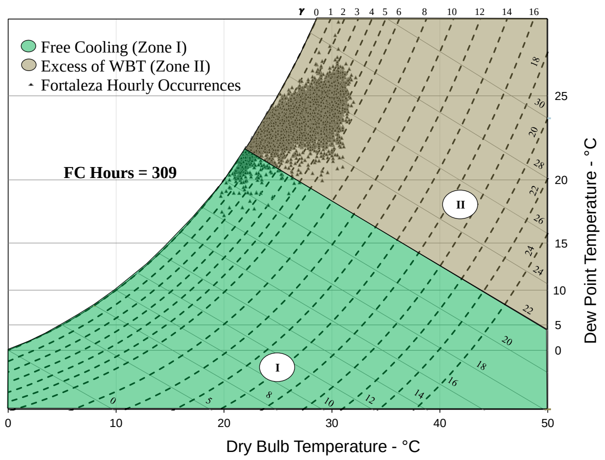
Furthermore, in order to achieve at least 3000 hours of free cooling in Fortaleza, a combination of $DBT_{in,max}$ and γ which results in $WBT_{out,max} \geq 24$°C is required. Figure 3.16 presents, graphically, those examples of free cooling results for Fortaleza.



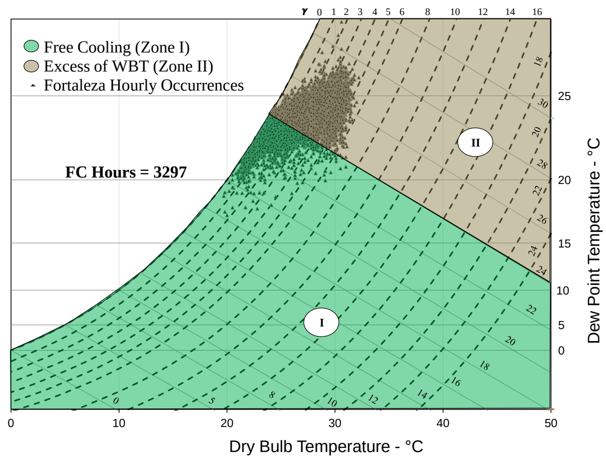
(a) $DBT_{in,max} = 27^{o}$C and $\gamma = 15^{o}$C.



(b) $DBT_{in,max} = 27^{o}$C and $\gamma = 10^{o}$C or $DBT_{in,max} = 32^{o}$C and $\gamma = 15^{o}$C.



(c) $DBT_{in,max} = 27^{o}$C and $\gamma = 5^{o}$C or $DBT_{in,max} = 35^{o}$C and $\gamma = 13^{o}$C.



(d) $WBT_{out,max} = 24^{o}$C, the lowest integer value which provides at least 3000 hours of free cooling.

Figure 3.16 – Fortaleza hourly weather occurrences plotted on a psychrometric chart with the free cooling zone defined for different scenarios of $DBT_{in,max}$ and γ.

3.6 Conclusion

In this chapter, criteria to assess the waterside free cooling potential for data centers using a cooling tower system were developed. The procedure was made in such a way to be as general as possible aiming to provide a tool that could be suitable for different kinds of data centers and, also, to be independent of restrictions that could change in the future.

It was found that parameters such as the approach of the cooling tower Ap_{WCT}, the approach of the heat exchangers Ap_{HX} and the maximum acceptable supply air temperature $DBT_{in,max}$ are relevant to estimate the free cooling hours, as they define the maximum allowable outdoor wet-bulb temperature $WBT_{out,max}$ for free cooling usage. The geographical location is also important because it is associated with the frequency of WBT, which defines the outdoor condition to the free cooling potential criteria.

The methodology was applied to assess the free cooling potential of 14 Brazilian capital cities, by creating specific scenarios, based on literature review, and comparing them with the cities hourly weather data. Results for an average scenario showed that Curitiba displayed the highest free cooling potential among all 14 cities, being able to operate without mechanical cooling for 6301 hours in a year, even considering the most restrictive operating range limit recommended by ASHRAE. Cities such as Porto Alegre, São Paulo and Brasília displayed potential to free cooling for more than 3000 hours under those conditions, while the North and Northeast region of the country presented poor results in this regard.

Finally, it was shown that using cumulative frequency distributions of WBT, it is possible to estimate the waterside free cooling potential considering different combinations of $DBT_{in,max}$ and the sum of cooling tower and heat exchangers approaches. A comparison between the waterside and the airside free cooling potential of these cities should be made to verify which category of economizer suits better the studied cities.

4 FREE COOLING POTENTIAL OVERVIEW AND COMPARISON FOR DATA CENTERS IN BRAZIL

4.1 Introduction

Free cooling is defined as the use of natural weather to cool an indoor environment [Oró et al., 2015a]. When the outdoor temperature is sufficiently low compared to the indoor operating temperature, it is possible to take advantage of this and cool the data center indoor environment without mechanical cooling [Amoabeng and Choi, 2016]. This compressor-less operation is commonly known as economizer mode [Zhang et al., 2014].

There are 15 economizer types that can be realistically used in data centers [Niemann et al., 2011], classified mainly according to their heat transfer design. They can be roughly divided into the airside and waterside categories according to Oró et al., 2015b; Nadjahi et al., 2018. Five economizers types stand out in these categories, namely: direct and indirect airside, direct water cooled, air cooled and cooling tower waterside.

Free cooling is considered an effective solution for reducing the energy consumption of cooling systems in data center when its operation is viable for a high number of hours in a year, which is called free cooling potential [Oró et al., 2015a; Malkamäki and Ovaska, 2012; Siriwardana et al., 2013]. The free cooling potential varies significantly depending on local climate [Amoabeng and Choi, 2016].

A free cooling potential assessment compares weather data from a given local with established criteria related to the outdoor air conditions. Chapter 2 proposed criteria to assess the free cooling potential of direct airside economizers for Brazilian capital cities, while Chapter 3 did the same considering cooling tower waterside economizers. In both works, these criteria were applied to assess the free cooling potential of Brazilian key cities. The work presented in this chapter aimed to propose criteria to free cooling for all the five main economizer types in the airside and waterside categories, and compare these economizers qualitatively based on literature research, and regarding their free cooling potential performance using weather data of fourteen Brazilian key cities.

4.2 Free cooling potential criteria

The main types of economizers in the airside and waterside categories are shown in Figure 4.1.

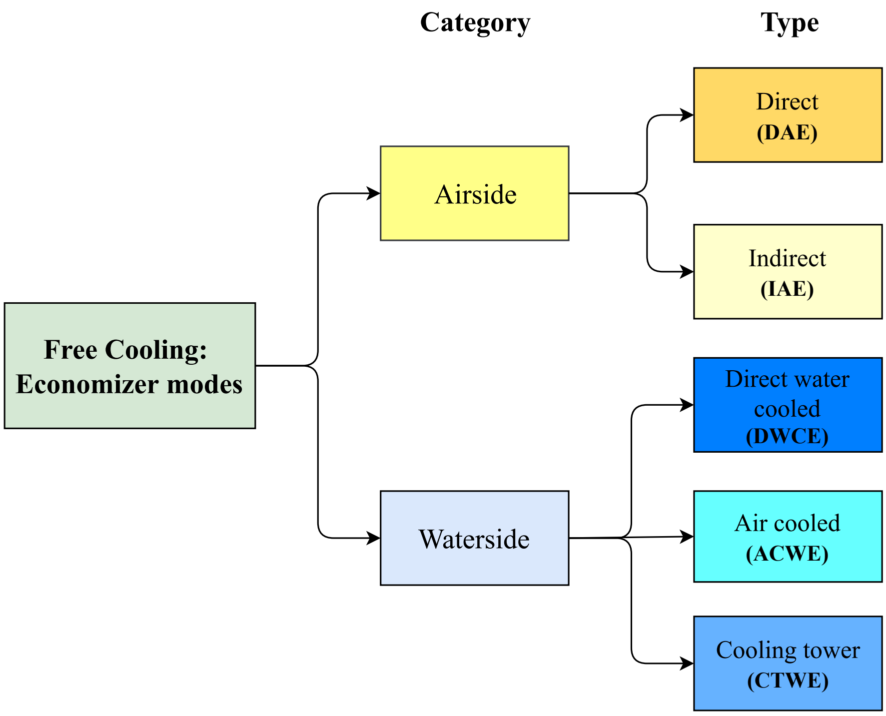
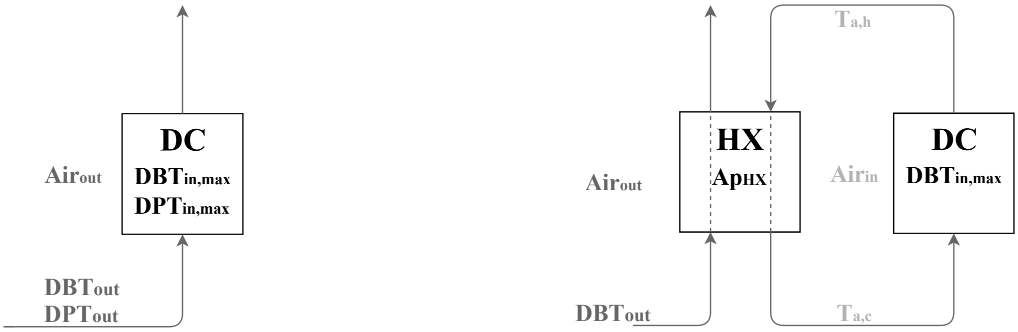


Figure 4.1 – Classification of the main types of economizer modes according to Amoabeng and Choi, 2016; Zhang et al., 2014.

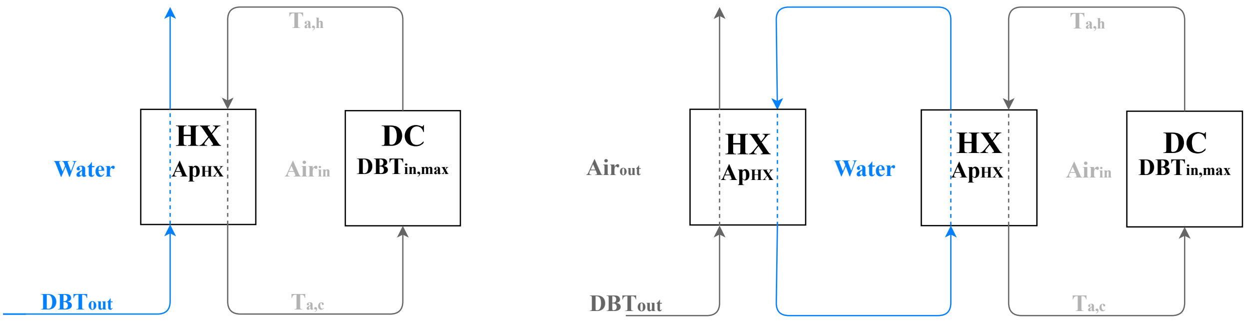
Figure 4.2 schematically shows the two types in the airside category: the direct airside (DAE) and the indirect airside economizer (IAE). Figure 4.3 shows schemes of the main three types inside the waterside category, namely: direct water cooled waterside (DWCE), air cooled waterside (ACWE) and cooling tower waterside economizer (CTWE).

In these figures, DBT_{out}, DPT_{out} and WBT_{out} account for the outdoor dry-bulb, dew-point and wet-bulb temperatures respectively. All types besides the DAE are indirect (even the DWCE) since there is no mixture between the indoor and outdoor air. For the indirect types, only the maximum dry-bulb temperature of the supplied air intake $DBT_{in,max}$ is controlled in the indoor DC environment, whereas for the DAE the max-



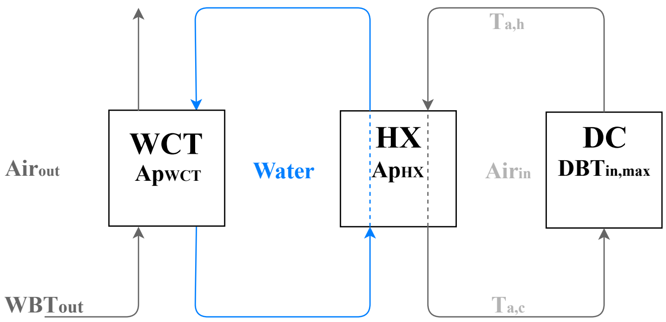
(a) Direct airside economizer (DAE) scheme. (b) Indirect airside economizer (IAE) scheme.

Figure 4.2 – Schematic of airside economizers.



(a) Direct water cooled waterside economizer (DWCE) scheme.

(b) Air cooled waterside economizer (ACWE) scheme.



(c) Cooling tower waterside economizer (CTWE) scheme.

Figure 4.3 – Schematic of waterside economizers.

imum dew-point temperature of the supplied air intake $DPT_{in,max}$ must be considered as well.

The indirect types rely on system components such as heat exchangers (HX) and wet cooling tower (WCT). The approach of the heat exchangers Ap_{HX} and the approach of the wet cooling tower Ap_{WCT} are the parameters responsible for taking into account the performance of these system components. Figure 4.4 presents a summary of the five economizer types, their system components and parameters.

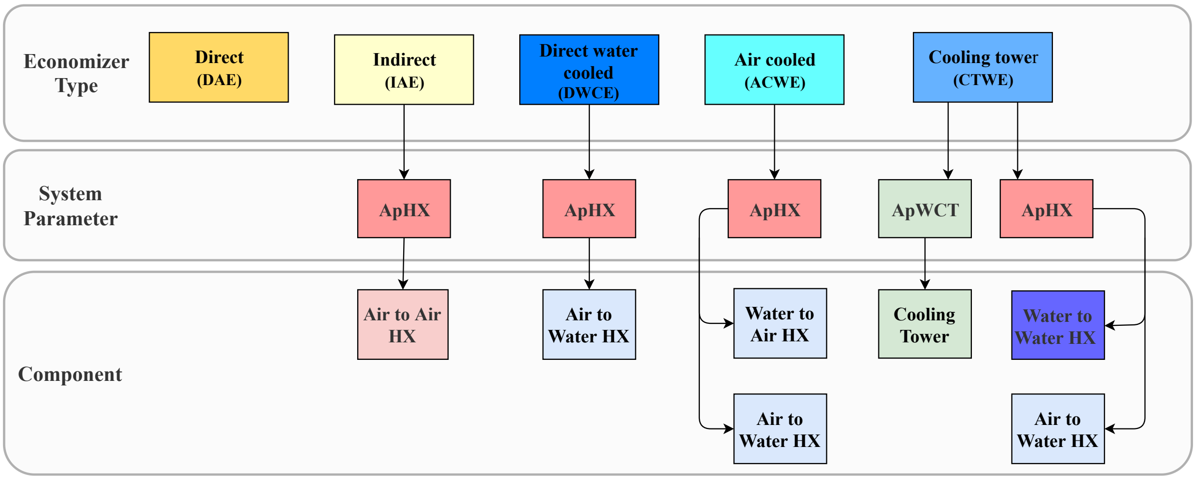


Figure 4.4 – Components and system parameters of the economizer types considered.

Chapter 2 proposed free cooling potential criteria for Brazilian cities considering the DAE type, while Chapter 3 proposed criteria to free cooling potential for Brazilian cities considering CTWE systems. Similar criteria than the ones developed for the CTWE can be proposed to the IAE, DWCE and ACWE types since they are all indirect. Table 4.1 brings the criteria for all the five main types in the airside and waterside categories.

Table 4.1 – Free cooling potential criteria summary

Category	Type	Criteria	Reference
Airside	Direct[a]	$DBT_{out} \leq DBT_{in,max}$[b] & $DPT_{out} \leq DPT_{in,max}$[b]	Chapter 2
	Indirect	$DBT_{out} \leq DBT_{in,max}$[b] $- Ap_{HX}$[c]	Chapter 4
Waterside	Direct Water Cooled	$DBT_{out} \leq DBT_{in,max}$[b] $- Ap_{HX}$[c]	Chapter 4
	Air Cooled	$DBT_{out} \leq DBT_{in,max}$[b] $- Ap_{HX}$[c]	Chapter 4
	Cooling Tower	$WBT_{out} \leq DBT_{in,max}$[b] $- Ap_{HX}$[c] $- Ap_{WCT}$[d]	Chapter 3

[a] The criteria could be reduced to consider only the DPT criterion without causing major differences for the free cooling assessment in Brazilian capital cities as shown in Chapter 2.
[b] This value should be set.
[c] This value should be set or calculated as shown in Chapter 3.
[d] This value should be set considering the conditions presented in Chapter 3.

4.3 Free cooling potential comparison

In this section, the free cooling potential of the five main economizer types are compared based on the results of Chapters 2 and on the criteria proposed in Section 4.2.

4.3.1 Methodology for the comparison

The five economizer types free cooling potential comparison started by setting as default values for $DBT_{in,max}$ and $DPT_{in,max}$ the limits from ASHRAE thermal guidelines (Table 4.2). All of the ranges were taken into account.

Table 4.2 – Dry-bulb temperature limits ($DBT_{in,max}$) and dew-point temperature limits ($DPT_{in,max}$) considering all of the ASHRAE suggested ranges [Adapted from ASHRAE TC 9.9, 2015].

Range	Recommended	Allowable A1	Allowable A2	Allowable A3	Allowable A4
$DBT_{in,max}$ (°C)	27	32	35	40	45
$DPT_{in,max}$ (°C)	15	17	21	24	24

It was decided to use the direct airside economizer (DAE) as reference for this comparison, as it results in the most straightforward assessment and it does not rely on additional inputs such as the heat exchanger and cooling tower approaches. The remaining four economizer types were compared directly with the DAE, by setting their free cooling hours as equal to the reference type and calculating the value of their approaches for this condition.

The results achieved in Chapter 2 were used to evaluate this comparison (Table 4.3). They were assessed considering 14 Brazilian capital cities representing all regions of the country as shown in Table 4.4.

Table 4.3 – Direct airside free cooling potential in 14 Brazilian capitals. Assessed in Chapter 2.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	3783	5309	7927	8735	8735
Florianópolis	SC	27°36'S	1925	3760	7004	8470	8470
Curitiba	PR	25°26'S	5575	7299	8726	8760	8760
São Paulo	SP	23°33'S	4259	6418	8665	8760	8760
Rio de Janeiro	RJ	22°54'S	255	1134	5481	8555	8555
Vitória	ES	20°19'S	447	1417	5304	8494	8494
Brasília	DF	15°47'S	3028	5079	8745	8760	8760
Salvador	BA	12°58'S	17	261	5061	8729	8729
Maceió	AL	9°40'S	8	130	5795	8759	8759
Recife	PE	8°03'S	0	4	2521	8694	8694
Natal	RN	5°48'S	0	6	3048	8697	8697
Fortaleza	CE	3°43'S	0	1	221	6657	6657
São Luís	MA	2°32'S	0	1	168	8141	8141
Belém	PA	1°27'S	0	2	387	7888	7888

Table 4.4 – Capital cities assessed by country region. Weather data obtained from LabEEE, 2018.

Region	City (State) assessed
South	Porto Alegre (RS), Florianópolis (SC), Curitiba (PR)
Southeast	São Paulo (SP), Rio de Janeiro (RJ), Vitória (ES)
Midwest	Brasília (DF)
Northeast	Salvador (BA), Maceió (AL), Recife (PE), Natal (RN), Fortaleza (CE), São Luís (MA)
North	Belém (PA)

The sum of the approaches is defined as γ as shown in Equation 4.1.

$$\gamma \equiv Ap_{HX} + Ap_{WCT} \tag{4.1}$$

It is worth noticing that the Ap_{WCT} would be equal to zero and, consequently, $\gamma = Ap_{HX}$ for economizer types without a cooling tower. Besides, it is important to consider the differences of each type to evaluate their approaches as it was shown in Figure 4.4.

The result of this comparison is a value of γ that makes the number of free cooling hours of the indirect economizer types equal to the DAE: γ_{eq}. An indirect economizer system with a γ higher than γ_{eq} will have a lower free cooling potential than the reference system (DAE). And an economizer system with a $\gamma < \gamma_{eq}$ will have more free cooling hours than the DAE. Microsoft Excel software was used to evaluate this comparison.

4.3.2 Comparison results and discussion

The comparison results are divided into three parts. The first is the performance of CTWE in relation to the DAE. The second is the performance of the other indirect types in relation to the DAE. And the last part is the comparison between CTWE and the other indirect types.

CTWE and DAE

Table 4.5 presents the comparison results (γ_{eq}) between the CTWE and DAE.

The low standard deviation for γ_{eq} in Table 4.5 shows that this comparison does not rely heavily on which city is being assessed. However, γ_{eq} varies significantly when considering different operating ranges, i.e., different $DBT_{in,max}$ and $DPT_{in,max}$ values.

γ_{eq} assumes a mean value of 10.7°C for the Recommended range. This result means that a CTWE system which is capable to operate with a sum of approaches lower than 10.7°C will display more free cooling hours than a DAE. An average scenario considering $\gamma = 10$°C can be defined for the CTWE system based on literature values [Beaty et al., 2019; Belizário, 2018]. Thus, the cooling tower waterside economizer results in more free cooling hours than the direct airside system considering an average scenario for all cities aside from Brasília.

Table 4.5 – Sum of approaches of the cooling tower waterside economizer which results in the same free cooling hours of the direct airside free cooling assessment.

City	State	Latitude	γ_{eq} (°C) considering Recommended range	γ_{eq} (°C) considering A1 range	γ_{eq} (°C) considering A2 range	γ_{eq} (°C) considering A3 range	γ_{eq} (°C) considering A4 range
Porto Alegre	RS	30°02'S	10.5	13.4	12.4	13.5	18.5
Florianópolis	SC	27°36'S	10.6	13.7	12.9	14.7	19.7
Curitiba	PR	25°26'S	10.6	13.5	12.2	15.6	20.6
São Paulo	SP	23°33'S	10.6	13.4	12.2	13.6	18.6
Rio de Janeiro	RJ	22°54'S	10.9	13.7	12.6	14.2	19.2
Vitória	ES	20°19'S	10.7	13.8	12.8	14.4	19.4
Brasília	DF	15°47'S	9.9	13.4	12.1	15.3	20.3
Salvador	BA	12°58'S	11.3	13.1	12.3	14.3	19.3
Maceió	AL	9°40'S	10.9	13.8	12.5	13.8	18.8
Recife	PE	8°03'S	-*	13.4	12.5	14.7	19.7
Natal	RN	5°48'S	-*	13.7	12.5	14.3	19.3
Fortaleza	CE	3°43'S	-*	13.7	13.1	14.6	19.6
São Luís	MA	2°32'S	-*	12.1	12.8	14.4	19.4
Belém	PA	1°27'S	-*	12.0	13.0	14.4	19.4
Mean	-	-	10.7	13.4	12.6	14.4	19.4
Standard deviation	-	-	1.4	0.6	0.3	0.6	0.6

* There were zero free cooling potential hours considering direct airside economizer in this situation. Therefore a γ_{eq} value does not make sense in this case.

Other indirect types and DAE

The same comparison was made to the other indirect economizer modes as shown in Table 4.6. The γ_{eq} results were different from the results of Table 4.5 because the outdoor condition for the other indirect types depends on DBT_{out}, while for the CTWE system depends on the WBT_{out}.

The results for γ_{eq} from Table 4.6 behave similarly than the ones from Table 4.5. Low standard deviations were found, meaning that the difference among these cities is not relevant for this comparison. The mean γ_{eq} value considering the Recommended range is 9.4°C. This result indicates that an IAE, DWCE or ACWE which is capable to operate with Ap_{HX} lower than 9.4°C provides more free cooling hours than the DAE.

The results from Table 4.5 and Table 4.6 can be used in the decision-making process of which economizer mode will provide more benefit to a given DC facility. The fact that γ_{eq} has low dependence on which city is being analyzed makes this result more general. However, these comparisons were made only in reference to the direct airside

Table 4.6 – Sum of approaches of the indirect airside, direct water cooled and air cooled waterside economizers modes which results in the same free cooling hours of the direct airside free cooling assessment.

City	State	Latitude	γ_{eq} (°C) considering Recommended range	γ_{eq} (°C) considering A1 range	γ_{eq} (°C) considering A2 range	γ_{eq} (°C) considering A3 range	γ_{eq} (°C) considering A4 range
Porto Alegre	RS	30º02'S	8.9	11.2	7.8	5.0	10.0
Florianópolis	SC	27º36'S	9.4	12.2	10.7	11.5	16.5
Curitiba	PR	25º26'S	9.1	10.9	5.6	9.0	14.0
São Paulo	SP	23º33'S	8.9	10.9	4.9	9.9	14.9
Rio de Janeiro	RJ	22º54'S	9.8	12.4	10.5	9.8	14.8
Vitória	ES	20º19'S	9.7	12.5	11.0	9.9	14.9
Brasília	DF	15º47'S	8.0	10.8	4.9	9.9	14.9
Salvador	BA	12º58'S	10.8	12.1	9.3	9.8	14.8
Maceió	AL	9º40'S	10.4	13.3	9.6	9.7	14.7
Recife	PE	8º03'S	-*	12.2	10.0	11.0	16.0
Natal	RN	5º48'S	-*	13.0	10.6	9.7	14.7
Fortaleza	CE	3º43'S	-*	12.3	12.6	11.5	16.5
São Luís	MA	2º32'S	-*	11.7	12.2	9.7	14.7
Belém	PA	1º27'S	-*	11.7	12.6	9.7	14.7
Mean	-	-	9.4	11.9	9.5	9.7	14.7
Standard deviation	-	-	0.8	0.8	2.7	1.5	1.5

* There were zero free cooling potential hours considering direct airside economizer in this situation. Therefore a γ_{eq} value does not make sense in this case.

economizer mode. It was still necessary to compare the CTWE with the other indirect economizer modes.

CTWE and the other indirect types

The γ_{eq} values from Table 4.6 were higher than the ones from Table 4.5. This result was expected. The CTWE system depends on the WBT_{out}, while the other indirect types depend on DBT_{out}. The γ_{eq} of the cooling tower type will be higher than the γ_{eq} of the other indirect economizer types, since the WBT_{out} is always lower than or equal to the DBT_{out}. However, the CTWE system has to take into account the Ap_{WCT} while the other types have not, as it can be seen in Table 4.1 and Figure 4.4.

Therefore, a rough way to compare the cooling tower system with the other indirect economizer systems is to compare the difference between their γ_{eq} ($\Delta\gamma_{eq}$ displayed in Table 4.7) with the Ap_{WCT} of a CTWE.

Table 4.7 – Difference between γ_{eq} from the cooling tower system and the other indirect economizer types.

City	State	Latitude	$\Delta\gamma_{eq}$ (°C) considering Recommended range	$\Delta\gamma_{eq}$ (°C) considering A1 range	$\Delta\gamma_{eq}$ (°C) considering A2 range	$\Delta\gamma_{eq}$ (°C) considering A3 range	$\Delta\gamma_{eq}$ (°C) considering A4 range
Porto Alegre	RS	30°02'S	1.6	2.2	4.6	8.5	8.5
Florianópolis	SC	27°36'S	1.2	1.5	2.2	3.2	3.2
Curitiba	PR	25°26'S	1.5	2.6	6.6	6.6	6.6
São Paulo	SP	23°33'S	1.7	2.5	7.3	3.7	3.7
Rio de Janeiro	RJ	22°54'S	1.1	1.3	2.1	4.4	4.4
Vitória	ES	20°19'S	1.0	1.3	1.8	4.5	4.5
Brasília	DF	15°47'S	1.9	2.6	7.2	5.4	5.4
Salvador	BA	12°58'S	0.5	1.0	3.0	4.5	4.5
Maceió	AL	9°40'S	0.5	0.5	2.9	4.1	4.1
Recife	PE	8°03'S	-*	1.2	2.5	3.7	3.7
Natal	RN	5°48'S	-*	0.7	1.9	4.6	4.6
Fortaleza	CE	3°43'S	-*	1.4	0.5	3.1	3.1
São Luís	MA	2°32'S	-*	0.4	0.6	4.7	4.7
Belém	PA	1°27'S	-*	0.3	0.4	4.7	4.7
Mean	-	-	1.2	1.4	3.1	4.7	4.7
Standard deviation	-	-	0.5	0.8	2.4	1.4	1.4

* There were zero free cooling potential hours considering direct airside economizer in this situation. Therefore a γ_{eq} value does not make sense in this case.

Table 4.7 shows that considering the Recommended range the $\Delta\gamma_{eq}$ assumes a mean value of 1.2°C and a maximum of 1.9°C. This result means that a CTWE system with an Ap_{WCT} lower than these values of $\Delta\gamma_{eq}$ has more free cooling hours than the other indirect types. However, Ap_{WCT} values lower than 2.8°C are very unlikely to happen [Beaty et al., 2018; SPX, 2019]. Thus, the CTWE would tend to have less free cooling hours than the other indirect economizer modes if they had similar values for Ap_{HX}.

The value of Ap_{HX} for each indirect economizer type depends on the number of heat exchangers and on the effectiveness of these processes. By looking to Figure 4.4 it is possible to infer that the DWCE has the lowest Ap_{HX}, since it consists of a single-step heat transfer process using water as one of the working fluids.

Discussion

The comparison results from Tables 4.5 and 4.6 showed that indirect economizer types display higher free cooling potential than the DAE considering average scenarios. This means that DAE is the economizer with the lowest free cooling potential between the types assessed in this work. However, there are authors and DCs stakeholders defending that the humidity limits are too conservative [Kontoyanis, 2018; Kristoff, 2019], or even that there is no evidence that humidity is an issue for data centers [Hydeman and Swenson, 2010]. In the last years, some researches caused ASHRAE thermal guidelines to relax the suggested humidity control limits [Gao et al., 2015; Shehabi et al., 2007; Wan et al., 2013]. If this trend keeps going on, the direct airside economizer should be favored and it will probably present the highest free cooling potential of all types even in cities with high humidity rates, such as most of the Brazilian ones.

The DWCE does not depend on Ap_{WCT} and has the lowest value of Ap_{HX} among the indirect types. Therefore, DWCE is the economizer type that tends to display the highest number of free cooling hours.

The IAE, ACWE and CTWE types belong to an intermediate free cooling potential group. The difference in the free cooling hours provided between these three types depends on the balance between their Ap_{WCT} and Ap_{HX} values. CTWE will tend to display less free cooling potential in relation to IAE and ACWE types if they present similar Ap_{HX}.

4.4 Free cooling types qualitative comparison

In the previous section, the most relevant economizer types were compared regarding their free cooling potential performance in fourteen Brazilian capital cities. However, there are other important factors to be considered when talking about free cooling techniques. This section briefly discusses some of these other aspects, qualitatively comparing the different types of economizers in data centers.

4.4.1 Quality of the air

Direct airside economizers raised concerns regarding the quality of air inside the DC facility. Bringing outside air directly into the data center may introduce dirt, dust, airborne particulates, and gaseous contamination, which could put the IT equipment life expectancy at risk [Lui, 2010].

However, Lawrence Berkeley National Laboratory and Pacific Gas & Electric [Shehabi et al., 2007] conducted a research which showed that modest improvements in filtration can reduce particle concentrations to nearly match the level found in DCs that do not use economizers. Regarding the gaseous contaminants, there are gas-phase filtration and real-time gas monitoring systems commercially available. These systems can alert the presence of gaseous contaminants that may harm the IT equipment and suggest to disable the economizer operation if needed [Lui, 2010]. These solutions add costs to the operation and the design engineer must consider this before requiring the installation of such systems.

The indirect economizer types have advantages with respect to the quality of the air inside the DC facility. It is possible for a DAE to achieve a good quality of air level with filtration and monitoring measures described above, but it may be expensive. Meanwhile, the indirect economizer types provide indoor environment conditions more similar to the mechanical cooling without these additional requirements [Zhang et al., 2014].

4.4.2 Environmental impacts

Direct water cooled waterside economizers present the disadvantage of relying on high quantities of natural water. This dependence results either in elevated treatment costs or environmental impact [ASHRAE, 2016]. Cooling tower economizers also display this disadvantage, but at a lower level.

It is worth noticing that economizer systems reduce the electricity consumption and the CO_2 emissions of a data center. Thus, the highest the energy saving achieved, the better the economizer is in the environmental aspect.

4.4.3 Costs

This is the most important aspect to be taken into account. If the initial and operational costs of an economizer are higher than its savings it will not be installed regardless of any other aspect. In this context, a financial feasibility study must be carried out before implementing the free cooling strategy in a data center.

The economizer system initial cost relies on the required extra equipment to be purchased and installed, which is dependent on the previous operating conditions of the DC facility. For example, the relative costs to adapt a big data center which already has a CRAH refrigeration system working to operate with a CTWE are much lower than these costs for a small DC which operates with CRAC in a direct expansion system [Amoabeng and Choi, 2016].

In general, DAE and DWCE systems display the lowest initial cost among the airside and waterside categories, respectively, due to their fewer number of components. However, their operational costs are usually higher due to strategies adopted to address the quality of the air and environmental impact problems [Lui, 2010]. All of these aspects should be taken into account before deciding which economizer strategy suits better a data center facility.

Figure 4.5 summarizes the comparison between the economizer types for data centers made in this section.

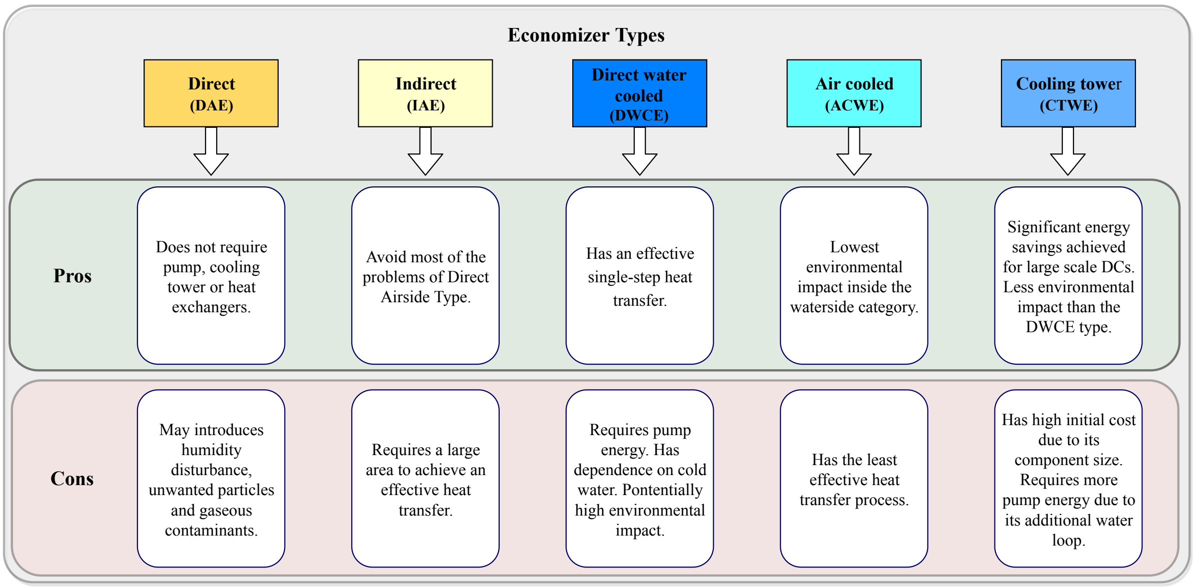


Figure 4.5 – Economizer types qualitative comparison summary. The review of Amoabeng and Choi, 2016 was used as reference.

4.5 Conclusion

In this chapter, free cooling potential criteria for the five main types of economizers were proposed. An overview of the characteristics of these economizers was provided followed by a comparison between their performances using results from 14 Brazilian key cities and a literature review to support this discussion.

In general, the indirect economizer types showed higher free cooling potential than the direct airside economizer, mainly due to the humidity criterion. Brazilian high humidity rates favored the indirect economizer types in this comparison. However, an ongoing trend for relaxing the humidity control in DCs may improve the position of direct airside economizers in the future.

It was shown that there is not a single and simple solution for the use of economizers in data centers. Each of the studied types has its own advantages and disadvantages that must be carefully considered and analyzed before its implementation. The direct water cooled type showed the highest free cooling potential among the types assessed, but it also presented disadvantages such as high environmental impact and operational costs.

This study aimed to be a reference regarding the free cooling potential for data centers, being able to provide a comprehensive overview of this subject inserted in the context of the Brazilian capitals. This study intended by no means to model and provide specific and accurate results for a DC cooling system. Yet, it expects to be a starting point and a useful tool for those more complex and specific analyses.

Data centers are very sophisticated facilities that require careful studies and measures to ensure a proper, reliable and efficient operation. Free cooling is a technique to improve this last mentioned aspect; thus, it should only be considered when the first two have already been addressed. Nonetheless, energy efficiency improvements perform a central role in a really competitive scenario such as the DC market. Despite not being the main goal of a data center, it may determine if a given facility shall succeed or not.

5 CONCLUSION

The present work has provided a broad overview of the data center free cooling potential in the context of Brazilian cities. Criteria to estimate the free cooling potential considering airside and waterside categories of economizers have been proposed in a general manner and in accordance with ASHRAE thermal guidelines recommendations. These criteria were then applied to assess the free cooling potential of key cities in Brazil representing all regions of the country. Differences between the performance and characteristics of the five main types of economizers inside those categories have also been discussed.

The airside free cooling potential assessment presented in Chapter 2 was made considering two parameters as criteria: the maximum dry-bulb ($DBT_{in,max}$) and dew-point ($DPT_{in,max}$) temperatures of the supplied air intake. In addition, a graphical representation of the criteria containing the free cooling zone on a psychrometric chart was provided. These criteria were applied to 14 capital cities in Brazil, by comparing the criteria to the cities hourly weather data.

Results showed that Curitiba displayed the highest free cooling potential in this category, achieving 5575 of economizer hours in a year, even considering the most conservative operating limit. Cities such as Porto Alegre, São Paulo and Brasília also showed potential to free cooling, displaying more than 3000 economizer hours in those limits. Cities from North and Northeast did not show potential to free cooling considering conservative operating limits. However, when considering more flexible ranges such as Allowable A3 and A4 limits more than 7000 economizer hours were achieved. A further analysis detailing these results for Curitiba, São Paulo and Fortaleza showed that the DPT parameter was the critical criterion in this assessment. The DBT criterion had a slight impact in comparison to the DPT for the free cooling potential results of the 14 cities assessed, suggesting that indirect types of economizers might suit better these cities.

The waterside free cooling potential assessment was made considering a cooling tower economizer type. The criteria to free cooling proposed in this category considered the maximum supply air temperature ($DBT_{in,max}$) and the system approaches (Ap_{CT} and Ap_{HX}) as parameters to compare with the outdoor wet-bulb temperature (WBT_{out}). A graphical representation was developed to illustrate the criteria dependence with the sum of the system approaches (γ) on a psychrometric chart.

The waterside free cooling criteria were evaluated and discussed considering an average scenario of $\gamma = 10$°C based on literature values. The results behaved similarly to the airside free cooling potential assessment. Curitiba displayed the highest free cooling potential in this category, achieving 6301 economizer hours in a year considering the most conservative operating limits. Porto Alegre, São Paulo and Brasília also showed potential to free cooling displaying more than 3000 economizer hours in that limit. North and Northeast cities of the country only presented potential to free cooling considering Allowable A2 limits onwards. Additional results for other scenarios ranging from $\gamma = 5$°C to $\gamma = 15$°C are presented in the Appendix C. It was also shown that it is possible to estimate the free cooling waterside potential of a given city considering different combinations of $DBT_{in,max}$ and γ by using its WBT cumulative frequency distribution.

In Chapter 4, it was provided an overview of the five main types of economizers for DCs. Criteria to assess free cooling potential of these economizers were proposed followed by a free cooling potential comparison between them using the results from Chapters 2 and 3. It was shown that the indirect economizer types have higher free cooling potential for all cities assessed aside from Brasília while considering an average scenario. Then, it was found that the direct water cooled waterside type was capable to provide the highest economizer hours among these. Finally, a qualitative discussion was made, pointing out other important factors regarding economizers such as air quality, environmental impact and costs.

5.1 Future works

The study presented in this thesis may be used as a reference and a starting point for an array of other studies regarding the free cooling potential for data centers. Some of these possibilities are highlighted in this section.

- This study can be expanded to evaluate the airside or waterside free cooling potential for other cities in Brazil and Latin America. Maps similarly to the ones developed by the Green Grid to Europe, North America and Japan [The Green Grid, 2012] can be made using the present work as a reference;

- From the criteria and results achieved in this work it is possible to assess integrated solutions between the free cooling with other alternative energy efficiency strategies for DCs, such as thermal energy storage systems and liquid cooling;

- The free cooling potential results presented in this work can be compared to more detailed results achieved by specific data center modeling and simulations;

- Case studies to estimate PUE reductions, energetic and financial savings for different economizers can be performed starting from the free cooling potential hours found in this study and making further considerations.

REFERENCES

Afonso, C. and Moreira, J. Data Center: Energetic and Economic Analysis of a More Efficient Refrigeration System with Free Cooling and the avoided CO2 Emissions, **International Journal of Engineering Research and Application**, vol. 7(11), p. 7, 2017.

Agrawal, A., Khichar, M., and Jain, S. Transient simulation of wet cooling strategies for a data center in worldwide climate zones, **Energy and Buildings**, vol. 127, p. 352–359, 2016.

Amoabeng, K. O. and Choi, J. M. Review on Cooling System Energy Consumption in Internet Data Centers, **International Journal of Air-Conditioning and Refrigeration**, vol. 24(04), p. 1630008, 2016.

ASHRAE. **ASHRAE handbook: heating, ventilating, and air-conditioning systems and equipment, SI Edition**, 2016.

ASHRAE. **Functions: ASHRAE 9.9 Mission Critical Facilities**. `http://tc0909.ashraetcs.org/functions.php`, 2019, Accessed 14-02-2019.

ASHRAE TC 9.9. ASHRAE Thermal Guidelines for Data Processing Environments, **White Paper**, (Second Edition), 2008.

ASHRAE TC 9.9. ASHRAE Thermal Guidelines for Data Processing Environments, **White Paper**, (Third Edition), 2011.

ASHRAE TC 9.9. ASHRAE Thermal Guidelines for Data Processing Environments, **White Paper**, (Fourth Edition), 2015.

ASHRAE TC 9.9. Data Center Power Equipment Thermal Guidelines and Best Practices, **White Paper**, 2016.

Avgerinou, M., Bertoldi, P., and Castellazzi, L. Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency, **Energies**, vol. 10(10), p. 1470, 2017.

Beaty, D. L., Quirk, D. P., and Morrison, F. T. Designing Data Center Water-Side Economizers For Cold Climates, **ASHRAE Journal**, p. 74–79, 2018.

Beaty, D. L., Quirk, D. P., and Morrison, F. T. Designing Data Center Waterside Economizers, **ASHRAE Journal**, p. 57–61, 2019.

Belizário, A. C. **Avaliação energética e financeira para utilização de sistemas de ar condicionado acionados por energia solar em ambientes de missão crítica para diferentes regiões climáticas**. PhD. Thesis, Universidade de São Paulo, São Paulo, 2018.

Bhalerao, A., Fouladi, K., Silva-Llanca, L., and Wemhoff, A. P. Rapid prediction of exergy destruction in data centers due to airflow mixing, **Numerical Heat Transfer, Part A: Applications**, vol. 70(1), p. 48–63, 2016.

Bulut, H. and Aktacir, M. A. Determination of free cooling potential: A case study for İstanbul, Turkey, **Applied Energy**, vol. 88(3), p. 680–689, 2011.

Capozzoli, A., Serale, G., Liuzzo, L., and Chinnici, M. Thermal Metrics for Data Centers: A Critical Review, **Energy Procedia**, vol. 62, p. 391–400, 2014.

Cho, K., Chang, H., Jung, Y., and Yoon, Y. Economic analysis of data center cooling strategies, **Sustainable Cities and Society**, vol. 31, p. 234–243, 2017.

Clidaras, J., Stiver, D. W., and Hamburgen, W. **Water-based data center Patent**, 2009.

DC Huddle. **CRAC vs CRAH**. `http://www.dchuddle.com/2011/crac-v-crah/`, 2011, Accessed 14-02-2019.

Driemeyer, R. **Projeto de Melhoria de um Data Center com Ênfase em Infraestrutura e Melhoria Energética**. PhD thesis, UNIVATES, 2016.

EPA. **Energy Star for Data Centers**. `https://www.energystar.gov/ia/partners/prod_development/downloads/DataCenters_GreenGrid02042010.pdf`, 2010, Accessed 14-02-2019.

EXAME. **Com receita de US$ 2,8 bilhões na América Latina, mercado de data centers demanda investimento brasileiro**. `https://exame.abril.com.br/negocios/dino/com-receita-de-us-28-bilhoes-na-america-latina-mercado-de-data-centers-demanda-investimento-brasileiro/`, 2018, Accessed 06-08-2018.

Gao, X., Talebzadeh, A., Swenson, D. E., Moradian, M., Han, Y., and Pommerenke, D. Dependence of ESD Charge Voltage on Humidity in Data Centers (Part-3 Estimation of ESD-Related Risk in Data Centers Using Voltage Level Extrapolation and Chebyshev's Inequality), **ASHRAE Journal**, p. 22, 2015.

Hong, T. Comparisons of HVAC Simulations between EnergyPlus and DOE-2.2 for Data Centers, **White Paper**, p. 19, 2008.

Hydeman, M. and Swenson, D. Humidity Controls for Data Centers Are They Necessary?, **ASHRAE Journal**, p. 48–55, 2010.

Intel. Server Thermal Considerations to Enable High Temperature Ambient Data Center Operations, **White Paper**, p. 7, 2012.

Johnson, P. and Marker, T. Data Centre Energy Efficiency Product Profile, **White Paper**, p. 28, 2009.

Kang, S., Schmidt, R. R., Kelkar, K. M., and Patankar, S. V. A methodology for the design of perforated tiles in raised floor data centers using computational flow analysis, **IEEE Transactions on Components and Packaging Technologies**, vol. 24(2), p. 177–183, 2001.

Kontoyanis, A. **Novos limites de umidade - ASHRAE Thermal Guidelines 2015**. https://www.linkedin.com/pulse/novos-limites-de-umidade-ashrae-thermal-guidelines-2015-kontoyanis/, 2016, Accessed 04-07-2018.

Kristoff, J. **Are Data Center Humidity Levels Important?** https://www.colocationamerica.com/blog/data-center-humidity-levels.htm, 2013, Accessed 19-02-2019.

LabEEE. **Arquivos Climáticos**. http://www.labeee.ufsc.br/downloads, Accessed 20-06-2018.

Lee, K.-P. and Chen, H.-L. Analysis of energy saving potential of air-side free cooling for data centers in worldwide climate zones, **Energy and Buildings**, vol. 64, p. 103–112, 2013.

Ling, L., Zhang, Q., Yu, Y., Ma, X., and Liao, S. Energy saving analysis of the cooling plant using lake water source base on the optimized control strategy with set points change, **Applied Thermal Engineering**, vol. 130, p. 1440–1449, 2018.

Lui, Y. Y. Waterside and Airside Economizers Design Considerations for Data Center Facilities, **ASHRAE Transactions**, vol. 116, p. 12, 2010.

Malkamäki, T. and Ovaska, S. J. Solar Energy and Free Cooling Potential in European Data Centers, **Procedia Computer Science**, vol. 10, p. 1004–1009, 2012.

Marcinichen, J. B., Olivier, J. A., and Thome, J. R. On-chip two-phase cooling of datacenters: Cooling system and energy recovery evaluation, **Applied Thermal Engineering**, vol. 41, p. 36–51, 2012.

Nadjahi, C., Louahlia, H., and Lemasson, S. A review of thermal management and innovative cooling strategies for data center, **Sustainable Computing: Informatics and Systems**, vol. 19, p. 14–28, 2018.

Ni, J. and Bai, X. A review of air conditioning energy performance in data centers, **Renewable and Sustainable Energy Reviews**, vol. 67, p. 625–640, 2017.

Niemann, J., Bean, J., and Avelar, V. Economizer Modes of Data Center Cooling Systems, **White Paper**, p. 19, 2011.

Oró, E., Depoorter, V., Garcia, A., and Salom, J. Energy efficiency and renewable energy integration in data centres. Strategies and modelling review, **Renewable and Sustainable Energy Reviews**, vol. 42, p. 429–445, 2015a.

Oró, E., Depoorter, V., Pflugradt, N., and Salom, J. Overview of direct air free cooling and thermal energy storage potential energy savings in data centres, **Applied Thermal Engineering**, vol. 85, p. 100–110, 2015b.

Phan, L. and Lin, C.-X. A multi-zone building energy simulation of a data center model with hot and cold aisles, **Energy and Buildings**, vol. 77, p. 364–376, 2014.

Rambo, J. and Joshi, Y. Modeling of data center airflow and heat transfer: State of the art and future trends, **Distributed and Parallel Databases**, vol. 21(2-3), p. 193–225, 2007.

Rareshide, M. **The Challenges of Site Selection for Cryptocurrency Data Centers in North America**. `https://info.siteselectiongroup.com/blog/the-challenges-of-site-selection-for-cryptocurrency-data-centers-in-north-america`, 2018, Accessed 13-02-2019.

Rong, H., Zhang, H., Xiao, S., Li, C., and Hu, C. Optimizing energy consumption for data centers, **Renewable and Sustainable Energy Reviews**, vol. 58, p. 674–691, 2016.

Rouse, M., Broncato, D., and Jones, D. S. **What is colocation (colo)?** `https://searchmicroservices.techtarget.com/definition/colocation-colo`, 2015, Accessed 13-02-2019.

Shehabi, A., Tschudi, W., and Gadgil, A. **Data Center Economizer Contamination and Humidity Study**. Technical Report LBNL-2424E, 971864, 2007.

Shende, S. Colocation Market by Type (Retail Colocation and Wholesale Colocation), End-User (Large Enterprises and Small and Medium Enterprises) and Industry Vertical (BFSI, Government & Public sector, Telecom & IT, Healthcare & Life sciences, Energy) - Global Opportunity Analysis and Industry Forecast, 2014 - 2020. Available at: <https://www.alliedmarketresearch.com/colocation-market>, **Technical Report**, 2015.

Siriwardana, J., Jayasekara, S., and Halgamuge, S. K. Potential of air-side economizers for data center cooling: A case study for key Australian cities, **Applied Energy**, vol. 104, p. 207–219, 2013.

SPX. **Cooling Tower Performance - Basic Theory and Practice**. `http://proofinperformance.com/pdfs/library/CTII-01A.pdf`, 2012, Accessed 28-01-2019.

Statista. **Global datacenter colocation market revenue 2014-2021**. `https://www.statista.com/statistics/496373/datacenter-colocation-revenue-worldwide/`, 2019, Accessed 13-02-2019a.

Statista. **Worldwide IT spending data center systems 2012-2020**. `https://www.statista.com/statistics/314596/total-data-center-systems-worldwide-spending-forecast/`, 2019, Accessed 13-02-2019b.

Stein, J. Waterside Economizing in Data Centers: Design and Control Considerations, **ASHRAE Transactions**, vol. 115, p. 192–201, 2009.

The Green Grid. The Green Grid Data Center Power Efficiency Metrics: PUE and DCiE, **White Paper**, 2007.

The Green Grid. Air-side Free Cooling Maps, **White Paper**, 2009.

The Green Grid. Updated Air-side Free Cooling Maps: The impact of ASHRAE 2011 Allowable Ranges, **White Paper**, 2012.

Wan, F., Swenson, D., Hillstrom, M., Stayer, C., and Pommerenke, D. The Effect of Humidity on Static Electricity Induced Reliability Issues of ICT Equipment in Data Centers —Motivation and Setup of the Study, **ASHRAE Transactions**, vol. 119, p. 341–358, 2013.

WCEC. Psych Plugin. Available at <https://wcec.ucdavis.edu/resources/software-resource-applications/>, **Software tool**, 2013.

Wemhoff, A. and Frank, M. Predictions of energy savings in HVAC systems by lumped models, **Energy and Buildings**, vol. 42(10), p. 1807–1814, 2010.

Zavřel, V., Torrens, J. I., Bynum, J. D., and Hensen, J. L. M. MODEL DEVELOPMENT FOR SIMULATION BASED GLOBAL OPTIMISATION OF ENERGY EFFICIENT DATA CENTRES, **Proceedings of 14th Conference of Building Performance Simulation**, p. 8, 2015.

Zhang, H., Shao, S., Xu, H., Zou, H., and Tian, C. Free cooling of data centers: A review, **Renewable and Sustainable Energy Reviews**, vol. 35, p. 171–182, 2014.

Zhang, K., Zhang, Y., Liu, J., and Niu, X. Recent advancements on thermal management and evaluation for data centers, **Applied Thermal Engineering**, vol. 142, p. 215–231, 2018.

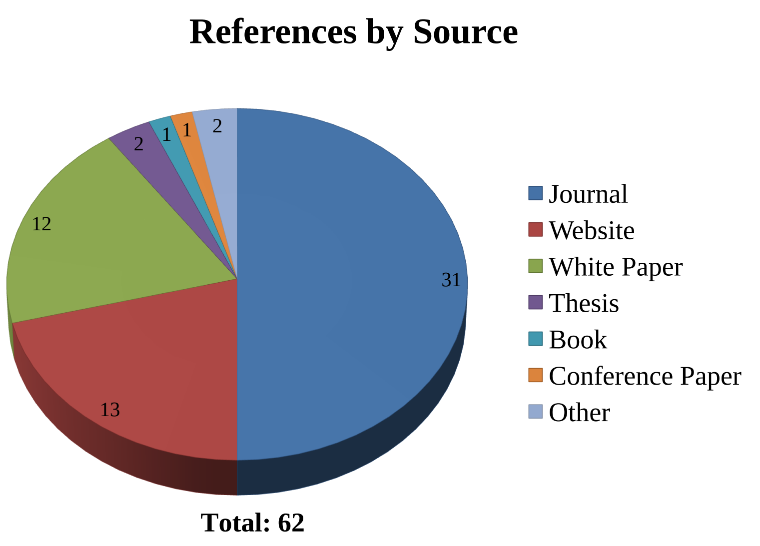
APPENDIX A – Bibliometrics

Table A.1 – References summary

Author	Title	Source	Year
Afonso, C. and Moreira, J.	Data Center: Energetic and Economic Analysis of a More Efficient Refrigeration System with Free Cooling and the avoided CO2 Emissions	International Journal of Engineering Research and Application	2017
Agrawal, A., Khichar, M., and Jain, S.	Transient simulation of wet cooling strategies for a data center in worldwide climate zones	Energy and Buildings	2016
Amoabeng, K. O. and Choi, J. M.	Review on Cooling System Energy Consumption in Internet Data Centers	International Journal of Air-Conditioning and Refrigeration	2016
ASHRAE	ASHRAE Handbook 2016 - HVAC Systems and Equipment	Book	2016
ASHRAE	ASHRAE TC 9.9 Functions: Mission Critical Facilities, Data Centers, Technology Spaces and Electronic Equipment	Website	2019
ASHRAE TC 9.9	Thermal Guidelines for Data Processing Environments (Second Edition)	White Paper	2008
ASHRAE TC 9.9	Thermal Guidelines for Data Processing Environments (Third Edition)	White Paper	2011
ASHRAE TC 9.9	Thermal Guidelines for Data Processing Environments (Fourth Edition)	White Paper	2015
ASHRAE TC 9.9	Data Center Power Equipment Thermal Guidelines and Best Practices	White Paper	2016
Averignou, M., Bertoldi, P., and Castellazzi, L.	Trends in Data Centre Energy Consumption under the European Code of Conduct for Data Centre Energy Efficiency	Energies	2017
Beaty, D.L., Quirk, D.P., and Morrison, F.T.	Designing Data Center Water-Side Economizers for Cold Climates	ASHRAE Journal	2018
Beaty, D.L., Quirk, D.P., and Morrison, F.T.	Designing Data Center Waterside Economizers	ASHRAE Journal	2019
Belizário, A.C.	Avaliação energética e financeira para utilização de sistemas de ar condicionado acionados por energia solar em ambientes de missão crítica para diferentes regiões climáticas	PhD Thesis	2018
Bhalerao, A., Fouladi, K., Silva-Llanca, L., and Wemhoff, A. P.	Rapid prediction of exergy destruction in data centers due to airflow mixing	Numerical Heat Transfer	2016
Bulut, H. and Aktacir, M.A.	Determination of free cooling potential: A case study for Istanbul, Turkey	Applied Energy	2011
Capozzoli, A., Serale, G., Liuzzo, L., and Chinnici, M.	Thermal Metrics for Data Centers: A Critical Review	Energy Procedia	2014
Cho, K., Chang, H., Jung, Y., and Yoon, Y.	Economic analysis of data center cooling strategies	Sustainable Cities and Society	2017
Clidaras, J., Stiver, D. W., and Hamburgen, W.	Water-based data center	Patent	2009
DC Huddle	CRAC vs CRAH	Website	2011
Driemeyer, R.	Projeto de Melhoria de um Data Center com Ênfase em Infraestrutura e Melhoria Energética	PhD Thesis	2016
EPA: U.S. Environmental Protective Agency	Energy Star for Data Centers	Website	2010
Exame	Com receita de US$ 2,8 bilhões na América Latina, mercado de data centers demanda investimento brasileiro	Website	2018
Gao, X., Talebzadeh A., Swenson, D. E., Moradian, M., Han, Y., and Pommerenk, D.	Dependence of ESD Charge Voltage on Humidity in Data Centers	ASHRAE Journal	2015
Hong, T.	Comparisons of HVAC Simulations between EnergyPlus and DOE-2.2 for Data Centers	White Paper	2008
Hydeman, M. and Swenson, D.	Humidity Controls for Data Centers Are They Really Necessary ?	ASHRAE Journal	2010
Intel	Server Thermal Considerations to Enable High Temperature Ambient Data Center Operations	White Paper	2012
Johnson, P. and Marker, T.	Data Centre Energy Efficiency Product Profile	White Paper	2009
Kontoyanis, A.	Novos Limites de umidade - ASHRAE Thermal Guidelines 2015	Website	2016
Kristoff, J.	Are Data Center Humidity Levels Important ?	Website	2013
LabEEE	Arquivos Climáticos	Website	2018

Table A.2 – References summary (continued)

Author	Title	Source	Year
Lee, K. P. and Chen, H. L.	Analysis of energy saving potential of air-side free cooling for data centers in worldwide climate zones	Energy and Buildings	2013
Ling, L., Zhang, Q., Yu, Y., Ma, X., and Liao, S.	Energy saving analysis of the cooling plant using lake water source based on the optimized control strategy with set points change	Applied Thermal Engineering	2018
Lui, Y. Y.	Waterside and Airside Economizers Design Considerations for Data Center Facilities	ASHRAE Transactions	2010
Malkamäki, T. and Ovaska, S. J.	Solar Energy and Free Cooling Potential in European Data Centers	Procedia Computer Science	2012
Marcinichen, J.B., Olivier, J. A., and Thome, J.R.	On-chip two-phase cooling of datacenters: Cooling system and energy recovery evaluation	Applied Thermal Engineering	2012
Nadjahi, C., Louahlia, H., and Lemasson, S.	A review of thermal management and innovative cooling strategies for data center	Sustainable Computing: Informatics and Systems	2018
Ni, J. and Bai, X.	A review of air conditioning energy performance in data centers	Renewable and Sustainable Energy Reviews	2017
Niemann, J., Bean, J., and Avelar, V.	Economizer Modes of Data Center Cooling Systems	White Paper	2011
Oró, E., Depoorter, V., Garcia, A., and Salom, J.	Energy efficiency and renewable energy integration in data centres. Strategies and modelling review	Renewable and Sustainable Energy Reviews	2015
Oró, E., Depoorter, V., Garcia, A., and Salom, J.	Overview of direct air free cooling and thermal energy storage potential energy savings in data centres	Applied Thermal Engineering	2015
Phan, L. and Lin, C. X.	A multi-zone building energy simulation of a data center model with hot and cold aisles	Energy and Buildings	2014
Rambo, J. and Joshi, Y.	Modeling of data center airflow and heat transfer: State of the art and future trends	Distributed and Parallel Databases	2007
Rareshide, M.	The Challenges of Site Selection for Cryptocurrency Data Centers in North America	Website	2018
Rong, H., Zhang, H., Xiao, S., Li, C., and Hu, C.	Optimizing energy consumption for data centers	Renewable and Sustainable Energy Reviews	2016
Rouse, M., Broncato, D., and Jones, D. S.	What is colocation (colo)?	Website	2015
Kang, S., Schmidt, R. R., Kelkar, K. M., Radmehr, A., and Patankar, S. V.	A methodology for the design of perforated tiles in raised floor data centers using computational flow analysis	IEEE Transactions on Components and Packaging Technologies	2001
Shehabi, A., Tschudi, W., and Gadgil, A.	A Data Center Economizer Contamination and Humidity Study	White Paper	2007
Shende, S.	Colocation Market by Type, End-User, and Industry Vertical - Global Opportunity Analysis and Industry Forecast	Website	2015
Siriwardana, J., Jayasekara, S., and Halgamuge, S. K.	Potential of air-side economizers for data center cooling: A case study for key Australian cities	Applied Energy	2013
SPX	Cooling Tower Performance - Basic Theory and Practice	Website	2012
Statista	Global datacenter colocation market revenue 2014-2021	Website	2019
Statista	Worldwide IT spending data center systems 2012-2020	Website	2019
Stein, J.	Waterside Economizing in Data Centers: Design and Control Considerations	ASHRAE Transactions	2009
The Green Grid	Data Center Power Efficiency Metrics: PUE and DCiE	White Paper	2007
The Green Grid	Air-side Free Cooling Maps	White Paper	2009
The Green Grid	Updated Air-side Free Cooling Maps: The impact of ASHRAE 2011 Allowable Ranges	White Paper	2012
Wan, F., Swenson, D., Hillstrom M., Stayer, C., and Pommerenke, D.	The Efect of Humidity on Static Electricity Induced Reliability Issues of ICT Equipment in Data Centers - Motivation and Setup of the Study	ASHRAE Transactions	2013
WCEC	Psych Plugin	Software tool	2013
Wemhoff, A. and Frank, M.	Predictions of energy savings in HVAC systems by lumped models	Energy and Buildings	2010
Zavřel, V., Torrens, J. I., Bynum, J. D., and Hensen, J. L. M.	Model Development for Simulation Based Global Optimisation of Energy Efficient Data Centres	Proceedings of 14th Conference of Building Performance Simulation	2015
Zhang, H., Shao, S., Xu, H., Zou, H., and Tian, C.	Free cooling of data centers: A review	Renewable and Sustainable Energy Reviews	2014
Zhang, K., Zhang Y., Liu, J., and Niu, X.	Recent advancements on thermal management and evaluation for data centers	Applied Thermal Engineering	2018



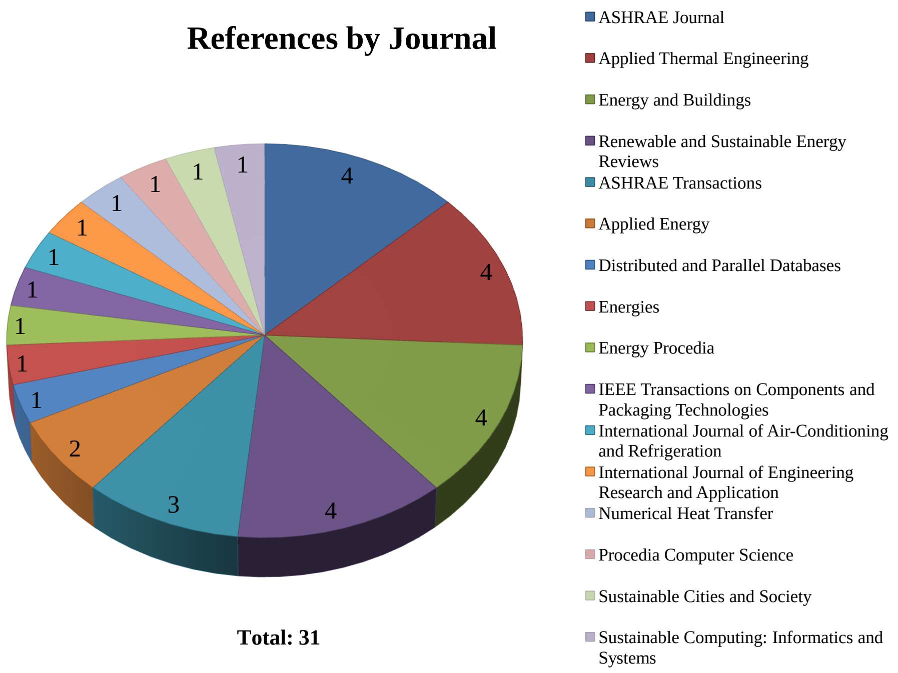
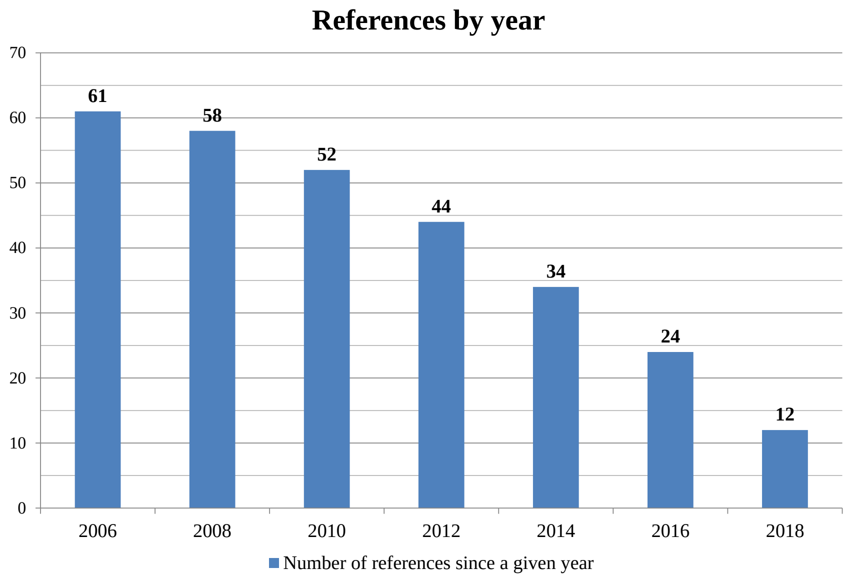


Figure A.1 – References categorization by their source.



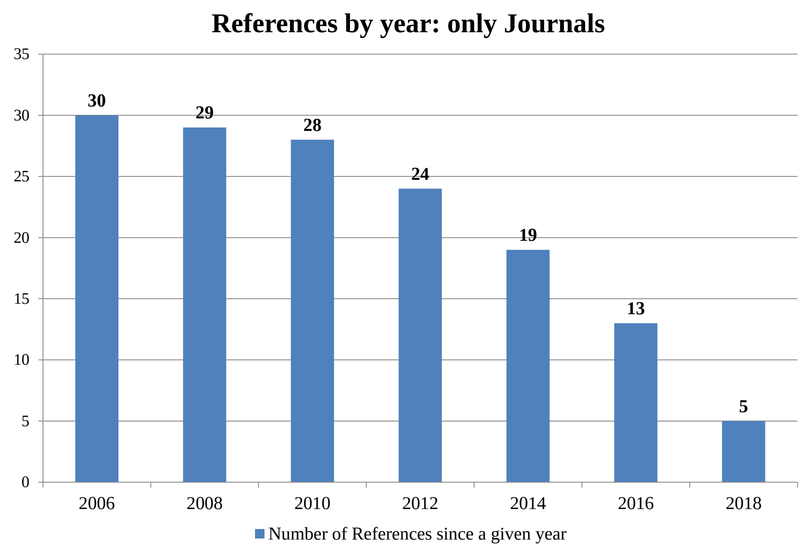


Figure A.2 – References categorization by their publication year.

APPENDIX B – γ isolines customized psychrometric chart

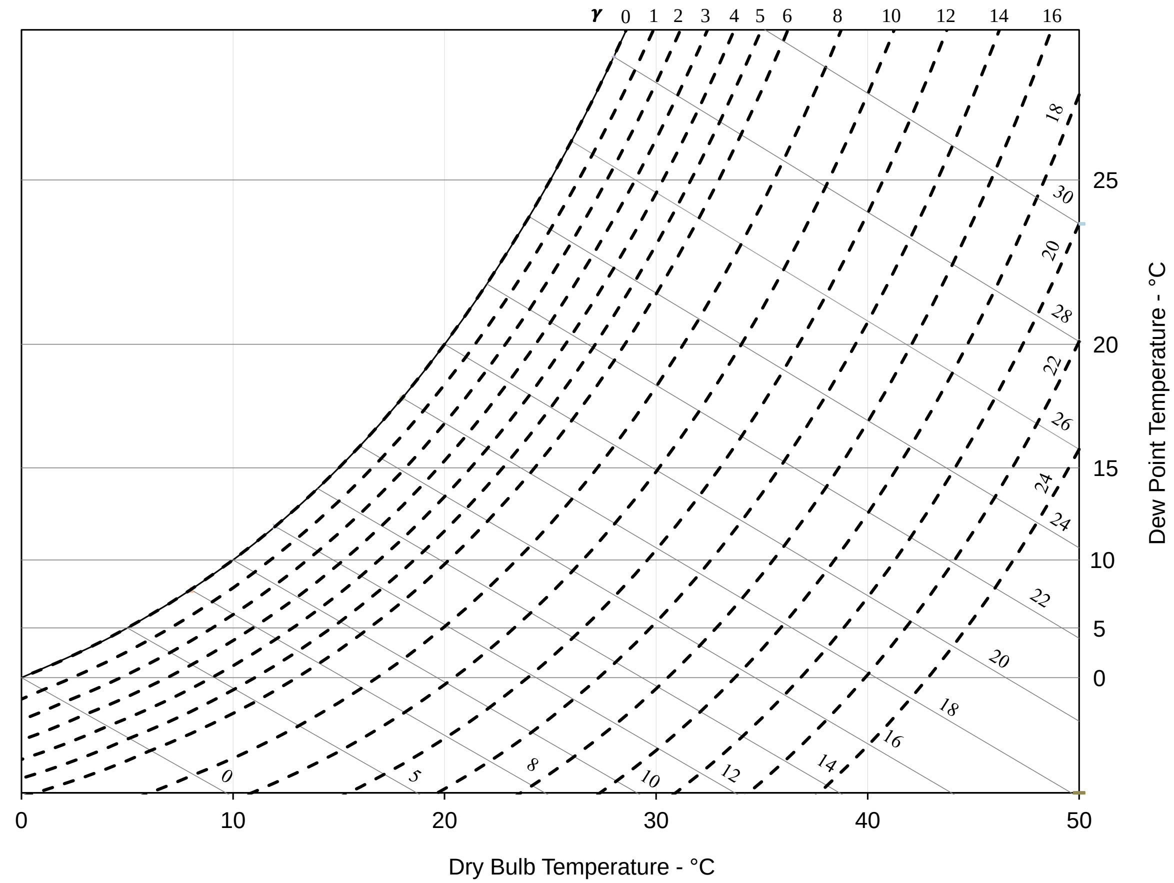


Figure B.1 – Full-size customized psychrometric chart with the γ isolines.

APPENDIX C – Additional waterside free cooling potential results

C.1 Optimistic scenario

Table C.1 – Free cooling potential hours in 14 Brazilian capitals considering the optimistic scenario ($\gamma = 5^{o}$C).

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	7700	8751	8760	8760	8760
Florianópolis	SC	27°36'S	7077	8690	8752	8760	8760
Curitiba	PR	25°26'S	8664	8760	8760	8760	8760
São Paulo	SP	23°33'S	8569	8760	8760	8760	8760
Rio de Janeiro	RJ	22°54'S	5238	8698	8760	8760	8760
Vitória	ES	20°19'S	5215	8720	8760	8760	8760
Brasília	DF	15°47'S	8660	8760	8760	8760	8760
Salvador	BA	12°58'S	4113	8760	8760	8760	8760
Maceió	AL	9°40'S	5051	8760	8760	8760	8760
Recife	PE	8°03'S	1726	8760	8760	8760	8760
Natal	RN	5°48'S	2302	8760	8760	8760	8760
Fortaleza	CE	3°43'S	309	8663	8760	8760	8760
São Luís	MA	2°32'S	132	8746	8760	8760	8760
Belém	PA	1°27'S	609	8680	8760	8760	8760

C.2 Conservative scenario

Table C.2 – Free cooling potential hours in 14 Brazilian capitals considering the conservative scenario ($\gamma = 15^{o}$C).

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	1327	4291	6407	8613	8760
Florianópolis	SC	27°36'S	445	2600	5555	8389	8752
Curitiba	PR	25°26'S	1958	6301	8184	8760	8760
São Paulo	SP	23°33'S	546	5117	7772	8754	8760
Rio de Janeiro	RJ	22°54'S	5	578	3009	8242	8760
Vitória	ES	20°19'S	8	832	3023	8261	8760
Brasília	DF	15°47'S	645	3032	7355	8760	8760
Salvador	BA	12°58'S	0	79	1096	8553	8760
Maceió	AL	9°40'S	0	34	1159	8700	8760
Recife	PE	8°03'S	0	0	98	8613	8760
Natal	RN	5°48'S	0	0	234	8380	8760
Fortaleza	CE	3°43'S	0	0	15	5939	8760
São Luís	MA	2°32'S	0	0	0	6922	8760
Belém	PA	1°27'S	0	0	4	6875	8760

C.3 Intermediate scenarios

Table C.3 – Free cooling potential hours in 14 Brazilian capitals considering $\gamma = 6°C$.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	7057	8710	8760	8760	8760
Florianópolis	SC	27°36'S	6366	8590	8747	8760	8760
Curitiba	PR	25°26'S	8505	8760	8760	8760	8760
São Paulo	SP	23°33'S	8282	8759	8760	8760	8760
Rio de Janeiro	RJ	22°54'S	4147	8597	8754	8760	8760
Vitória	ES	20°19'S	4039	8576	8760	8760	8760
Brasília	DF	15°47'S	8236	8760	8760	8760	8760
Salvador	BA	12°58'S	2347	8749	8760	8760	8760
Maceió	AL	9°40'S	2743	8755	8760	8760	8760
Recife	PE	8°03'S	480	8746	8760	8760	8760
Natal	RN	5°48'S	778	8745	8760	8760	8760
Fortaleza	CE	3°43'S	84	7819	8759	8760	8760
São Luís	MA	2°32'S	9	8498	8760	8760	8760
Belém	PA	1°27'S	69	8366	8760	8760	8760

Table C.4 – Free cooling potential hours in 14 Brazilian capitals considering $\gamma = 7°C$.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	6407	8613	8760	8760	8760
Florianópolis	SC	27°36'S	5555	8389	8734	8760	8760
Curitiba	PR	25°26'S	8184	8760	8760	8760	8760
São Paulo	SP	23°33'S	7772	8754	8760	8760	8760
Rio de Janeiro	RJ	22°54'S	3009	8242	8737	8760	8760
Vitória	ES	20°19'S	3023	8261	8752	8760	8760
Brasília	DF	15°47'S	7355	8760	8760	8760	8760
Salvador	BA	12°58'S	1096	8553	8760	8760	8760
Maceió	AL	9°40'S	1159	8700	8760	8760	8760
Recife	PE	8°03'S	98	8613	8760	8760	8760
Natal	RN	5°48'S	234	8380	8760	8760	8760
Fortaleza	CE	3°43'S	15	5939	8757	8760	8760
São Luís	MA	2°32'S	0	6922	8759	8760	8760
Belém	PA	1°27'S	4	6875	8751	8760	8760

Table C.5 – Free cooling potential hours in 14 Brazilian capitals considering $\gamma = 8°C$.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	5771	8428	8751	8760	8760
Florianópolis	SC	27°36'S	4597	8093	8690	8760	8760
Curitiba	PR	25°26'S	7717	8758	8760	8760	8760
São Paulo	SP	23°33'S	6917	8729	8760	8760	8760
Rio de Janeiro	RJ	22°54'S	1870	7544	8698	8760	8760
Vitória	ES	20°19'S	2126	7570	8720	8760	8760
Brasília	DF	15°47'S	5963	8756	8760	8760	8760
Salvador	BA	12°58'S	362	7647	8760	8760	8760
Maceió	AL	9°40'S	424	8295	8760	8760	8760
Recife	PE	8°03'S	14	7291	8760	8760	8760
Natal	RN	5°48'S	49	6872	8760	8760	8760
Fortaleza	CE	3°43'S	3	3297	8663	8760	8760
São Luís	MA	2°32'S	0	4113	8746	8760	8760
Belém	PA	1°27'S	0	4600	8680	8760	8760

Table C.6 – Free cooling potential hours in 14 Brazilian capitals considering $\gamma = 9°C$.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	5045	8077	8710	8760	8760
Florianópolis	SC	27°36'S	3681	7532	8590	8760	8760
Curitiba	PR	25°26'S	7089	8736	8760	8760	8760
São Paulo	SP	23°33'S	5999	8685	8759	8760	8760
Rio de Janeiro	RJ	22°54'S	1052	6349	8597	8760	8760
Vitória	ES	20°19'S	1397	6405	8576	8760	8760
Brasília	DF	15°47'S	4278	8747	8760	8760	8760
Salvador	BA	12°58'S	158	5769	8749	8760	8760
Maceió	AL	9°40'S	128	6826	8755	8760	8760
Recife	PE	8°03'S	0	3991	8746	8760	8760
Natal	RN	5°48'S	0	4301	8745	8760	8760
Fortaleza	CE	3°43'S	1	1010	7819	8760	8760
São Luís	MA	2°32'S	0	1053	8498	8760	8760
Belém	PA	1°27'S	0	2032	8366	8760	8760

Table C.7 – Free cooling potential hours in 14 Brazilian capitals considering $\gamma = 11^oC$.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30º02'S	3639	7057	8428	8760	8760
Florianópolis	SC	27º36'S	1798	6366	8093	8747	8760
Curitiba	PR	25º26'S	5356	8505	8758	8760	8760
São Paulo	SP	23º33'S	4030	8282	8729	8760	8760
Rio de Janeiro	RJ	22º54'S	262	4147	7544	8754	8760
Vitória	ES	20º19'S	414	4039	7570	8760	8760
Brasília	DF	15º47'S	2254	8236	8756	8760	8760
Salvador	BA	12º58'S	28	2347	7647	8760	8760
Maceió	AL	9º40'S	9	2743	8295	8760	8760
Recife	PE	8º03'S	0	480	7291	8760	8760
Natal	RN	5º48'S	0	778	6872	8760	8760
Fortaleza	CE	3º43'S	0	84	3297	8759	8760
São Luís	MA	2º32'S	0	9	4113	8760	8760
Belém	PA	1º27'S	0	69	4600	8760	8760

Table C.8 – Free cooling potential hours in 14 Brazilian capitals considering $\gamma = 12^oC$.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30º02'S	2991	6407	8077	8760	8760
Florianópolis	SC	27º36'S	1302	5555	7532	8734	8760
Curitiba	PR	25º26'S	4377	8184	8736	8760	8760
São Paulo	SP	23º33'S	2890	7772	8685	8760	8760
Rio de Janeiro	RJ	22º54'S	104	3009	6349	8737	8760
Vitória	ES	20º19'S	148	3023	6405	8752	8760
Brasília	DF	15º47'S	1733	7355	8747	8760	8760
Salvador	BA	12º58'S	9	1096	5769	8760	8760
Maceió	AL	9º40'S	3	1159	6826	8760	8760
Recife	PE	8º03'S	0	98	3991	8760	8760
Natal	RN	5º48'S	0	234	4301	8760	8760
Fortaleza	CE	3º43'S	0	15	1010	8757	8760
São Luís	MA	2º32'S	0	0	1053	8759	8760
Belém	PA	1º27'S	0	4	2032	8751	8760

Table C.9 – Free cooling potential hours in 14 Brazilian capitals considering $\gamma = 13^{o}C$.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	2401	5771	7700	8751	8760
Florianópolis	SC	27°36'S	884	4597	7077	8690	8760
Curitiba	PR	25°26'S	3433	7717	8664	8760	8760
São Paulo	SP	23°33'S	1756	6917	8569	8760	8760
Rio de Janeiro	RJ	22°54'S	45	1870	5238	8698	8760
Vitória	ES	20°19'S	40	2126	5215	8720	8760
Brasília	DF	15°47'S	1296	5963	8660	8760	8760
Salvador	BA	12°58'S	2	362	4113	8760	8760
Maceió	AL	9°40'S	0	424	5051	8760	8760
Recife	PE	8°03'S	0	14	1726	8760	8760
Natal	RN	5°48'S	0	49	2302	8760	8760
Fortaleza	CE	3°43'S	0	3	309	8663	8760
São Luís	MA	2°32'S	0	0	132	8746	8760
Belém	PA	1°27'S	0	0	609	8680	8760

Table C.10 – Free cooling potential hours in 14 Brazilian capitals considering $\gamma = 14^{o}C$.

City	State	Latitude	Free Cooling (FC) hours considering Recommended range	FC hours considering A1 range	FC hours considering A2 range	FC hours considering A3 range	FC hours considering A4 range
Porto Alegre	RS	30°02'S	1819	5045	7057	8710	8760
Florianópolis	SC	27°36'S	623	3681	6366	8590	8760
Curitiba	PR	25°26'S	2624	7089	8505	8760	8760
São Paulo	SP	23°33'S	1004	5999	8282	8759	8760
Rio de Janeiro	RJ	22°54'S	15	1052	4147	8597	8760
Vitória	ES	20°19'S	12	1397	4039	8576	8760
Brasília	DF	15°47'S	960	4278	8236	8760	8760
Salvador	BA	12°58'S	0	158	2347	8749	8760
Maceió	AL	9°40'S	0	128	2743	8755	8760
Recife	PE	8°03'S	0	0	480	8746	8760
Natal	RN	5°48'S	0	0	778	8745	8760
Fortaleza	CE	3°43'S	0	0	84	7819	8760
São Luís	MA	2°32'S	0	0	9	8498	8760
Belém	PA	1°27'S	0	0	69	8366	8760

APPENDIX D – WBT_{out} cumulative frequency distribution

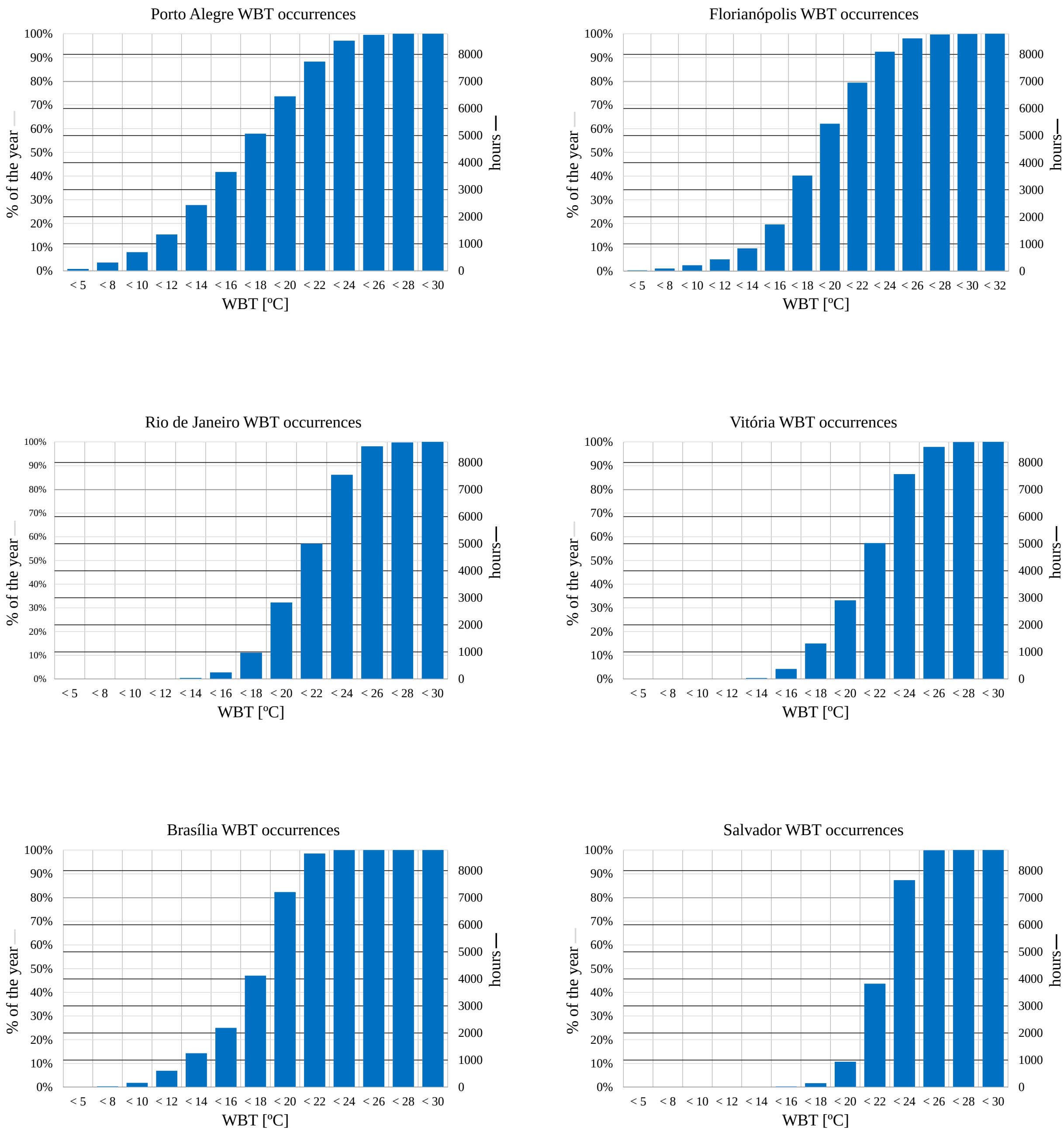


Figure D.1 – Brazilian cities WBT cumulative distribution.

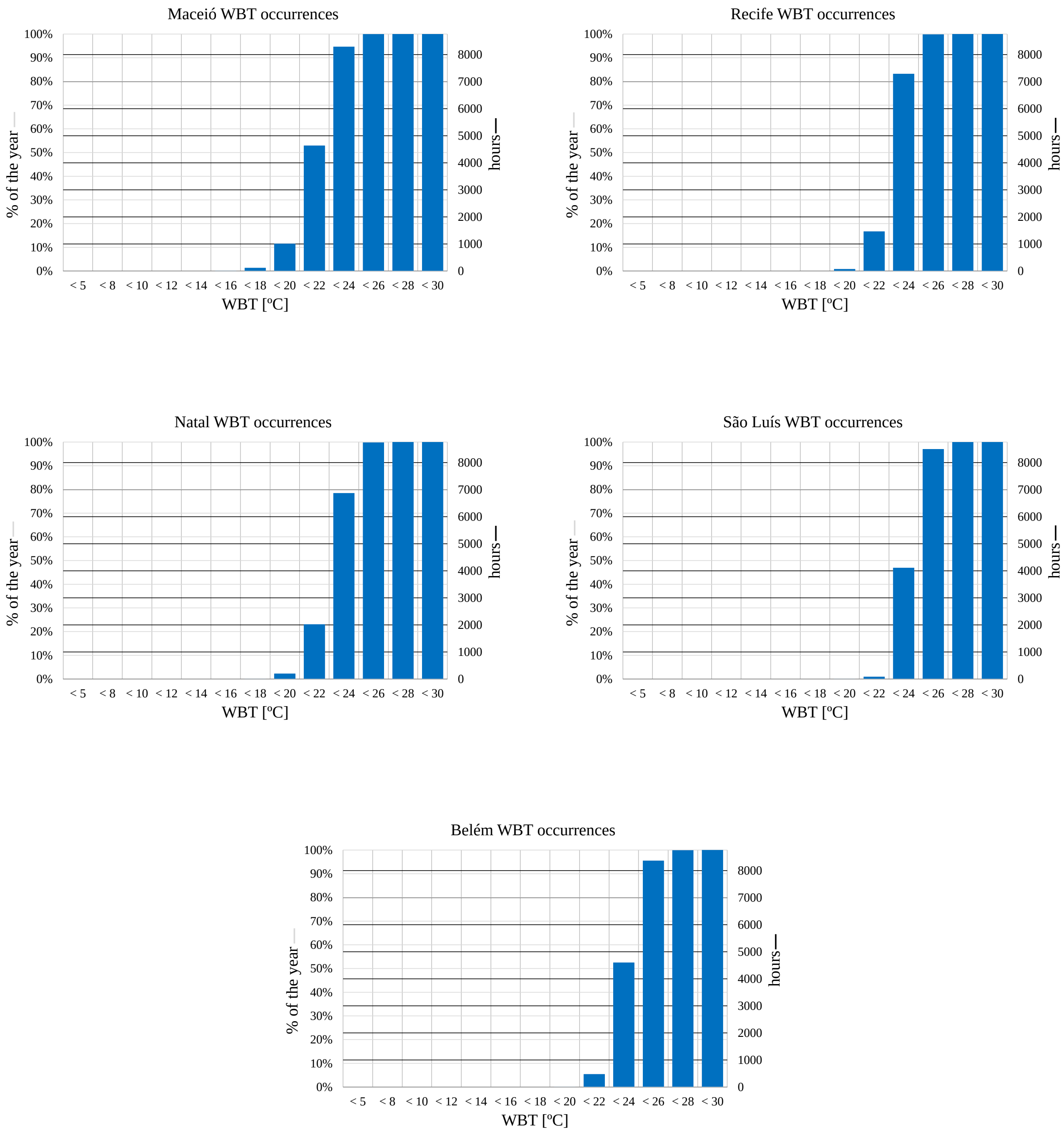


Figure D.2 – Brazilian cities WBT cumulative distribution (continued).