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## **Characterization of natural ventilation in the São Cristóvão church in Lisbon - numerical modeling**

Dissertação para obtenção do Grau de Mestre em  
Engenharia Civil

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**Junho, 2021**



FACULDADE DE  
CIÊNCIAS E TECNOLOGIA  
UNIVERSIDADE NOVA DE LISBOA

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## **Acknowledgment**

Throughout the writing of this dissertation, I have received a great deal of support and assistance.

I would first like to thank my supervisor, Professor Luís Gonçalo Correia Baltazar, whose expertise and guidance was invaluable in formulating the research questions and methodology. Your insightful feedback pushed me to hone my thinking and brought my work to a higher level.

I would like to acknowledge the NOVA School of Science and Technology docents, whose guidance throughout my education set the first stone of a, hopefully, long journey.

I would also like to thank Instituto Português do Mar e da Atmosfera (IPMA) in the person of Ricardo Deus for the availability to share some climatic data.

In addition, I would like to thank my family for their wise advice, and continuous support in every sense of the word. To my parents: -thank you and yes, I finished it!

Finally, and most importantly, the biggest thank you to my better half, Ana, the person who put up with me during the painstaking and head-scratching nights of running simulation and crashing excel sheets. Without your comforting words, patience, and mid-day chocolate brownies, this dissertation would have been much harder to complete.



## Abstract

Visitors have a relevant impact on indoor climate of buildings housing works of art, the link between the number of visitors, the indoor air quality, and the safeguarding of art pieces that are exposed without protective equipment is an important factor in the overall study of the indoor climate of historical buildings without mechanical ventilation or the possibility of its implementation.

Regarding this concern and, simultaneously, the lack of studies on natural ventilation in historic buildings, this dissertation intends to analyse the performance of natural ventilation of São Cristóvão Church in Lisbon.

For the preparation of this study, an analysis of the natural ventilation of this church was carried out by creating a model in the *CONTAM software* and the indoor air quality was analyzed by applying different international standards and guidelines for carbon dioxide levels and airflow rates.

Estimating the current ventilation strategy, an average ACH of 0.75 (about 1100m<sup>3</sup>/h) was detected during the time the church is open, and during the time the doors were closed, a ACH value of 0.15 was recorded. In a year-long analysis, an average ACH of 0.30 was obtained. These indoor air replacement values guarantee an EN-15251 category I air quality for 72% of the year, and a category II air quality of 18%.

Given the advanced state of degradation of some spans and the fact that masses, an occasional situation in which there is a high number of occupants, are always held just before the church closes, guarantees that the levels of carbon dioxide never exceed the limit of 350ppm above the outside values, imposed by EN-13779, registering a maximum of 291ppm.

Different ventilation strategies were analyzed; three scenarios exploring different cross-ventilation tactics; a scenario that assumes the church is closed all year round; and a scenario which, estimating an increase in the number of users, gives a notion of human pollutants variations and possible consequences.

Keywords: Indoor Air Quality, CONTAM, sustainability, ACH, historical building, CO<sub>2</sub>.



## Resumo

Os visitantes têm um impacto relevante no clima interior de edifícios que albergam obras de arte, a ligação entre o número de visitantes, a qualidade do ar interior, e a salvaguarda das peças de arte que são expostas sem equipamento de proteção é um fator importante no estudo geral do clima interior que se apresenta em edifícios históricos sem ventilação mecânica ou a possibilidade da sua implementação.

Face a esta preocupação e, dada a escassez de estudos sobre ventilação natural em edifícios antigos de carácter histórico, esta dissertação pretende analisar o desempenho da ventilação natural na Igreja de São Cristóvão em Lisboa.

Para a elaboração deste estudo, procedeu-se à análise do comportamento desta igreja no que respeita à ventilação, criando um modelo no *software* CONTAM analisando a qualidade do ar interior. Com base nos resultados obtidos das taxas de renovação de ar, concentração de dióxido de carbono e caudais, realizou-se uma análise crítica aplicando diferentes normas e diretrizes internacionais.

Estima-se a estratégia de ventilação actual, obtendo-se um valor médio de 0.75 rph (cerca de 1100m<sup>3</sup>/h) durante o período em que a igreja está aberta, e 0.15 rph durante o tempo em que as portas se encontram fechadas. Numa análise com a duração de um ano, 0.30 rph é o valor médio. Estes valores de substituição do ar interior garantem uma qualidade do ar pertencente à categoria I da EN-15251 em 72% do ano e uma qualidade do ar pertencente à categoria II de 18%.

Dado o avançado estado de degradação de alguns vãos e do facto das missas, situação pontual em que existe um número elevado de ocupantes, serem sempre realizadas imediatamente antes da igreja fechar, garante que os níveis de dióxido de carbono nunca ultrapassam o limite de 350ppm acima dos valores exteriores de CO<sub>2</sub>, imposto pela EN-13779, registando um máximo de 291ppm.

Foram ainda analisados diferentes cenários que exploram distintas estratégias de ventilação; um cenário cuja premissa é a igreja se encontrar encerrada todo o ano; e um cenário que, estimando um aumento no número de utilizadores, permita estabelecer a variação dos níveis de poluentes humanos e possíveis consequências.

Palavras-chave: Qualidade do ar interior, CONTAM, sustentabilidade, Rph, edifício histórico, CO<sub>2</sub>



## Lists

### Abbreviations, Acronyms and Symbols

<b>Abbreviation</b>	<b>Description</b>
ACH	Air Change per Hour
AER	Air Exchange Rate
AIVC	Air Infiltration and Ventilation Centre
AQG	Air Quality Guideline
ASHRAE	American Society of Heating, Refrigerating, and Air conditioning Engineers
CIBSE	Chartered Institution of Building Services Engineers
CO <sub>2</sub>	Carbon Dioxide
HVAC	Heating, Ventilation and Air Conditioning
IAQ	Indoor Air Quality
IDA	Indoor Air
IPMA	Instituto Português do Mar e da Atmosfera
LNEC	Laboratório Nacional de Engenharia Civil
OAQ	Outdoor Air Quality
WHO	World Health Organization
VOC	Volatile Organic Particles
Sim_00	Simulation ran in CONTAM with tabled infiltration rate values for the air pathways
Sim_01	Simulation ran in CONTAM with 2x the tabled infiltration rate values for the air pathways
Sim_02	Simulation ran in CONTAM with 1.5x the tabled infiltration rate values for the air pathways; represents the current ventilation performance
Sim_1	Simulation ran in CONTAM where the building is closed the entire year.
Sim_2	Simulation ran in CONTAM where the bell towers are open throughout Autumn and Spring, during the open hours
Sim_3.1	Simulation ran in CONTAM taking advantage of cross-ventilation 1
Sim_3.2	Simulation ran in CONTAM taking advantage of cross-ventilation 2
Sim_4	Simulation ran in CONTAM reflecting a potential growth in human occupancy



## Symbol notations

Symbol	Description	Units
$A, A_z$	Area of the analyzed compartment	$m^2$
$A_b$	Equivalent opening area	$cm^2$
$C$	Pressure coefficient.	NA
$C_d$	Discharge coefficient	NA
$C_{pe}, C_p$	External pressure coefficient	NA
$c_r(z)$	Roughness coefficient	NA
$c_0(z)$	Orography coefficient	NA
$C_t$	Indoor $CO_2$ concentration (ppm);	ppm
$C_{bg}$	Background $CO_2$ concentration equal to the outdoor concentration of the gas	ppm
$C_0$	$CO_2$ concentration at the initial point of the decay curve	ppm
$P$	Pressure	Pa
$\rho_0, \rho$	Air density	$kg/m^3$
$g$	Gravity acceleration	m/s
$H, h$	Height difference between the central point of the openings	m
$v, u, U$	Wind speed	m/s
$v_b, u_m, U_{met}$	Average wind speed	m/s
$K, a$	Constants to reflect the terrain characteristics the building is inserted on the <i>software</i> CONTAM	NA
$\delta_{met}$	Wind boundary layer thickness for the meteorological station	m
$Q$	Outdoor air supply rate	L/s or $m^3/h$
$\alpha_{met}$	Wind boundary layer exponent for the meteorological station	NA
$\delta$	Wind boundary layer thickness for the local building terrain	m
$n, P_z$	Number of people in the analyzed compartment	NA
$q_p, R_p$	Ventilation according to bio effluents/ per person	L/s or $m^3/h$
$q_b, R_a$	Ventilation according to pollution level expectancy per $m^2$	L/s or $m^3/h$
$T_{med}$	Average temperature	K or $C^0$
$T_0$	Reference temperature	K or $C^0$
$T_{int}$	Interior temperature	K or $C^0$
$T_{out}$	Exterior temperature	K or $C^0$



# Content

<b>1. Introduction .....</b>	<b>1</b>
1.1 Context.....	1
1.2. Motivation and research objective .....	2
1.3 Dissertation structure .....	2
<b>2. Indoor air quality and natural ventilation .....</b>	<b>5</b>
2.1. Brief history of ventilation and IAQ.....	5
2.2. IAQ based on comfort perception.....	6
2.3. IAQ based on human health.....	7
2.4. IAQ based on Conservation .....	8
2.5. Ventilation principles.....	11
2.5.1. Natural ventilation mechanisms .....	12
2.5.2. Types of ventilation.....	14
2.5.3. Natural ventilation by temperature difference .....	15
2.5.4. Natural ventilation by wind pressure .....	15
2.6. Revision of international guidelines and standards for IAQ and ventilation.....	19
2.6.1. EN 15251 and EN 13779 .....	19
2.6.2. ASHRAE 62.1 .....	22
2.6.3. CIBSE Guide A.....	23
2.6.4. EN 15759-2 .....	25
2.7. Revision of relevant literature for IAQ and ventilation in church-like buildings	27
<b>3. Research methodology .....</b>	<b>35</b>
3.1. Case study .....	35
3.2. Lisbon Climate.....	36
3.2.1. Temperature .....	36
3.2.2. Weather file analysis .....	39
3.3. <i>CONTAM</i> - multizone IAQ and ventilation analysis software .....	43
3.3.1 Input parameters .....	43
<b>4. Simulation results .....</b>	<b>51</b>
4.1. Implementation and analysis of the start-off simulation and its refinements .....	51
4.1.1. Simulation 00 .....	51
4.1.2. Simulation 01 .....	55
4.1.3. Simulation 02 .....	57
4.2. Ventilation strategies .....	60

4.2.1. Ventilation strategies: Sim_02 .....	61
4.2.2. Ventilation strategies: Sim_1 .....	73
4.2.3. Ventilation strategies: Sim_2 .....	76
4.2.4. Ventilation strategies: Sim_3 .....	86
4.2.4.1. Ventilation strategies: Sim_3.1 .....	87
4.2.4.2. Ventilation strategies: Sim_3.2 .....	97
4.2.5. Ventilation strategies: Sim_4 .....	106
4.3. Comparison of the results .....	115
<b>5. Conclusion and future works .....</b>	<b>129</b>
5.1. Summary .....	129
5.2. Future work .....	131
<b>References.....</b>	<b>133</b>
<b>Appendix .....</b>	<b>141</b>
A.1. Ventilation by temperature difference .....	141
A.1.1. Model.....	141
A.1.2. Analytical calculus .....	142
B. Wind intensity and direction from different sources.....	143
C. CONTAM flow paths layout.....	143
C. Simulations ACH data.....	150

## List of figures

Figure 1- NHAPS usage of time.....	7
Figure 2- Isopleths for mycelium growth of various fungus species considered in the model and the Lowest Isopleth for Mould (LIM) resulting from that. The left illustration applies to fungi of hazardous class A, the right illustration to class B/C.....	9
Figure 3- The response of cottonwood to changes in RH – fully restrained in tangential direction.....	10
Figure 4- Psychrometrics diagram.....	11
Figure 5- Wind-induced pressure on building envelope .....	12
Figure 6- Natural driving mechanism, stack driven flow .....	13
Figure 7- Combined effect of wind and temperature difference on ventilation rate and air flow pattern.....	13
Figure 8- Cross flow Ventilation.....	14
Figure 9- Single-sided Ventilation .....	14
Figure 10- The direction of airflow based on the air temperature.....	15
Figure 11- Example of pressure coefficient on a building .....	18
Figure 12- Variation of Surface-Averaged Wall Pressure Coefficients for Low-Rise Buildings.....	18
Figure 13- Reduction in fresh air rate for intermittent pollutant source.....	25
Figure 14- Step-by-step approach to managing ventilation.....	26
Figure 15- a) Cathedral of the Nativity of the Blessed Virgin Mary; 14th-century b) St. Bartholomew's Church; 15th century .....	27
Figure 16- Waalse church in Delft .....	28
Figure 17- Comparison of measured and calculated results.....	28
Figure 18- Sypekerk in (Nieuw-)Loosdrecht.....	29
Figure 19- St. Liduina's Basilica.....	29
Figure 20- St. Martinus' church .....	29
Figure 21- Vertical temperature mapping at May, 2012 .....	30
Figure 22- Target band of tolerable fluctuations according to the EN 15757 and the new methodology; a) T; b) RH. ....	30
Figure 23- Graphical representation of the microclimatic classification of the four approaches in analysis .....	31
Figure 24- Church of São Cristóvão.....	35
Figure 25- Köppen-Geiger Climate Classification for the Iberian Peninsula and the Balearic Islands.....	36
Figure 26- Evolution of the average yearly temperature in Lisbon.....	37
Figure 27- Climate normal values for air temperature in Portugal relating to the 1971-2000 time-frame; Instituto Geofísico .....	37
Figure 28- Extreme temperatures in Lisbon relating to the 1971-2000 time-frame.....	38
Figure 29- Percentage of days per month by range of temperature.....	38
Figure 30- Wind direction of the four data sets.....	39
Figure 31- Wind rose diagram of the four data sets .....	40
Figure 32- Wind speed of the four data sets; the black dotted line represents the weekly average.....	41
Figure 33- Sunday mass schedule and corrective factor of 0.3, 15 minutes before mass starts.....	46

Figure 34- Weekly percentage of time for each church activity period .....	47
Figure 35- Schematic of São Cristóvão's church levels in CONTAM .....	48
Figure 36 – Sim_00 hourly ACH throughout 1 year, considering open and closed doors intervals .....	53
Figure 37- Sim_00 hourly ventilation rates in m <sup>3</sup> /h .....	53
Figure 38- Exterior temperature monthly average vs ACH monthly average.....	54
Figure 39- Wind speed monthly average vs ACH monthly average.....	54
Figure 40- Sim_01 hourly ACH throughout 1 year, considering open and closed doors intervals .....	57
Figure 41- Sim_01 hourly ventilation rates in m <sup>3</sup> /h .....	57
Figure 42- Sim_02 hourly ACH throughout 1 year, considering open and closed doors intervals .....	59
Figure 43- Sim_02 hourly ventilation rates in m <sup>3</sup> /h .....	59
Figure 44- Sim_02: floor 1 open/closed spans schematic .....	61
Figure 45- Sim_02: Monthly average ACH .....	62
Figure 46- Sim_02: ACH values for each season throughout the year .....	62
Figure 47- Sim_02: Average ACH and standard deviation values for each church attendance status by season .....	63
Figure 48- EN 15251 prescribed airflow rates for são Cristóvão's church by number of occupants .....	63
Figure 49- Sim_02: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period.....	64
Figure 50- Sim_02: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period.....	64
Figure 51- Sim_02: Main door hourly airflow balance throughout the year .....	65
Figure 52- Sim_02: ventilation rates vs EN 15251 hourly prescribed ventilation rates: closed period.....	65
Figure 53- Sim_02: Percentage of time spent in each EN 15251 category per church attendance status .....	66
Figure 54- Sim_02: CO <sub>2</sub> levels in São Cristóvão's main nave (units in ppm above outdoor concentration).....	67
Figure 55- Sim_02: CO <sub>2</sub> concentration levels and ACH values recorded in the church nave from October 08 <sup>th</sup> to October 14 <sup>th</sup> . The 8 <sup>th</sup> of October represents a day type 1(Sunday) .....	67
Figure 56- Sim_02: CO <sub>2</sub> hourly average concentration levels by day of the week and season .....	68
Figure 57- ΔCO <sub>2</sub> levels and ACH average per day of the week and by Season .....	68
Figure 58- Sim_02: ASHRAE 62.1 prescribed ACH for visitation attendance status...	70
Figure 59- Sim_02: Ashrae 62.1 prescribed ACH for mass attendance status.....	70
Figure 60- Sim_02: Ashrae 62.1 prescribed ACH for closed attendance status .....	71
Figure 61- Sim_02: CIBSE guide A prescribed ACH for visitation attendance status..	71
Figure 62- Sim_02: CIBSE guide A prescribed ACH for mass attendance status.....	72
Figure 63- Sim_1: Monthly average ACH .....	73
Figure 64- Sim_1: ACH values for each season throughout the year .....	73
Figure 65- Sim_1: ventilation rates vs EN 15251 hourly prescribed ventilation rates...	74
Figure 66- Sim_1: Percentage of time spent in each EN 15251 .....	75
Figure 67- Sim_1: ASHRAE 62.1 prescribed ACH for visitation attendance status .....	75

Figure 68 Sim_2: 1 <sup>st</sup> floor and 4 <sup>th</sup> floor open span schematic (light grey walls and airflow paths represent the floor below) .....	76
Figure 69- Sim_2: Monthly average ACH .....	77
Figure 70- Sim_2: ACH values for each season throughout the year .....	77
Figure 71- Sim_2: Average ACH and standard deviation values for each church attendance status by season .....	78
Figure 72- Sim_2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period.....	78
Figure 73- Sim_2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period.....	79
Figure 74- Sim_2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: closed period.....	79
Figure 75- Sim_2: Percentage of time spent in each EN 15251 category per church attendance status .....	80
Figure 76- Sim_2: CO <sub>2</sub> levels in São Cristovão’s main nave (units in ppm above outdoor concentration) .....	80
Figure 77- Sim_2: CO <sub>2</sub> concentration levels and ACH values recorded in the church nave from March 12 <sup>th</sup> to March 14 <sup>th</sup> . The 12 <sup>th</sup> of March represents a day type 1 (Sunday)...	81
Figure 78- Sim_2: CO <sub>2</sub> hourly average concentration levels by day of the week and season .....	81
Figure 79- Sim_2: ΔCO <sub>2</sub> levels and ACH average per day of the week and by Season	82
Figure 80- Sim_2: ASHRAE 62.1 prescribed ACH for visitation attendance status .....	83
Figure 81- Sim_2: ASHRAE 62.1 prescribed ACH for mass attendance status .....	83
Figure 82- Sim_2: ASHRAE 62.1 prescribed ACH for closed attendance status.....	84
Figure 83- Sim_2: Percentage of time in compliance with ASHRAE 62.1 ventilation rates per church attendance status .....	84
Figure 84- Sim_2: CIBSE guide A prescribed ACH for visitation attendance status....	85
Figure 85- Sim_2: CIBSE guide A prescribed ACH for mass attendance status.....	85
Figure 86- Sim_2: Percentage of time respecting CIBSE guide A acceptable ventilation rates for visitation and mass attendance status .....	85
Figure 87- Sim_3.1 and Sim_3.2 implemented cross ventilation strategies .....	86
Figure 88 Sim_3.1: floor 1 open spans schematic.....	87
Figure 89- Sim_3.1: Monthly average ACH .....	87
Figure 90 Sim_3.1: ACH values for each season throughout the year.....	88
Figure 91- Sim_3.1: Average ACH and standard deviation values for each church attendance status by season .....	88
Figure 92- Sim_3.1: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period.....	89
Figure 93- Sim_3.1: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period.....	89
Figure 94- Sim_3.1: ventilation rates vs EN 15251 hourly prescribed ventilation rates: closed period.....	89
Figure 95- Sim_3.1: Percentage of time spent in each EN 15251 category per church attendance status .....	90
Figure 96- Sim_3.1: CO <sub>2</sub> levels in São Cristovão’s main nave (units in ppm above outdoor concentration) .....	91
Figure 97- Sim_3.1: ΔCO <sub>2</sub> average levels per day of the week and by Season .....	91

Figure 98- Sim_3.1: $\Delta\text{CO}_2$ levels and ACH average per day of the week and by Season .....	92
Figure 99- Sim_3.1: ASHRAE 62.1 prescribed ACH for visitation attendance status ..	93
Figure 100- Sim_3.1: ASHRAE 62.1 prescribed ACH for mass attendance status .....	93
Figure 101- Sim_3.1: ASHRAE 62.1 prescribed ACH for closed attendance status .....	93
Figure 102- Sim_3.1: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates .....	94
Figure 103- Sim_3.1: CIBSE guide A prescribed ACH for visitation attendance status	94
Figure 104- Sim_3.1: CIBSE guide A prescribed ACH for mass attendance status .....	95
Figure 105- Sim_3.2: Percentage of time respecting CIBSE guide A acceptable ventilation rates for visitation and mass attendance status .....	95
Figure 106 Sim_3.2: 1 <sup>st</sup> floor and 2 <sup>nd</sup> floor open span schematic .....	97
Figure 107- Sim_3.2: Monthly average ACH .....	97
Figure 108 Sim_3.2: ACH values for each season throughout the year .....	98
Figure 109- Sim_3.2: Average ACH values for each church attendance status by season .....	98
Figure 110- Sim_3.2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period .....	99
Figure 111- Sim_3.2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period .....	99
Figure 112- Sim_3.2: Percentage of time spent in each EN 15251 category per church attendance status .....	100
Figure 113- Sim_3.2: $\text{CO}_2$ levels in São Cristóvão's main nave (units in ppm above outdoor concentration) .....	101
Figure 114- Sim_3.2: $\Delta\text{CO}_2$ levels and ACH average per day of the week and by Season .....	101
Figure 115- Sim_3.2: $\Delta\text{CO}_2$ levels and ACH average per day of the week and by Season .....	102
Figure 116- Sim_3.2: ASHRAE 62.1 prescribed ACH for visitation attendance status .....	103
Figure 117- Sim_3.2: ASHRAE 62.1 prescribed ACH for mass attendance status .....	103
Figure 118- Sim_3.2: Ashrae 62.1 prescribed ACH for closed attendance status .....	103
Figure 119- Sim_3.2: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates .....	104
Figure 120- Sim_3.2: CIBSE guide A prescribed ACH for visitation attendance status .....	105
Figure 121- Sim_3.2: CIBSE guide A prescribed ACH for mass attendance status .....	105
Figure 122- Sim_3.2: Percentage of time respecting CIBSE guide A acceptable ventilation rates for visitation and mass attendance status .....	105
Figure 123- Sim_4: floor 1 open/closed spans schematic .....	106
Figure 124- Sim_4: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period .....	107
Figure 125- Sim_4: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period .....	108
Figure 126- Sim_4: Percentage of time spent in each EN 15251 category per church attendance status .....	109

Figure 127- Sim_4: CO <sub>2</sub> levels in São Cristovão's main nave (units in ppm above outdoor concentration) .....	109
Figure 128- Sim_4: CO <sub>2</sub> hourly average concentration levels by day of the week and season .....	110
Figure 129- Sim_4: Average hourly ACH and CO <sub>2</sub> concentrations above out-door levels by day type and season .....	110
Figure 130- Sim_4: ASHRAE 62.1 prescribed ACH for visitation attendance status .	111
Figure 131- Sim_4: ASHRAE 62.1 prescribed ACH for mass attendance status.....	112
Figure 132- Sim_4: ASHRAE 62.1 prescribed ACH for closed attendance status.....	112
Figure 133- Sim_4: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates.....	112
Figure 134- Sim_4: CIBSE guide A prescribed ACH for visitation attendance status	113
Figure 135- Sim_4: CIBSE guide A prescribed ACH for mass attendance status.....	113
Figure 136 - Sim_4: Percentage of time respecting CIBSE guide A acceptable ventilation rates for visitation and mass attendance status .....	114
Figure 137- Average daily ach for each simulation .....	115
Figure 138- Average seasonal ach for each simulation .....	116
Figure 139- Average monthly ach for each simulation .....	116
Figure 140- Average seasonal ΔCO <sub>2</sub> (ppm), by simulation .....	118
Figure 141- Average daily ΔCO <sub>2</sub> (ppm), by simulation.....	118
Figure 142- Average ΔCO <sub>2</sub> (ppm) for each simulation, by day type .....	119
Figure 143- Average ΔCO <sub>2</sub> (ppm) for each simulation by day type for all seasons. ....	120
Figure 144 Average hourly CO <sub>2</sub> concentration by day of the week comparison between Sim_02 and Sim_2 .....	121
Figure 145- Average hourly CO <sub>2</sub> concentration by day of the week comparison between Sim_02 and Sim_3.1 .....	121
Figure 146- Average hourly CO <sub>2</sub> concentration by day of the week comparison between Sim_02 and Sim_3.2 .....	122
Figure 147- Average hourly CO <sub>2</sub> concentration by day of the week comparison between Sim_02 and Sim_4 .....	122
Figure 148- Comparison of the percentage of time respecting EN 15251 recommended ventilation rates for the entire year. ....	123
Figure 149- Comparison of the percentage of time respecting EN 15251 recommended ventilation rates for the visitation attendance status. ....	124
Figure 150- Comparison of the percentage of time respecting EN 15251 recommended ventilation rates for the mass attendance status. ....	125
Figure 151- Comparison of the percentage of time respecting EN 15251 recommended ventilation rates for the closed attendance status.....	125
Figure 152- Comparison of all simulations for the percentage of time spent on IDA 1 and respecting EN 13779 recommended ventilation rates for the mass attendance status. ....	126
Figure 153- Sim_4: Percentage of time spent in each IDA category for mass period .	126
Figure 154- Comparison of the percentage of time respecting ASHRAE 62.1's recommended ventilation rates for the visitation attendance status. ....	127
Figure 155- Comparison of the percentage of time respecting ASHRAE 62.1's recommended ventilation rates for the mass attendance status. ....	127
Figure 156- Comparison of the percentage of time respecting ASHRAE 62.1's recommended ventilation rates for the closed attendance status. ....	127

Figure 157- Comparison of the percentage of time respecting CIBSE Guide A recommended ventilation rates for the visitation attendance status. ....	128
Figure 158- Comparison of the percentage of time respecting CIBSE Guide A recommended ventilation rates for the mass attendance status. ....	128
Figure 159- Geometric setup for the test simulation .....	141
Figure 160- Airflow due to temperature difference with two openings model [61] ....	142
Figure 161- Wind direction and intensity throughout the year of 2016 [92] .....	143
Figure 162- Wind direction and intensity throughout the year; 1kts = 0.5144m/s [93]	143
Figure 163- Wind direction and intensity throughout the year (2) [94] .....	143
Figure 164- Wind direction throughout the year [95] .....	143
Figure 165- CONTAM layout: Ground Floor .....	144
Figure 166- CONTAM layout: 1st Floor.....	145
Figure 167- CONTAM layout: 2nd Floor .....	146
Figure 168- CONTAM layout: 3rd Floor .....	147
Figure 169- CONTAM layout: 4th Floor .....	148
Figure 170- Sim_02: ACH data.....	151
Figure 171- Sim_1: ACH data.....	152
Figure 172- Sim_2: ACH data.....	153
Figure 173- Sim_3.1: ACH data.....	154
Figure 174- Sim_3.2: ACH data.....	155
Figure 175- Sim_4: ACH data.....	156

## List of tables

Table 1- Description of the applicability of the categories used for buildings IAQ expectation.....	19
Table 2- Classes of building pollutant and their requirements.....	20
Table 3- Prescribed ventilation rates by human bio effluents and building polluting level .....	21
Table 4- Basic classification of indoor air quality classes.....	21
Table 5- Minimum recommended rates of outdoor air intake per person and floor area for non-smoking areas of non-residential rooms.....	22
Table 6- Minimum ventilation rates in breathing zones.....	23
Table 7- Recommended comfort criteria for specific applications .....	23
Table 8- Performance of retrofit measures concerning the case without retrofits for Lisbon’s historical climate.....	32
Table 9- Ventilation rates from 14 different churches, chapels and Basilicas .....	32
Table 10- Average ACH values for different weather databases .....	41
Table 11- Source models used to characterize source emission rates in CONTAM.....	44
Table 12- São Cristóvão church’s schedule used in CONTAM.....	47
Table 13- CONTAM floor height setting .....	48
Table 14- Flow path types identified at São Cristóvão’s Church.....	49
Table 15- AIVC Guide 5: ELA values .....	52
Table 16- Sim_00 Average ACH values vs Coelho et al. ....	52
Table 17- Average temperature, and wind speed by month .....	54
Table 18- AIVC Guide 5: Equivalent leakage values factored by 2 .....	56
Table 19- Sim_01 Average ACH values vs other simulations .....	56
Table 20- Sim_02 Average ACH values vs other simulations.....	58
Table 21- Sim_02: ACH values for each season and church attendance status throughout the year .....	62
Table 22- Sim_02: EN 15251 prescribed ACH rates for each attendance status .....	63
Table 23- Sim_02 EN 15251 Category based on ACH values.....	66
Table 24- Sim_02: IDA Category based on CO <sub>2</sub> levels and prescribed airflows verification.....	69
Table 25- ASHRAE 62.1 Recommended airflow rates.....	69
Table 26- Sim_02: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status.....	71
Table 27- Sim_02: Percentage of time respecting CIBSE Guide A prescribed ventilation rates.....	72
Table 28- Sim_1: Average ACH values by season .....	74
Table 29- Sim_1: EN 15251 prescribed ACH rates .....	74
Table 30- Sim_1: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates.....	75
Table 31- Sim_2: ACH average values for each season and church attendance status throughout the year.....	77
Table 32- Sim_2: EN 15251 Category based on ACH values .....	79
Table 33- Sim_2: IDA Category based on CO <sub>2</sub> levels and prescribed airflows compliance .....	82

Table 34- Sim_2: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status.....	83
Table 35- Sim_3.1: ACH values for each season and church attendance status throughout the year .....	88
Table 36- Sim_3.1: EN 15251 Category based on ACH values .....	90
Table 37- Sim_3.1: IDA Category based on CO2 levels and prescribed airflows verification.....	92
Table 38- Sim_3.1: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status.....	94
Table 39- Sim_3.2: ACH values for each season and church attendance status throughout the year .....	98
Table 40- Sim_3.2: EN 15251 Category based on ACH values .....	100
Table 41- Sim_3.2: IDA Category based on CO2 levels and prescribed airflows verification.....	102
Table 42- Sim_3.2: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status.....	104
Table 43- Sim_4: ACH values for each season and church attendance status throughout the year .....	106
Table 44- Sim_4: EN 15251 Category based on ACH values .....	108
Table 45 Sim_4: IDA Category based on CO2 levels and prescribed airflows verification .....	111
Table 46- ASHRAE 62.1 Prescribed airflow rates.....	111
Table 47- Sim_4: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status.....	113
Table 48- Ventilation rate comparison to the current ventilation performance, by month .....	117
Table 49- Monthly average $\Delta\text{CO}_2$ concentration, by month in ppm .....	119
Table 50- Monthly average $\Delta\text{CO}_2$ concentration comparison to the current ventilation performance, by month.....	123
Table 51- Average ACH value by church status, for each simulation .....	129
Table 52- Results from project:test_Buoyancy .....	141
Table 53- Location and dimensions of spans and air paths implemented in the Contam simulations.....	149
Table 54- Description of the types of spans and air paths encountered in São Cristóvão's Church .....	149

# 1. Introduction

## 1.1 Context

Cultural heritage is a fundamental pillar in societies across the world due to, but not only, its cultural and religious characteristics but also its economical and touristic aspects. Therefore, it is of vital importance, the implementation of a sustainable balance between the preservation of artwork and monuments, and the nefarious cultural tourism consequences.

According to a European Report made in 2015 [1], 40% of tourism is, at its core, cultural and based on a statistical report presented by Turismo de Portugal, from 2014 up to the present time (2020) Lisbon Metropolitan Area has received over 6 million tourists per year [2]. The increasing number of visitors can be viewed as a way to achieve financial sustainability, but to maintain this trend is necessary to adopt certain parameters to ensure the preservation of buildings and collections displayed, and also to maintain the comfort and health levels of users, visitors and staff [3]. Visitors that are a source of heat, moisture, carbon dioxide (CO<sub>2</sub>), and odors, are also a vehicle to outside pollutants that can affect the indoor climate of buildings.

Many historical buildings, namely churches, have a double function. On one hand, they serve as worshipping grounds, gathering people on a weekly basis to pray and celebrate special occasions and festive periods. On the other hand, due to their cultural history, these buildings are used as exhibition rooms displaying both religious art in the form of frescos, woodwork, and relics, but also modern art. This dual-purpose leads to a variable influx of visitors that could harm the art displayed and create an uncomfortable environment for visitors that can be responsible for symptoms like eye irritations and in long-term exposure may cause serious health problems like cancer [4].

In some cases, the use of mechanical climate control systems has been applied to limit the nefarious effect of excessive occupancy creating a stable indoor microclimate. However, the seamless integration of these powerful systems in historical buildings is, in most cases, impossible to implement due to design and architectural characteristics. The invasive introduction of modern climate control devices is highly criticized by several authors underlining the dichotomy between the maintenance of the building's characteristics and the conservation of the artwork they roost [5].

Even more, the energy used to power such systems is currently debated in the scope of sustainable building and energy efficiency giving natural ventilation an important role.

A balanced and sustainable relationship between ventilation and occupancy is of the most importance for cultural heritage as it plays a fundamental role in indoor climate steadiness, energy consumption and maximization of visitors. Although some standards and documents present assumptions, values and criteria, useful for indoor air quality (IAQ) analysis [6–10], no consensus is achieved as the content and methodology vary. Recent studies have reflected the spread of results and showed the impossibility to find the same ventilation rates in the different analyzed researches [11–19].

## **1.2. Motivation and research objective**

In an attempt to study the microclimatic behaviour of São Cristóvão Church in Lisbon, Portuguese researchers (Guilherme Coelho, Hugo Entradas Silva, and Fernando Henriques of the Faculdade e Ciências Tecnologia da Universidade Nova de Lisboa) among others focused their attention on this historical building; however, one aspect not yet analyzed is the ventilation performance of the church.

Because tourism has a relevant impact on buildings that roost artwork, the linkage between the number of visitors, the IAQ, and the safeguard of art pieces that are displayed without protective equipment is an important factor in the general study of the interior climate that presents itself on ancient historical buildings without mechanical ventilation or the possibility of the implementation of one.

This dissertation aims to define the ventilation rates throughout the different periods of the day, when it is open to visitors, during mass service and when it is closed, in order to establish presumable concentration rates of pollutants and deduce the level of satisfaction of occupants in terms of air quality. Even more, five additional ventilation strategies are studied with the objective of having different types of air renewal strategies to compare the current one.

The implication of ventilation rates on indoor temperature, RH, certain pollutants, outside air quality, and deposition rates on different types of artwork are not approached in this study as they fall outside its scope.

## **1.3 Dissertation structure**

This document is divided into 5 chapters.

In chapter 1 the context of this dissertation, its objectives, and structure are presented.

In the following sub-chapters, sub-chapter 2.1 through sub-chapter 2.4, a summary is made regarding the history and evolution of IAQ and its definitions based on different parameters, followed by a compilation of ventilation principles that were, in some way, utilize in the development of this dissertation.

Sub-Chapter 2.6 revises some of the most used standards and guidelines that are relevant to the theme of IAQ and ventilation, with a special focus on the regulation of church-like building's prescribed ventilation rates.

Sub-Chapter 2.7 presents a compilation of studies that are directly relevant for the IAQ and ventilation rates in churches throughout Europe. Emphasis is made on the studies that depict the São Cristóvão Church in Lisbon.

The geometrical and historic detailing of the case study, the selection and implementation of the weather data used in the simulations and the assumptions and inputs made in the CONTAM *software* are all presented in chapter 3.

Chapter 4 is separated into three parts. Sub-chapter 4.1 is where the base model of the ventilation simulations is described and what reasons lead to the alteration of some tabulated values. In sub-chapter 4.2, six ventilation strategies are detailed and analyzed in terms of ventilation rates and CO<sub>2</sub> concentrations through different times of the

simulated year. Even more, some of the standards and international guidelines mentioned in sub-chapter 2.6 are directly applied to all ventilation strategies.

In sub-chapter 4.3 a comparison and a discussion of all simulation results for the different standards is pursued.

Chapter 5 summarizes the findings and concludes the dissertation.



## 2. Indoor air quality and natural ventilation

### 2.1. Brief history of ventilation and IAQ

The need for ventilation in buildings dates to the days when men brought fire inside for cooking and comfort purposes. It was rapidly discovered the necessity of controlled ventilation for the exhaust the combustion produces and the maintenance of the burning source which was accomplished by an opening in the roof. This marks the first time ventilation needs were attended.

In the ancient Egyptian Era, ventilation was linked to health issues when respiratory distress was noticed with a higher incidence in stone carvers working indoor. Visible dust particles needed to be removed from the workshops and natural ventilation accomplished the goal [20].

Throughout the Greek and Roman periods, a ratio of windows per floor area was adopted concerning solar exposure, and to mitigate the excessive air intake, wooden windows served as a control device. Furthermore, with the development of radiant heating, the need for fireplaces, in palaces and villas, was negated. Hot air from stoves and fire pits in the kitchen area was conducted by hollow tiles on the floor to a smokestack, heating the indoor spaces [20, 21]. These societies were aware of the effects of air pollution in big metropolis and mines regarding health issues (Hippocrates, 460– 377 BC)

The dangers to health by living in buildings with damp manifestations, as mentioned in the Bible, was considered a “*plague of leprosy*” and the remedy was the removal of all “*infected parts*” (Leviticus 14, 34–57).

King Charles I of England, in 1631, took measures in order to improve the indoor air quality, decreeing that the ceilings of any house built in the kingdom must be 3 meters or higher and the windows should be higher than their width to allow better natural ventilation in response to an increase in numbers of respiratory diseases registered at the time. This was one of the earliest legislation regarding the ventilation of buildings that was implemented but only enforced after the great fire of London of 1666 destroyed an approximate number of 13.000 houses and 90 churches [22].

The works of Boyle (1627–1691), Hooke (1635–1703) and Lavoisier (1781) are seen as crucial to the understanding of the human body regarding the respiratory system and its metabolism and shed some light on the relation of oxygen consumption and carbon dioxide release. It was adopted from the 1800 forward the level of CO<sub>2</sub> as an indicator of whether the air was fresh or stale [21].

The linkage between ventilation rate and air quality perception was introduced by Yaglou in 1936, after a series of trials in ventilated cameras where people were subjected to different kinds of odors and different fresh air ventilation rates were asked to rate the quality of the air in diverse types of scales of intensity [23]. Although the concept of adaptability to exposure was neglected, this study was the base for many of the standards and guidelines for many years [21, 23, 24].

The notion of air quality is present throughout the times but only after the industrial revolution and the London fog killed thousands of people, modern research on this topic

developed, and therefore, the history of IAQ is highly intertwined with outdoor air quality (OAQ) [23].

Studies conducted in the second half of the 20<sup>th</sup> century showed the correlation between ventilation rates and perceived IAQ [25–28], corroborating the methodology used by Yaglou.

## 2.2. IAQ based on comfort perception

IAQ is assessed by humans according to the combination of smell and perception of irritation obtained through the nasal mucosae and the eyes [29, 30]. The perception of clean air, as mentioned before, is detrimental to human comfort as it is, historically, the first resource for IAQ assessment. Human comfort can be conditioned by CO<sub>2</sub> emissions amongst other gases and odors emitted by the occupants of a space, the building itself, its components, and air-conditioning systems [6]. However, human sensitivity to different pollutants varies greatly according to several factors ranging from time adaptation to individual sensitivity and one way to achieve consensus regarding environmental comfort is by a simple analysis of the percentage of satisfied people in relation to the mean vote of the IAQ perception [7].

The link between IAQ/comfort and ventilation was firstly studied by Yaglou in 1936; to evaluate and predict comfort sensation several tests were made where occupants of a ventilated chamber submitted to different gases, concentrations, and fresh air ventilation rates evaluated using different scales the IAQ. Although some factors were discarded, such as adaptability to the environment, the results from Yaglou's research were the basis for international standards and guidelines [20, 31].

The concept of adapted and non-adapted occupants was later included in the '80s and '90s by several studies [25, 27, 28] taken across the world that showed a strong correlation validating the methods and results proposed. The ventilation rate per person, for an adapted occupant can be estimated as one-third of the value for a non-adapted, to achieve the same level of acceptance [32].

Both EN 15251 [6] and ASHRAE 62.1 [9] based their methodology and principles proposed by the studies previously mentioned as well as the concepts introduced by Fanger in 1988 [33] regarding the olf unit and the decipol units. IAQ can be evaluated as a percentage of dissatisfied occupants in function of their mean vote and approximated with a high level of confidence by equations (1) and (2) [33]:

$$PD = 395 \cdot e^{(-1.83 \cdot (\frac{q}{3.6})^{0.25})} \quad \text{for } q \geq 1.15 \text{ m}^3/\text{h.olf} \quad (1)$$

$$PD = 100 \quad \text{for } q \leq 1.15 \text{ m}^3/\text{h.olf} \quad (2)$$

Where  $PD$  is the percentage of dissatisfied people (%),  $q$  is the airflow (m<sup>3</sup>/h.olf) and one olf corresponds to the bio effluents emitted by a standard person.

Since while people releasing CO<sub>2</sub> are also releasing odors, a relationship between the percentage of dissatisfied people and the concentration of indoor CO<sub>2</sub> can be established and has proven to be a good indicator of IAQ as commonly used across standards. These

results allowed the conclusion that an airflow of 27 m<sup>3</sup>/h per person corresponds to 80% of satisfied people, which corresponds to a CO<sub>2</sub> concentration of about 650 ppm above the external value [25]. Applying this methodology, an expeditious way to determine IAQ can be achieved since CO<sub>2</sub> concentrations are easier to obtain in opposition to ventilation rates, which can be calculated using a mass balance equation according to CO<sub>2</sub> emissions per person [32].

Fanger also addresses the fact that pollution load caused by occupants is not the lone contributor to poor IAQ since the building itself, furniture, carpets, and even ventilation systems should be taken in to account [33] as they release a wide range of volatile organic compound (VOC's). Even more, the combination of VOCs, temperature and humidity can highly influence the perception of IAQ compromising the results of any survey taken without these factors accounted for. In the *CEN/CR-Report 1752-1998* [7] a fairly extensive approach is taken to make sure such variables are included in the design criteria for the indoor environment.

### 2.3. IAQ based on human health

Due to the fact that humans spent 87% of their time indoors [34] the importance of IAQ monitoring and maintenance is vital to their wellbeing. Even more, the new Coronavirus reinforced the notion of well-ventilated buildings and the impacts on human health.

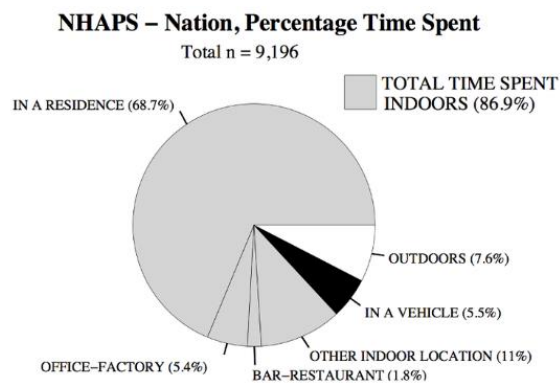


Figure 1- NHAPS usage of time [34]

IAQ, summing to comfort levels, should guarantee a safe environment regarding the health of the space's occupants. The consequences of poor IAQ on humans may vary from acute discomfort, in the form of rashes and irritations, to long exposure effects such as cancer [21, 29, 35-39].

To mitigate the nefarious effects on human health, maximum concentrations and exposure times were defined according to the specificities of different pollutants. One of the main promoters of air quality was the *World Health Organization (WHO)* and the *Air Quality Guidelines (AQG's)* published in 1948. Progress towards standardization start is usually linked to the *WHO Technical Report 157* which, although 26 pages long, presented a strong introduction to air pollution, pollutants, methods of measurement and emphasized particular effects on human health by gases such as smoke and sulfur dioxide (SO<sub>2</sub>) [40].

A series of technical reports based on the research by Barker, Lawther, Martin & Wilkins, among others [26, 41, 42], boosted the need for both indoor and ambient air quality

control, and establishing maximum pollution levels, that in some cases differ from one and other without any explanation offered by the authors [40].

Since 2015, the WHO is moving towards the creation of separate indoor AQG's "*providing health-based recommendations on specific pollutants, biological agents, such as mold and dampness, and household fuel combustion*" [40].

Several standards utilize CO<sub>2</sub> concentrations as indicators of comfort, relating it to apparent IAQ [6, 9, 43–46]. Symptoms manifestation from excessive exposure to CO<sub>2</sub> can present themselves in a variety of ways such as fatigue, headaches, reduced cognitive performance and increased perception of heat but can also affect blood acidity, the kidneys, bones and the respiratory, cardiovascular and nervous systems [32, 39, 47–50]. Although the consensus is achieved regarding the 10000 ppm lower concentration limit [47] to safeguard the inexistence of severe effects on human health, the *ASHRAE Standard 62.1* from 2013 [9] recommends the application of the necessary ventilation to ensure indoor CO<sub>2</sub> concentrations below 700 ppm above outdoor concentrations.

Besides the fact that some authors found greater health risks at concentrations values above 30000 or 50000 ppm, a recent study conducted by Jacobson *et al*, in which the authors gather information from over 80 related papers, articles, and standards, found that "*Emerging evidence supports the possibility that CO<sub>2</sub> (at concentrations <5,000 ppm) poses direct risks to human health. These risks include inflammation, reduced higher-level cognitive abilities, bone demineralization, kidney calcification, oxidative stress and endothelial dysfunction*" [46].

Summing to the variety of CO<sub>2</sub> threshold values existing in the literature, the exposure time to the contaminant is also a factor not to be dismissed.

## **2.4. IAQ based on Conservation**

Different materials behave differently to variations in their environment. Three types of risks should be taken into account since they can affect permanently some materials. The risks are biological, mechanical, and chemical.

These degradation mechanisms, mainly caused by severe variations or incorrect settings of temperature and RH, although not being within the scope of this document, are important factors for the conservation of the artwork, particularly in environments and buildings not capable of adapting their microclimate in response to extreme conditions. Even more, appropriate ventilation can play a significant role in the preservation of certain objects if a correct measurement of temperature and relative humidity is conducted.

Developed by Martens [51], the concept of response time is the amount of time that a material takes to get to 95 % of the end value in case of a relative humidity change. Such RH fluctuations can impose deformations in objects and if the strain caused is superior to the yield point, deformation and/or cracking can be observed, depending on the object or combination of objects. This tool is highly useful since the effects of microclimate changes may not be visible immediately.

- Biological risk

Some artwork housed in museums and churches is susceptible to fungal proliferation. Fungi needs the right temperature, RH, a nutritious substrate and a set of continuous microclimatic conditions in order to grow, as exemplified in Figure 2. Even more, some species of molds are capable of withstanding unfavorable conditions during the germination process and restart when conditions are met. The correct approach is to, firstly, understand the ideal conditions in which mycelium growth is achieved and then take the necessary precautions. A highly visited church that functions as a museum may not be able to extract the moisture released by its occupants and an uncontrolled rise in RH can cause the ideal indoor climate to fungal growth.

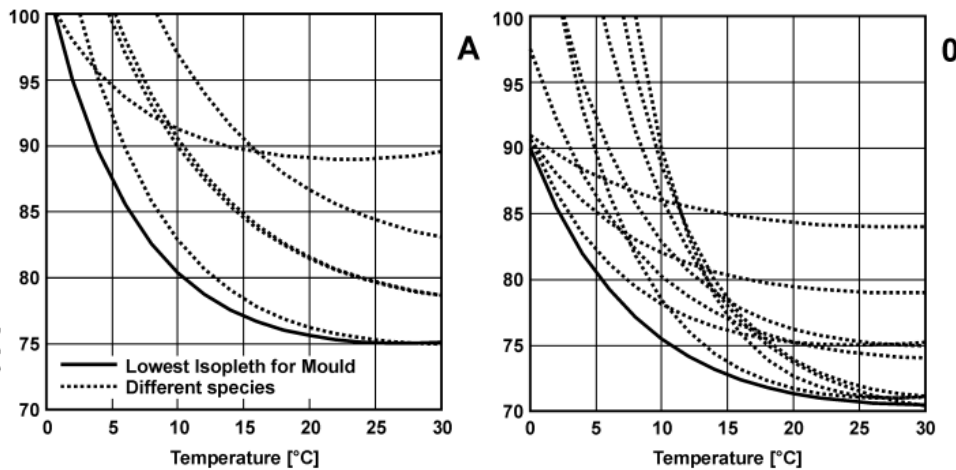


Figure 2- Isopleths for mycelium growth of various fungus species considered in the model and the Lowest Isopleth for Mould (LIM) resulting from that. The left illustration applies to fungi of hazardous class A, the right illustration to class B/C. (adapted from [52])

- Mechanical risk

When it comes to mechanical risk assessment of a certain hygroscopic object the main factor in play is the moisture content of an object and the variations on RH. As an object with moisture is submitted to an increase in RH it swells, and if a reduction in RH happens, it shrinks. Damage can occur when two or more materials are combined in the same piece. In this case, due to different moisture expansion coefficients, tensions can be created if one or more materials have their expansion/retraction restrained [53]. The relation between temperature and RH, and their impact on cottonwood when restrained can be seen in Figure 3, as an example.

The most accurate measurement is the moisture content of the piece and not the air fluctuation of its environment since variation in moist may not occur instantly [54]. Martens [51] also develop an analysis in function of the response of the materials instead of the air RH fluctuation.

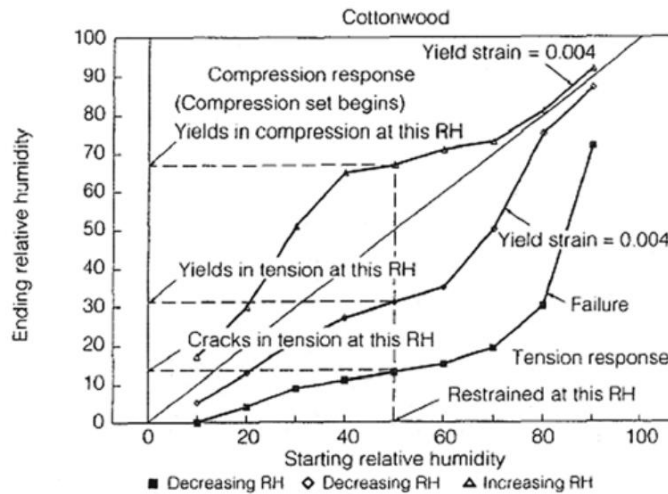


Figure 3- The response of cottonwood to changes in RH – fully restrained in tangential direction [53]

- Chemical risk

In order to assess the chemical degradation of objects, Michalski [55] developed the concept of *lifetime multiplier* based on the Arrhenius equation. Given the complexity of all possible chemical reactions, Michalski referenced a rule of thumb that can be applied to the generality of objects in the museum environment. Things in museums that suffer from inherent chemical decay can be assumed to last approximately twice as long for each 5°C drop in storage temperature. “... things age twice as fast for each 5°C rise, so in a sub-tropical gallery at 30°C, as compared to 20°C...”. Thus, the chemical decay of a material is proportional to the temperature and RH of its environment.

## 2.5. Ventilation principles

In this sub-chapter, to better understand the mechanism behind the renewal of used or polluted air inside buildings, a description of ventilation principles is presented.

Ventilation in buildings, which purpose is to exhaust and replace polluted air, is associated with the generated airflow by wind-induced pressure and/or temperature differential through buildings components such as doors, windows, ducts and others. The different pressure values between two rooms, or inside-outside conditions, are responsible for the movement of air and, as understandable, wind and temperature play a major role in this air mass travel [56–58].

Natural ventilation based on the pressure difference between two spaces causes the air mass movement from higher pressure zone to the lower pressure zone.

Natural ventilation caused by temperature difference, also known as thermal buoyancy or stack effect, occurs when air at different temperatures comes in contact. The differential in temperature, and therefore RH and pressure, forces the hot air mass to rise due to its lighter weight, compared to the cooler air. The correlation between temperature, water vapor concentration, RH, and pressure can be observed in the psychrometric diagram in Figure 4.

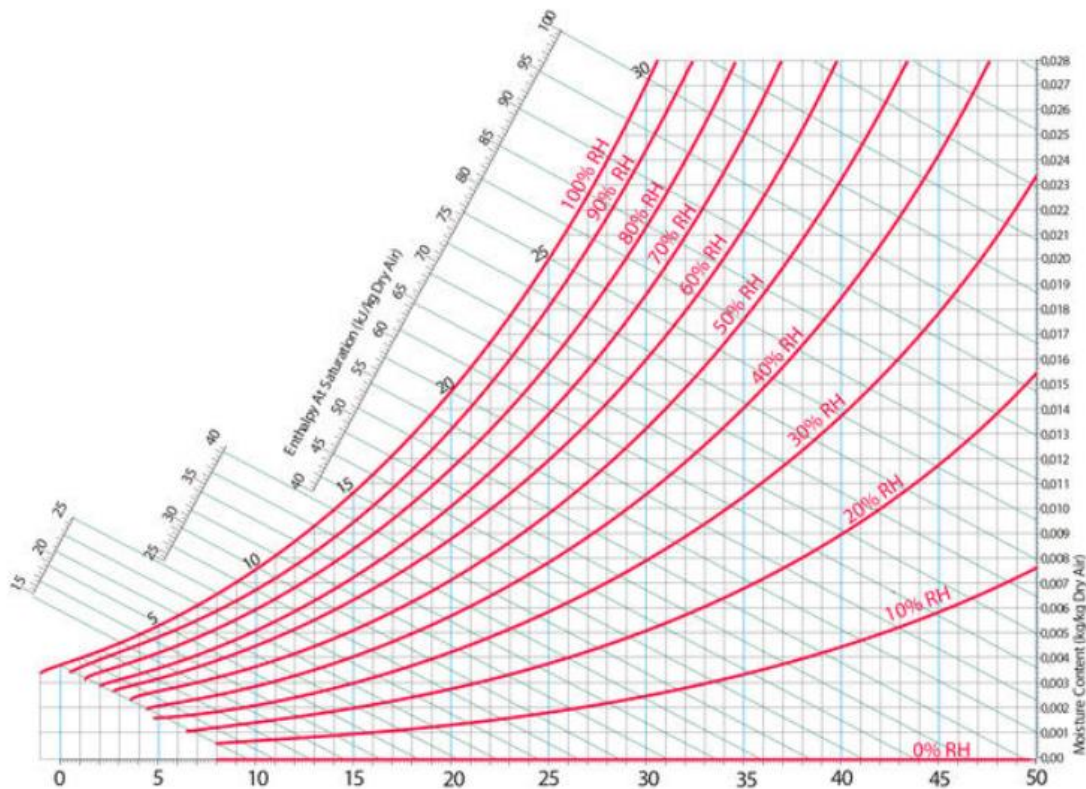


Figure 4- Psychrometrics diagram [59]

The effectiveness in the renewal of indoor air highly depends on wind direction, characteristics of the building envelope and the position of windows, doors and other openings responsible for the communication between the inside and the outside environments. Even more, location, topography and building shape are also factors in the determination of ventilation rates.

### 2.5.1. Natural ventilation mechanisms

For a typical residential dwelling, and given relative flexibility in indoor temperatures, it is possible to design a building using exclusively natural ventilation and obtain acceptable air renewal rates. To do so, a careful configuration of opening sizes, locations and permeability must be analyzed to maximize the driven forces of wind and indoor-outdoor temperature differential. The same could be true regarding other types of buildings.

#### 2.5.1.1. Driving Forces

As mentioned previously, natural ventilation has two distinct forces that are responsible for the air travel in and out of buildings, being them:

- Wind pressure:

When wind strikes perpendicularly a facade of a rectangular-shaped building it creates a positive pressure on that face and negative pressure on all other facades. This creates a differential in pressure on opposite sides of the building, creating the right conditions for outdoor air to enter the building from the high-pressure opening, passing through the air paths available in the dwelling, and exiting from the low-pressure opening on the downwind facades, as exemplified in Figure 5.

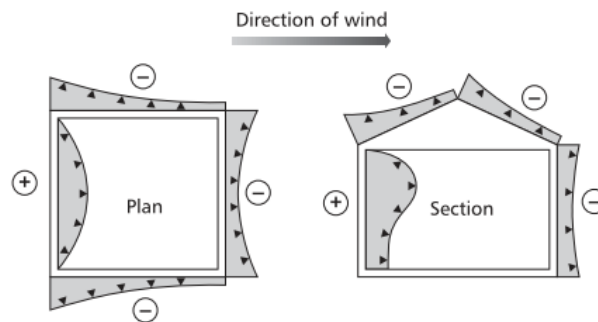


Figure 5- Wind-induced pressure on building envelope [10]

For a regular building, a simplistic view is adopted, using standardized coefficients for each area of the building's envelope and as for high-rises and complex structures, it may be necessary to utilize the wind tunnel method or computer simulations in order to determine the most approximate data to real pressure distribution [35].

- Stack pressure:

The harness of the stack effect has been utilized throughout the times and across the world despite the scientific know-how and complete comprehension of the natural phenomenon [21]. This effect is originated as a result of differences in air temperature, and consequently air density, between the interior and exterior ambient. This fact produces a vertical pressure difference as the warmer air moves upwards as represented in Figure 6.

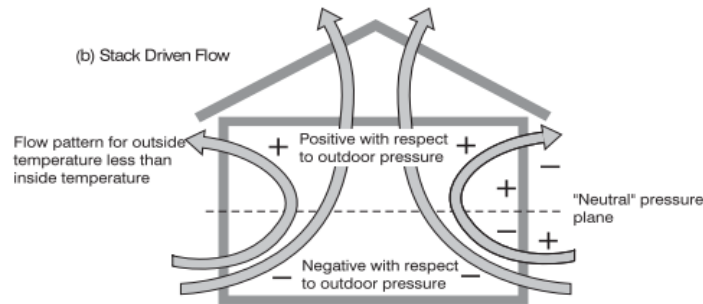


Figure 6- Natural driving mechanism, stack driven flow [10]

- Combined use of wind and stack pressures:

In order to maximize the effect of both driven forces and negate an adverse effect of these, a careful design approach should be implemented as wind-driven forces can oppose the ventilation driven by stack effect as demonstrated in Figure 7.

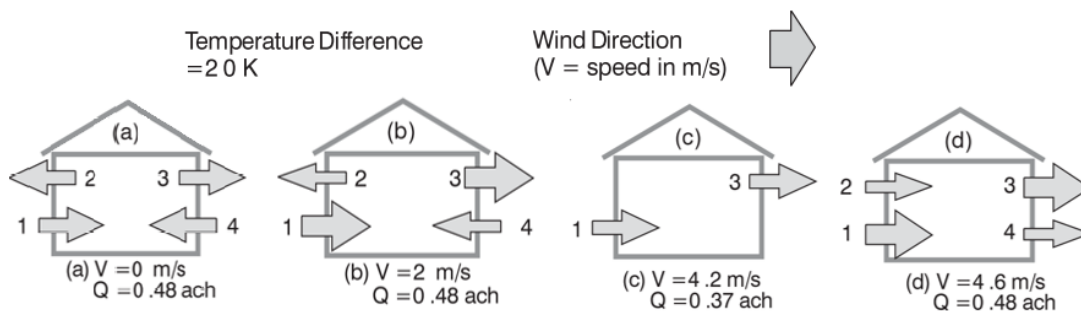


Figure 7- Combined effect of wind and temperature difference on ventilation rate and air flow pattern [35]

In Figure 7 a) there is only ventilation driven by stack effect (temperature dominant regime) and as such, air enters the building through the lower openings on opposite facades and exits through the upper openings.

Comparing case b) with temperature dominant regime, wind effect on the envelope pressures augments the intake on opening 1 and the outtake on opening 3. It is also responsible for the diminishing of the outtake on opening 2 and the intake on opening 4. Although the air flow's rate changes for each opening, the overall ach remains unaltered.

In case c), the magnitude of wind is such that the pressure exerted on openings 2 e 4 equals the positive pressure created by the stack effect. In this case, only openings 1 e 3 are responsible for the entire ventilation of the building resulting in a reduction of the number of openings and the decrease of the air change per hour (ach). Although this situation is possible in theory, given the multiple openings existing in common buildings, the chance of this situation occur is highly unlikely.

At high wind speeds (case d)), the intake openings are the ones in the windward face and the outtake openings are in the downwind face. From the moment this case is deployed a wind dominant regime is implemented.

## 2.5.2. Types of ventilation

Two main techniques can be applied and combined to provide natural ventilation. These are cross-flow ventilation and single-side ventilation.

- **Cross ventilation**

Depend on clear and unobstructed air flow path from the intake to the out-take point, crossing the space in which air is to be renewed. In order to ensure the effectiveness of cross-ventilation, a limit in the distance between opposite orifices exist as 2 to 2.5 times the ceiling height [35] but some studies increase this value to 10 m in some cases [60]. Due to the existence of multiple compartments in a regular dwelling, the intake should be limited to guarantee the thermal comfort levels required but also create air paths in doors (gaps and in-door pathways) to ensure the cross-ventilation effect.

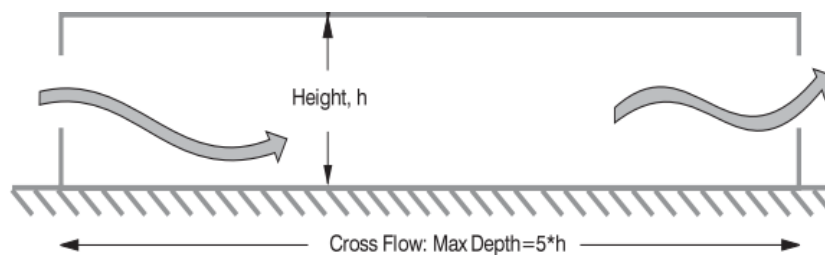


Figure 8- Cross flow Ventilation [35]

- **Single-side ventilation**

Ventilation through a small opening is driven by turbulent fluctuations, and as such, is not recommended as the sole ventilation mechanism implemented in a building (Figure 9 a)). Usually, single-sided ventilation is adopted using multiple openings or an orifice big enough for air to circulate in both directions (Figure 9 b)) and to maximize the effectiveness of this opening, a horizontal division should be implemented to separate de in/out air flows. From this point on ventilation is driven by wind and stack forces.

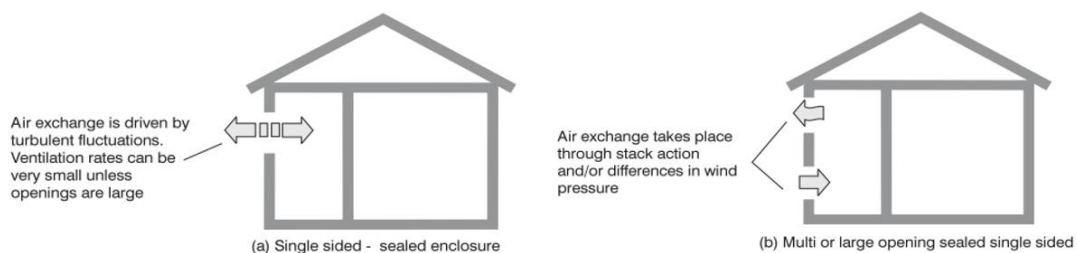


Figure 9- Single-sided Ventilation [35]

### 2.5.3. Natural ventilation by temperature difference

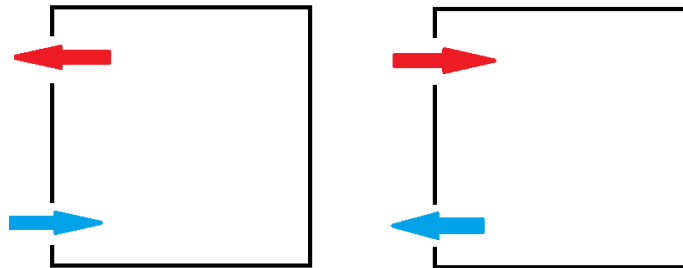
The temperature difference is an important factor that affects natural ventilation, and as such, the presence of openings with different sizes at different heights located between the exterior and interior of a building translates to a temperature differential and consequently pressure difference. The equation that correlates interior and exterior pressure and temperature differences are presented below (eq.3):

$$\Delta_{ph} = T_0 \cdot g \cdot h \cdot \rho_0 \cdot \left( \frac{1}{T_{ext}} - \frac{1}{T_{int}} \right) \quad (3)$$

Where:

- $T_0$  is the reference temperature (C°);
- $g$  is the gravity (m/s);
- $h$  difference in the elevation between the center lines of the openings (m);
- $\rho_0$  is the air density at  $T_0$  (kg/m<sup>3</sup>);
- $T_{ext}$  is the exterior temperature (C°);
- $T_{int}$  is the interior temperature (C°);

Excluding the effect of wind, if the interior temperature is superior to the exterior one, the outside air enters the building from the lower orifice and exits through the upper one. If the interior temperature is lower than the exterior the reverse occurs [35]. An example of these phenomena is presented in Figure 10.



a) the air flow direction when  $T_{int} \geq T_{ext}$  b) the air flow direction when  $T_{ext} \geq T_{int}$

Figure 10- The direction of airflow based on the air temperature adapted [61]

Naturally, the time of the year, and the climate a building is inserted on, are detrimental to the effectiveness of this phenomenon. In mild climates, the differential between exterior and interior temperature can be null and this effect lost.

### 2.5.4. Natural ventilation by wind pressure

The effect of wind in natural ventilation is represented by forces or pressure, applied on the facades of the building. The values of this representation vary with wind intensity and direction, the shape and size of the building, the characteristics of the building's envelope, and the characteristics of the terrain.

The European standards advise the use of *Bernoulli's* equation for the determination of the pressure coefficient (eq.4):

$$\frac{v^2}{2} + h + \frac{P}{\rho} = C \quad (4)$$

Where:

- $v$  is the wind speed (m/s);
- $h$  is the height from a referential (m);
- $P$  is the pressure;
- $\rho$  is the air specific mass (kg/m<sup>3</sup>);
- $C$  is the pressure coefficient.

Assuming no height change in the airflow, the previous equation, considering two different points, can be written (eq.5):

$$P = \rho \frac{v^2}{2} \quad (5)$$

Also, to determine the pressure in a particular facade of the building's envelope, an external pressure coefficient ( $C_{pe}$  in EC.1,1-4 and  $C_p$  in ASHRAE *handbook* and BS:5925) must be applied. Although the values of this coefficient vary across the standards, the concept is the same, the facade directly exposed to the wind direction presents positive pressure, and the remaining facades are subjected to negative pressure.

#### 2.4.4.1 Wind speed

The wind is a highly unpredictable phenomenon as it constantly changes in direction and velocity. Hence the importance of a reliable set of data to perform a reasonable prediction of its impact on ventilation design.

Because most weather data are collected at an atypical location for the implementation of buildings, such as airports and airfields, corrections to the values obtained must be applied for the ventilation design conducted, reflect, with a high degree of confidence, the real situation.

In the British standard 5925:1991 [62], for different types of terrain, the following formula may be used to estimate wind speed at a particular site (eq. 6):

$$\frac{u}{u_m} = Kz^a \quad (6)$$

Where:

- $u$  is the wind speed at height  $z$ ;
- $u_m$  is the wind speed measured at a large number of sites in the UK by the Meteorological Office, and is quoted for the equivalent height of 10m in open countryside;
- $z$  is the height of the building;
- $K$  and  $a$  are constants to reflect the terrain characteristics the building is inserted on.

ASHRAE *Handbook* [63] presents a different type of approach where the information of both the data collection and the building location is directly implemented in the determination of the design wind speed, as pointed in the following equation (eq.7):

$$U_H = U_{met} \cdot \left(\frac{\delta_{met}}{H_{met}}\right)^{\alpha_{met}} \cdot \left(\frac{H}{\delta}\right)^{\alpha} \quad (7)$$

Where:

- $U_H$  is approaching wind speed at upwind wall height H (m/s);
- $U_{met}$  is the wind speed measured at the meteorological station (m/s);
- $\delta_{met}$  is wind boundary layer thickness for the meteorological station;
- $H_{met}$  is the elevation at the meteorological station (m);
- $\alpha_{met}$  is wind boundary layer exponent for the meteorological station
- $H$  wall height (m);
- $\delta$  is wind boundary layer thickness for the local building terrain (m);
- $\alpha$  is wind boundary layer exponent for the local building terrain

According to Eurocode 1- part 1:4 [64], average wing speed can be obtained by affecting a reference value with coefficients that reflect the roughness and orography of the location. The reference values are attributed according to terrain characteristics. The wind speed equation is presented below (eq. 8):

$$v_m(z) = c_r(z) \cdot c_0(z) \cdot v_b \quad (8)$$

Where:

- $v_m(z)$  is the average wind speed;
- $c_r(z)$  is the roughness coefficient;
- $c_0(z)$  is the orography coefficient;
- $v_b$  is the reference wind speed (equivalent to  $u_m$  in the BS:5925);

#### 2.5.4.2 Pressure Coefficient

Due to the turbulent nature of approaching wind, surface pressure highly fluctuates on the surfaces it encounters, hence the use of the pressure coefficient. Figure 11 shows the multiple results of pressure values according to the location measured.,

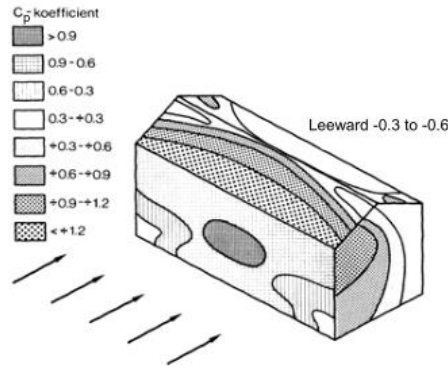


Figure 11- Example of pressure coefficient on a building [58]

This nondimensional value reflects, not only the wind angle of attack but also the shape of the building. The complex nature of determining the exact pressure coefficient of a particular building or structure leads to the use of wind tunnels and CFD (Computational Fluid Dynamics) simulation, which is only justified for certain cases. In a series of wind tunnel studies, Swami and Chandra [65] established the relationship between the pressure coefficient, wind speed, and the geometry of the block tested. This research presented equation 9:

$$C_p = 0,6 * \ln \left[ 1,248 - 0,703 \sin \left( \frac{\alpha}{2} \right) - 1,175 \sin^2(\alpha) + 0,131 \sin^3(2\alpha G) + 0,131 - 0,769 \cos \left( \frac{\alpha}{2} \right) + 0,07G^2 \sin^2 \left( \frac{\alpha}{2} \right) + 0,707 \cos^2 \left( \frac{\alpha}{2} \right) \right] \quad (9)$$

To simplify the analysis, it is considered the same pressure coefficient ( $C_p$ ) throughout the entirety of each wall. This generalization was shown to be acceptable for 80% of the entry points in the Swami and Chandra study.

Figure 12 shows the surface pressure coefficient averaged of a low-rise building's wall.

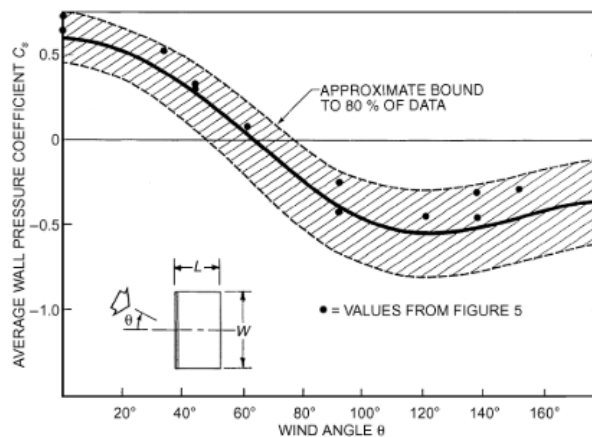


Figure 12- Variation of Surface-Averaged Wall Pressure Coefficients for Low-Rise Buildings [66]

## 2.6. Revision of international guidelines and standards for IAQ and ventilation

This sub-chapter's purpose is to provide the reader with an overview of the present standards and guidelines regarding ventilation parameters and IAQ analysis methods.

Although some standards do not directly relate to the case study, as they only apply to residential buildings, the values and assumptions on which they are based present an important marking for other types of buildings.

The standards reviewed are:

- EN 15251
- EN 13779
- ASHRAE 62.1 and 62.2
- CIBSE Guide A
- EN 15759-2

### 2.6.1. EN 15251 and EN 13779

The main focus of EN 15251 [6] was to present constrictions to previous documents, such as EN ISO 7730 and CR 1752 [7], and to facilitate the calculation of long-term energy consumption and indoor climate assessment. Based on the results and methodology presented by Fanger, Yaglou, and others [27, 33], IAQ was taken into account for non-adapted people.

EN 15251 defines four categories to be adopted considering the type of building, its use, and the level of IAQ expectation. In other standards, such as EN 13779 [8] and EN ISO 7730, these categories are also used with different nomenclature.

*Table 1- Description of the applicability of the categories used for buildings IAQ expectation [6]*

Category	Explanation
Category I	High level of expectation and is recommended for spaces occupied by very sensitive and fragile persons with special requirements like handicapped, sick, very young children and elderly persons.
Category II	Normal level of expectation and should be used for new buildings and renovations.
Category III	An acceptable, moderate level of expectation and may be used for an existing building.
Category IV	Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year.

Building components pollutant emissions are also taken into consideration with the definition of tree classes, ranging from Very-low polluting building, Low polluting

building, and Non-polluting building. The definition of such classes is synthesized in Table 2:

*Table 2- Classes of building pollutant and their requirements*

emission	Very low polluting	low polluting	Non-low polluting
(TVOC) (mg/m <sup>2</sup> h)	<0.1	<0.2	>0.2
formaldehyde (mg/m <sup>2</sup> h)	<0.02	<0.05	>0.05
ammonia (mg/m <sup>2</sup> h)	<0.01	<0.03	>0.03
carcinogenic compounds (IARC) (mg/m <sup>2</sup> h)	<0.002	<0.005	>0.005
inodorous (dissatisfaction percentage)	<10%	<15%	>15%

Due to the lack of consensus regarding a standard index for IAQ and taking into account the studies mentioned in sub-chapter 2.2, a fairly good way to measure air quality is based on CO<sub>2</sub> concentration levels. Being generally accepted as the main disturbers of IAQ, the emission from people and the activities they enroll in, and the emissions from the building components are the criteria to estimate ventilation rates for buildings. EN 15251 provides three methods to do so.

The first method (annex B1.2- Calculating required ventilation for people component (smoking, non-smoking) and add the required ventilation for the building component.) takes into account the emissions from humans, as bio effluents, and from building components such as furnishing and cleaning products.

Total ventilation requirement ( $q_{tot}$ ) is calculated by the following equation (eq.10):

$$q_{tot} = n \cdot q_p + A \cdot q_b \quad (10)$$

Where:

- $n$  Is the number of people in the analyzed compartment;
- $q_p$  Is the ventilation according to bio effluents;
- $A$  Is the area of the analyzed compartment;
- $q_b$  Is the ventilation according to pollution level expectancy per m<sup>2</sup>.

The second method (annex B.1.3 Method based on ventilation rate per person and per m<sup>2</sup> floor area) establishes ventilation rates per person or floor area. This dual approach assumes humans as the only source of emission for the first case (rates per person) and emissions from building components for the second case (rates per floor area). Although ventilation rates by emission source are analyzed separately, a combination of the two should be applied, but the standard does not define how to consider the combined effect as the following transcript shows.

“different methods are possible to use in this objective, sometimes addition of the values (see B.1.2), sometimes the highest value (maximum of the calculated value based on per person and the value based on per m<sup>2</sup> floor area from Table B.3) and sometimes a value between the highest value and the value based on addition (Table B.2). When national regulations don’t decide it, the designer shall make his own decision and report it.” [6].

The third and final method to determine ventilation rates is based on a mass balance and required criteria for the CO<sub>2</sub> level on a demand-controlled system. Despite the standard lack of values for this method, typical values for CO<sub>2</sub> and the respective ventilation rates are presented in EN 13779.

Although the airflow rates for the different methods may differ, the return level of IAQ is the same. To correlate the different airflow rates, a table (Table 3) was made comparing the prescribed values for the different methods.

Table 3- Prescribed ventilation rates by human bio effluents and building polluting level [6]

Category	Percentage of dissatisfied people [%]	q <sub>p</sub> - Airflow per person [m <sup>3</sup> / (h.person)]	q <sub>b</sub> - Airflow per floor area [m <sup>3</sup> / (h.m <sup>2</sup> )]		
			Very low polluting	low polluting	Non-low polluting
Category I	≤15	>36	>1.8	>3.6	>7.2
Category II	20	25.2	1.3	2.5	5.0
Category III	30	14.4	0.7	1.4	2.9
Category IV	>30	<14.4	<0.7	<1.4	<2.9

EN 13779 focus is to provide designers with relevant aspects and parameters to achieve a comfortable and healthy indoor environment in non-residential buildings. Although this standard’s field of application excludes natural ventilation systems, important criteria are mentioned, such as CO<sub>2</sub> levels and heat production of persons.

In order to evaluate IAQ, four categories were established (Table 4). The definition of categories depends on the nature of the pollutant sources that are to be considered.

Table 4- Basic classification of indoor air quality classes [8]

Category	Description
IDA 1	High indoor air quality
IDA 2	Medium indoor air quality
IDA 3	Moderate indoor air quality
IDA 4	Low indoor air quality

As for the methods to determine ventilation rates, there are three. The first is an indirect classification of fresh air rate per person. This is the most commonly used methodology for rooms that serve human activities. The second method is an indirect classification by air flow rate per floor area. This method may be used in the situation where spaces are not designed for human occupancy, such as storage rooms. Finally, the last method to assess ventilation rates is by classification of the pollutant level. Here, a distinction is made between a specific pollutant and CO<sub>2</sub>. Because CO<sub>2</sub> concentrations are a good indicator of human bio effluents, this method is particularly apt to situations where humans are the main or sole polluter. Table 5 presents the first two methods of prescribed ventilation rates.

Table 5- Minimum recommended rates of outdoor air intake per person and floor area for non-smoking areas of non-residential rooms [8]

Category	CO <sub>2</sub> -level above the level of outdoor air in ppm		Airflow per floor area [m <sup>3</sup> /(h.m <sup>2</sup> )]	Airflow per person [m <sup>3</sup> /(h.person)]
	Typical range	Default value		
IDA 1	≤ 400	350	a	>72
IDA 2	400 – 600	500	>2.52	45
IDA 3	600 – 1000	800	2.52 < to <1.26	29
IDA 4	> 1000	1200	<1.26	<18

a) For IDA 1 this method is not sufficient

## 2.6.2. ASHRAE 62.1

The purpose of ASHRAE 62.1 in its first publication was to set prescriptive minimum and recommended ventilation rates to assure adequate IAQ levels for human occupants, preventing undesirable health issues [9].

As the body of knowledge evolves so did the standard. In the present version, ASHRAE 62.1-2019 has three methods of ventilation design; *IAQ Procedure*, *Ventilation Rate Procedure* and *Natural Ventilation Procedure*.

*Ventilation Rate Procedure*: Prescribed ventilation rates are determined by space type/function, occupancy, and floor area. Similarly to EN 15251, the prescribed ventilation ( $V_{bz}$ ) is determined by the equation 11:

$$V_{bz} = R_p \cdot P_z + R_a \cdot A_z \quad (11)$$

Where:

- $R_p$  Is the prescribed ventilation per person;
- $P_z$  Is the number of people in the analyzed compartment;
- $R_a$  Is the prescribed ventilation per area;
- $A_z$  Is the area of the analyzed compartment;

Table 6 reports the minimum ventilation rates for churches and museums.

Table 6- Minimum ventilation rates in breathing zones (adapted from ASHRAE 62.1 [9])

Occupancy Category	Airflow per floor area	Airflow per person
	Ra [m <sup>3</sup> /(h.m <sup>2</sup> )]	Rp [m <sup>3</sup> /(h.person)]
Museums/galleries	1.08	13.7
Places of religious worship	1.08	9

*IAQ Procedure:* Ventilation rates and other system design parameters are determined based on contaminant sources and concentration limits, and level of perceived indoor air quality acceptability.

*Natural Ventilation Procedure:* This is based on geometrical constraints of the spaces and openings that allow indoor air quality to be guaranteed with the use of natural ventilation and allowing the incorporation of mechanical ventilation systems.

### 2.6.3. CIBSE Guide A

The CIBSE Guide A [10] is a widely used source for environmental designers due to its holistic approach regarding comfort, health, sustainability, and energy efficiency in building design. This document presents three methods to obtain ventilation rates.

The first method, self-described as prescriptive, provides airflow per person or air change rates to ensure sufficient comfort levels in situations where the main odorous pollutant source is humans. These recommended values are based primarily on chamber studies conducted by Yaglou, Fanger, Berg-Munch, Cain, Iwashita, and others [25–27, 67, 68], where pollutants other than human body odor and tobacco smoke were excluded. An extensive table (*table 1.5 Recommended comfort criteria for specific applications*) is presented in the document (Table 7) and adjustments to these values are available should the particular case demand so. For churches and museums, 10 L/s.person (36 m<sup>3</sup>/h.person) is the recommended value, equaling the category I of EN15251 for airflow per person.

Table 7- Recommended comfort criteria for specific applications [10]

Building/room type	Winter operative temp. range for stated activity and clothing levels			Summer operative temp. range (air-conditioned buildings) for stated activity and clothing levels (lux)			Suggested air supply rate (m <sup>3</sup> /h.person)
	T (° C)	Activity (met)	Clothing (clo)	T (° C)	Activity (met)	Clothing (clo)	
	Churches	19-21	1.3	1.15	22-24	1.3	
Museums and art galleries: display	19-21	1.4	1.0	21-23	1.4	0.65	36*

\* Assumes no smoking.

The second method should be used in situations when the pollutant, its source and location are known, and local extract ventilation is not feasible. In this situation, a ventilation strategy should be designed under the Control of Substances Hazardous to Health Regulations 1994 [69]. This standard provides two types of pollutant emission control, Steady-state conditions and Non-steady state conditions.

### 1. Steady-state conditions

When pollutants are emitted at a constant rate, the ventilation rate to ensure the equilibrium concentration does not rise above the prescribed limit can be estimated by the equation 12:

$$Q = \frac{P(10^6 - C_{pi})}{E_v(C_{pi} - C_{po})} \quad (12)$$

Where:

- $Q$  Is the outdoor air supply rate (L/s);
- $P$  Is the pollutant emission rate (L/s);
- $E_v$  Is the ventilation effectiveness;
- $C_{pi}$  Is the indoor concentration of pollutant (ppm);
- $C_{po}$  Is the outdoor concentration of pollutant (ppm).

### 2. Non-steady state conditions

The volume of the room analyzed has an important role in predicting the behaviour of pollutants concentration values and the time it takes to achieve equilibrium, particularly in cases where the sources of sed pollutants occur in a limited time frame. In such cases, the estimation of fresh air supply is greatly exceed using equation (9).

A reduction ratio for the steady-state ventilation rate can be obtained by the use of Figure 13 or equation 13:

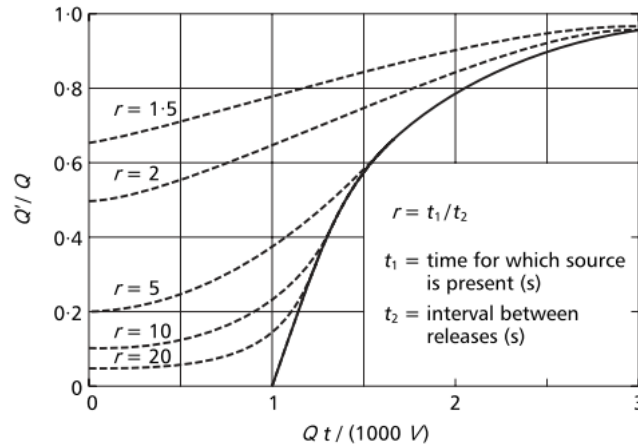


Figure 13- Reduction in fresh air rate for intermittent pollutant source [10]

$$\frac{Q'}{Q} = f\left(\frac{Q \cdot t_p}{1000 \cdot V}\right) \quad (13)$$

Where:

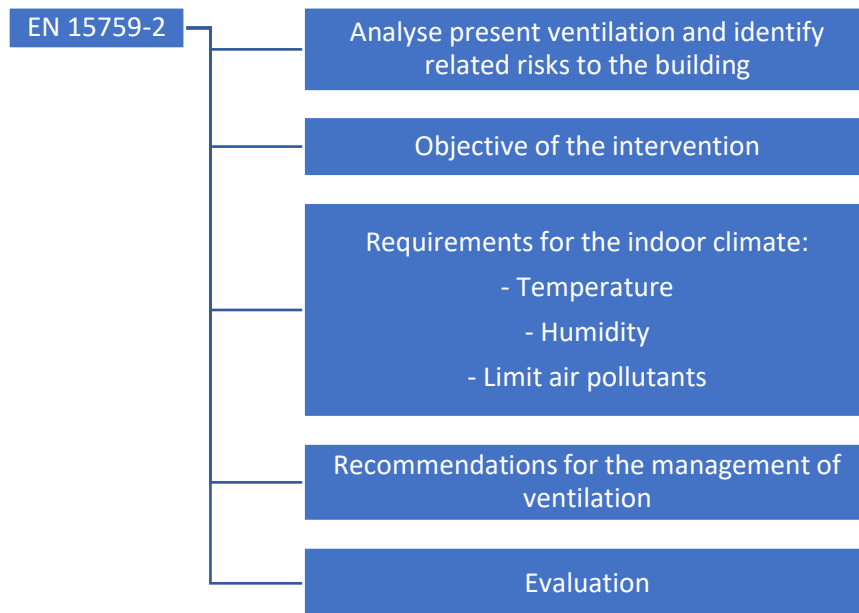
- $Q'$  Is the reduced ventilation rate (L/s);
- $Q$  Is the steady-state ventilation rate (L/s);
- $t_p$  Is the pollutant release duration (s);
- $V$  Is the volume of the space (m<sup>3</sup>);

CIBSE guide A also advises, in the case where the reduction ratio is greater than 1, and therefore, theoretically, no reduction is necessary, some ventilation should be provided due to possible subsequent pollutant releases. The bold line in figure 13 can be used to estimate the reduction ratio.

A third method to obtain ventilation rates is suggested [70]. This method proposed by Fanger is intended to be used when pollution sources are known but either, the emission rates of a specific pollutant are impossible to predict, the limiting concentration is unknown, or the odor perceived is a combination of different pollutants. Although the outdoors air supply rate is greater when this methodology is used, due to the lack of peer-reviewed analysis by the time of the release of CIBSE guide A, this ventilation rate determination method is not enforced.

#### 2.6.4. EN 15759-2

The aim of EN 15759-2 [71] is to facilitate the sustainable management of cultural heritage buildings and the collections they roost thru the use of ventilation. This standard, despite the useful step-by-step approach to managing ventilation (Figure 14), does not provide all the criteria necessary for a complete analysis such as the relationship between occupancy and ventilation.



*Figure 14- Step-by-step approach to managing ventilation (adapted from [71])*

In appendix A, two examples of the application of this standard are given: a cultural heritage building housing a museum with a mixed collection and a modern storage room.

In the first example, EN 15757:2010 [72] is mentioned in order to limit mechanical degradation due to excessive amplitude and frequency of fluctuations of indoor RH, assuming values ranging from 35% to 75%. Regarding temperature, 18°C to 26°C was adopted as an acceptable comfort interval. In the second case, the standard prescribes a maximum ventilation rate of  $0.04\text{h}^{-1}$  and limits the RH to 35% to 50%, and temperature to 7°C to 22°C.

## 2.7. Revision of relevant literature for IAQ and ventilation in church-like buildings

Mleczkowska et al. [73] have studied thoroughly the particle sources and deposition inside two historical churches in Poland for a time frame superior to 10 months and determined the air exchange rate (RPH) by fitting an exponential decay curve to the difference between indoor and outdoor CO<sub>2</sub> concentration levels (eq.14).

$$C_t - C_{bg} = (C_0 - C_{bg}) * e^{(-AER*t)} \quad (14)$$

Where:

- $t$  Is is time (s);
- $C_t$  is the indoor CO<sub>2</sub> concentration (ppm);
- $C_{bg}$  is the background CO<sub>2</sub> concentration equal to the outdoor concentration of the gas (ppm);
- $C_0$  is the CO<sub>2</sub> concentration at the initial point of the decay curve (ppm).

The two churches analyzed were a brick masonry Cathedral in the urban center of Tarnow and a wooden log construction church in Krakow (Figure 15).



Figure 15- a) Cathedral of the Nativity of the Blessed Virgin Mary; 14th-century b) St. Bartholomew's Church; 15th century (in [73])

The minimal RPH's determined by these researchers in the heating season was roughly 0.1 h<sup>-1</sup> for the brick cathedral and 0.35 h<sup>-1</sup> for the wooden church since windows and doors remained usually closed. In the cooling season, RPH's increased up to 1 h<sup>-1</sup> and 3 h<sup>-1</sup> for the brick and wooden construction, respectively.

In a follow-up paper [74] it was determined a characteristic RPH pattern ranging from 0.12–0.8 h<sup>-1</sup> for the brick masonry cathedral and 0.34–2.4 h<sup>-1</sup> for the wooden church.

In 2002, Schellen [75] reported on church heating systems and their effects on the deterioration of monumental churches in Holland. To accurately represent the indoor micro-climate a thorough detailing of several churches was made, including RPH's that are directly related to this document.

For the Waalse church in Delft (Figure 16), a 550-year-old stone masonry structure with interior limestone plaster and wooden roof, the air exchange rate was determined to be approximately  $0.29 \text{ h}^{-1}$ . This result was introduced as a parameter in a CFD simulation and the temperature and RH output compared to on-site measurements (Figure 17).



Figure 16- Waalse church in Delft (in [75])

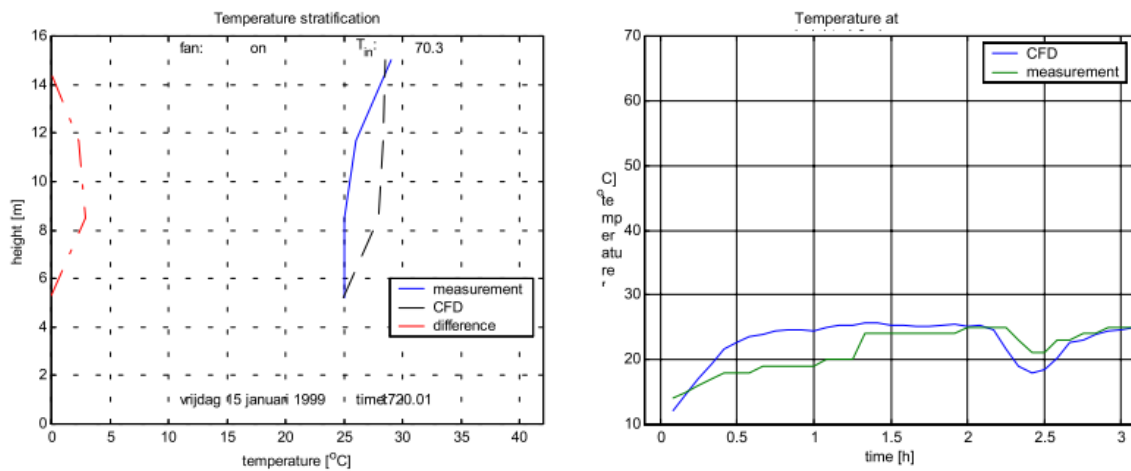


Figure 17- Comparison of measured and calculated results (in [75])

Although the results have shown themselves with reasonable accuracy, a stratification difference was detected at mid-height values, possibly due to an unrefined mixing parameter. Nevertheless, these results are highly acceptable as the temperature differences are inferior to 3 K.

The following church is highly relevant for the case study of this document as the floor area of  $210 \text{ m}^2$  and the total volume of  $3000 \text{ m}^3$  as well as the construction type are similar.

The Sypekerk in (Nieuw-)Loosdrecht, erected in the 15<sup>th</sup> century, has thick masonry walls, a wooden roof with visible cracks from the nave floor and plaster and whitewashed interior walls (Figure 18). The combined floor of the 3 naves that composed this church is  $365 \text{ m}^2$  and a total volume of  $3300 \text{ m}^3$ .



Figure 18- Sypekerk in (Nieuw-)Loosdrecht (in [75])

The air exchange rate determined by the tracer gas measurements conducted ranged from 0.8 to 1.0 h<sup>-1</sup>.

St. Liduina's Basilica is a masonry and natural stone church with no plaster on the inside, located in Schiedam (Figure 19).



Figure 19- St. Liduina's Basilica (in [75])

With an area of 850 m<sup>2</sup> and a volume of about 10,000 m<sup>3</sup> the air infiltration rate determined by the tracer gas measurements conducted ranged from 0.5 to 0.6 h<sup>-1</sup>.

St. Martinus' church in Weert dates to 1456. With an area of 1260 m<sup>2</sup> and a volume of 18,850 m<sup>3</sup> this monument is made of masonry walls, stone vaults and the glazing in the outdoor walls is made of stained glass (Figure 20).



Figure 20- St. Martinus' church (in [75])

The RPH determined by the tracer gas measurements conducted ranged from 0.08 to 0.33 h<sup>-1</sup>. These low values are justified by the large volume of the church and low Surface/volume ratio.

The São Cristóvão church, which is the case study of this document, has been the focus of some researchers such as Hugo Entradas Silva, Fernando M.A. Henriques and Guilherme B.A. Coelho [54, 76–78].

In 2012, Silva et al. [76] described the interior climate evolution of the church of São Cristóvão, studying the stratification of temperatures (Figure 21) and thermal delay compared with the external temperatures, to estimate the probability of surface condensations. It was also reported a very stable interior microclimate, with low cycles of temperature and relative humidity.

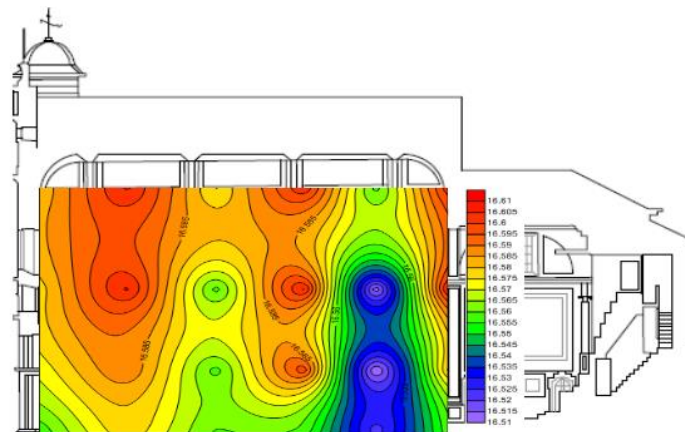


Figure 21- Vertical temperature mapping at May, 2012 (in [76])

In 2014, Silva et al. [77] through the microclimatic study of the Church of São Cristóvão were able to apply the standard EN 15757 to a historic building in a temperate climate, emphasized the variation in requirements for buildings in different locations and proposed a new methodology (Figure 22). *“The results obtained and the comparison with other case studies has showed that EN 15757 can present an overly rigid approach when applied in temperate climates, because it was developed based on buildings present in cold climates, which have other requirements. In temperate climates churches and most old buildings do not usually have HVAC systems and interiors climates largely depend on the variations of the outdoor climate. This justifies that short-term fluctuations are very controlled, although the seasonal cycle follows the outdoor cycle and shows more significant variations.”*

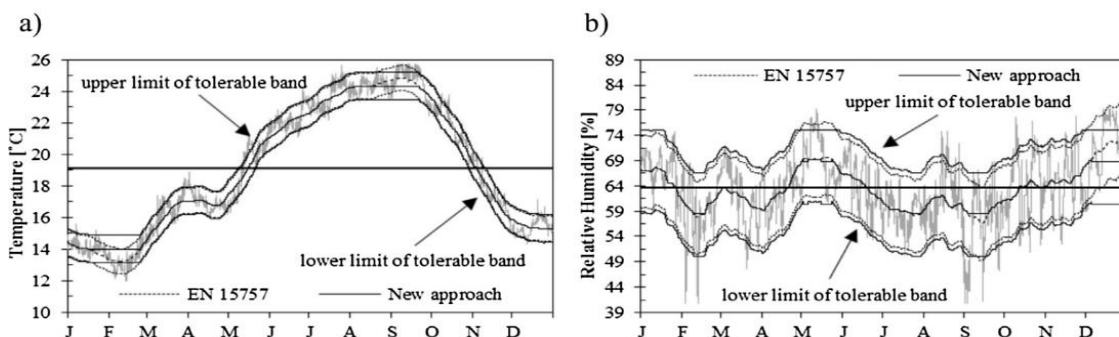


Figure 22- Target band of tolerable fluctuations according to the EN 15757 and the new methodology; a) T; b) RH. [77]

In 2015, Silva et al. [54] analyzed the influence of 3 microclimate targets (20°C – 50%, EN 15757 and PAS 198) in the Church of São Cristóvão and made a comparison between those targets and the natural climate by using a risk-based analysis reaching the following conclusions:

- Due to the dynamic target of EN 15757, a perfect mechanical response was reached for sculptures and a plastic response state in 5.3% of the year for painted wood. When the target outlined by PAS 198 was applied, a perfect mechanical response was found in painted wood and a plastic response in 0.6% of the year for sculptures. The 20 °C – 50% set-point leads to a perfect response in both sculptures and painted wood. Implementing the natural climate, plastic responses were found for sculptures and painted wood for 0.8% and 6.1% of the year, respectively.
- No biological risks were found in any of the four conditions set.
- When comparing the three microclimate targets to the natural climate, the 20 °C – 50% was found to be extremely taxing in terms of the hygrothermal response of the building, being reached only during 0.5% of the time, while the EN 15757 is reached in 75.3% and PAS 198 in 37.9%.

Figure 23 represents the degree of risk (0- high risk; 5 - ideal) for each of the microclimate targets and aspects examined (BR, building response; MRF, mold risk factor; eLM, equivalent lifetime multiplier).

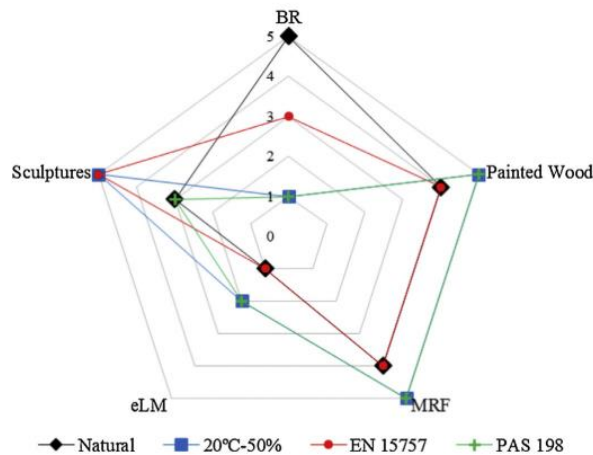


Figure 23- Graphical representation of the microclimatic classification of the four approaches in analysis.[54]

In 2018, Coelho et al. [78] studied the simulated accuracy of several models using hygrothermal data-based collections from the Instituto Português do Mar e da Atmosfera (IPMA), WUFI®Plus and EnergyPlus and compared to simulations run on *in situ* indoor and outdoor measurements. Additionally, simulations were conducted in order to establish simplifications with low impact on the model's results.

One conclusion of this paper with high relevance for the present document is the ACH variable utilized in the simulations. The development of a sensitivity analysis that included 48 simulations allowed them to create an accuracy optimization equation based on the goodness of fit and obtaining 0.4 ACH. This value attained from the several iterations, although optimized based on the real measurements taken, does not reflect real

conditions due to, firstly, other variables were also estimated and secondly, a ventilation simulation was not conducted.

Another conclusion reached was the lack of accuracy when utilizing the EnergyPlus temperature ( $T$ ) and water-vapor pressure ( $P_v$ ), database. EnergyPlus database attained much lower *Goodness of fit*, 56.5% for  $fit(T)$  and 40.1% for  $fit(P_v)$ , comparing with other data sets such as IPMA which attained a  $fit(T)$  of 71.8% and  $fit(P_v)$  of 71.5%.

In the most recent efforts, Coelho and Henriques [79] study multiple types of retrofit measures performance on the São Cristóvão church by taking into account climate change. This paper considered the impact of five wall insulation systems, two roof insulation systems, two ceiling insulation systems and window substitution, on the mitigation of climate change presumable consequences.

This research showed that passive retrofit measures can prevent some of the nefast effects of predicted climate change. Wall retrofit shows the greatest improvement in thermal comfort, biological decay, and mechanical decay (sculpture, base layer and pictorial layer), however, as depicted in several documents [54, 80], chemical decay is negatively influenced during the Summer months in mediterranean climates due to the warmer temperatures and low RH. The proposed retrofits, increasing the temperatures during Winter, decrease the overall eLM, as Table 8 shows.

Table 8- Performance of retrofit measures concerning the case without retrofits for Lisbon's historical climate. (extracted from [79])

Climate	Assessment	W1	W2	W3	W4	W5	R1	R2	C1	C2	Wd1
Lisbon	MRF	-0.06	-0.14	-0.11	-0.15	-0.12	-0.12	-0.12	-0.11	-0.11	-0.03
	eLM	-0.03	-0.03	-0.02	-0.02	-0.01	-0.03	-0.03	-0.02	-0.02	0.00
	Sculpture	-0.65	-0.26	-0.50	-0.08	0.06	-0.03	-0.02	-0.09	-0.08	-0.05
	Base layer	3.14	3.32	3.07	2.99	2.39	2.29	2.28	2.09	2.02	0.79
	Pictorial layer	-0.52	-0.84	-0.69	-0.94	-0.55	0.11	0.14	-0.12	-0.12	-0.13
	Thermal comfort	6.06	5.57	4.69	5.18	1.74	3.99	4.26	2.56	2.25	0.03

Because credible ACH values are detrimental to a relevant ventilation study, Table 9 was created to summarize the pertinent information from the consulted references mentioned previously.

Table 9- Ventilation rates from 14 different churches, chapels and Basilicas

Church/city	Area (m <sup>2</sup> )	Volume (m <sup>3</sup> )	walls	ACH (h <sup>-1</sup> )			reference
				min	avg	max	
Scrovegni Chapel	255	2500	brick	0.21	-	0.31	a
Church of São Cristóvão	286	3720	Lime stone	0.28	0.34	0.7	b
Nativity of the Blessed Virgin	NA	23100	brick	0.12	-	0.8	c
Bartholomew's church	NA	1450	wood	0.34	-	2.4	c
Waalse church	210	3050	brick	-	0.29	-	d
Sype church	365	3330	brick	0.8	-	1	d

church	Area (m <sup>2</sup> )	Volume (m <sup>3</sup> )	walls	ACH (h <sup>-1</sup> )			reference
				min	avg	max	
St. Liduina's church	850	10325	brick	0.5		0.6	d
St. Martinus's church	1260	18693	brick	0.08		0.33	d
St. Gerlachus's church	475	6680	brick	-	0.2	-	d
Roman catholic church	840	10600	brick	-	0.1	-	d
H. Donatus's church	840	9800	brick	-	0.6	-	d
St. Lawrence's church	2180	45720	brick	0.5	-	1.2	d
St. Paraskevi church	195	1020	Sand stone	0.1	3.5	20	e

a\* Baggio et al. [14]  
b\* Silva et al.[66]  
c\* Mleczkowska et al. [68]  
d\* Schellen [70]  
e\* Loupa et al. [71]



### 3. Research methodology

#### 3.1. Case study

São Cristovão's Church is located in the West hill of São Jorge's Castle in Lisbon, in Santa Maria Maior Parish (former São Cristovão e São Lourenço Parish), and can be seen in figure 24. On the top of Escadinhas de São Cristovão, dating back to the XIII century, a worshipping ground is mentioned in several documents [81–83] as a church in honor of Santa Maria de Alcamim, built during the Arab occupation of the Iberian Peninsula [81, 84]. After a fire destroyed most of the building in the last quarter of the XVI century, restoration works were made during the reign of D. Manuel I, and throughout de XVII major renovation occurred implementing deep changes relative to the original structure, which was design by Padre João Duarte [85–87].

As known, most historical buildings in Portugal and around the world are several centuries old, and therefore, the construction materials and techniques are different from those currently used. One of the aspects that characterize old buildings is the thick stone masonry walls that endow high thermal inertia. Despite this fact, this type of building presents a poor hygrothermal response that can contribute to an unstable microclimate leading to a sensitive balance between conservation, comfort, and sustainability [54, 88, 89].



*Figure 24- Church of São Cristóvão*

The cultural significance of this church is raised by the fact that is it one of the few that outlasted the 1755 Lisbon earthquake in which minimal damage to the bell towers was reported [81].

The amount of work done concerning restoration and reparation to gilded woodcarvings, painted canvas, panels and woodwork throughout the history of the church is well documented [87] and indicative of the sub-optimal conditions regarding the indoor atmospheric environment. In 2018, after winning a public budget initiative and being integrated in the Watch Program by the World Monuments Fund, major renovations to the roof and facades were conducted.

This church is composed of a nave and altar (ca. 286 m<sup>2</sup>), 13m of height in the center of the room, a funeral home to the south (ca. 71 m<sup>2</sup>), a sacristy (ca. 93 m<sup>2</sup>) to the north, an annex behind the altar (ca. 11 m<sup>2</sup>) and two bell towers (ca. 5 m<sup>2</sup>). Its walls appear 0.7-1m thick, lime stones on the corners, and on the exterior walls, lime mortar renders were used over mortared limestone [54].

The main nave is directly connected to the outside by the south-facing main door, a north side auxiliary door, and 14 windows of different sizes and typology. It is also connected to the sacristy by 2 door paths and to the funeral home by also 2 door paths.

More specific information about the geometry of the church will be referenced in sub-chapter 3.3.1.3 Model geometry.

## 3.2. Lisbon Climate

The influence of the outdoor climate is prominent when assessing the indoor climate of a building.

The purpose of the present sub-chapter is to 1) present the typical weather in the region of the case study and 2) explain the criteria behind the selection of the weather data set used for subsequent simulations.

### 3.2.1. Temperature

Lisbon's climate is defined, according to Köppen Climate Classification System, as a Temperate climate- Type C, *Csa* (temperate with dry or hot Summer) characteristic of Mediterranean countries (Figure 25). The proximity to the Atlantic Ocean provides a temperature buffer in the warmest months in the Summer and the coldest during the Winter period.

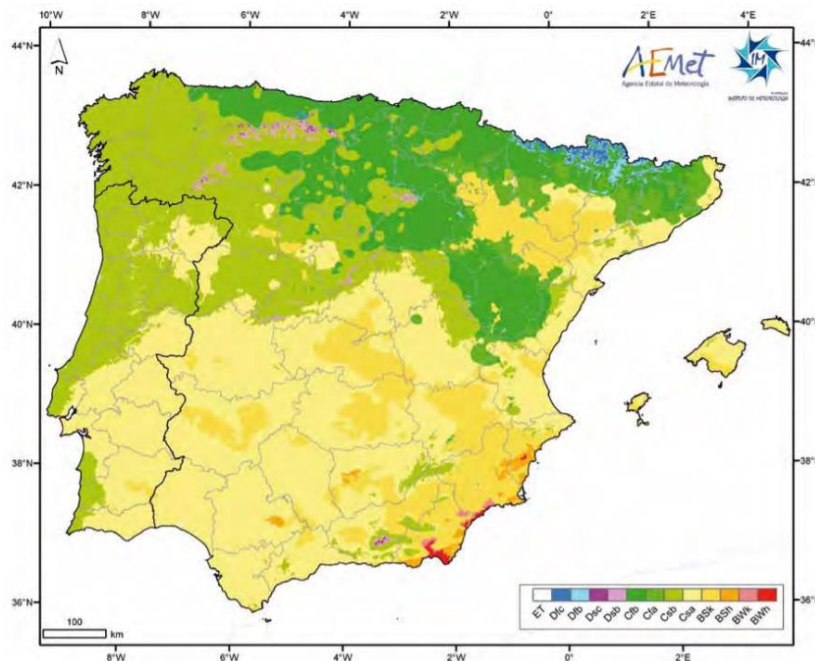


Figure 25- Köppen-Geiger Climate Classification for the Iberian Peninsula and the Balearic Islands. [90]

Lisbon’s yearly average temperature, in unison with world records, is rising at a steady state, as can be seen in Figure 26.

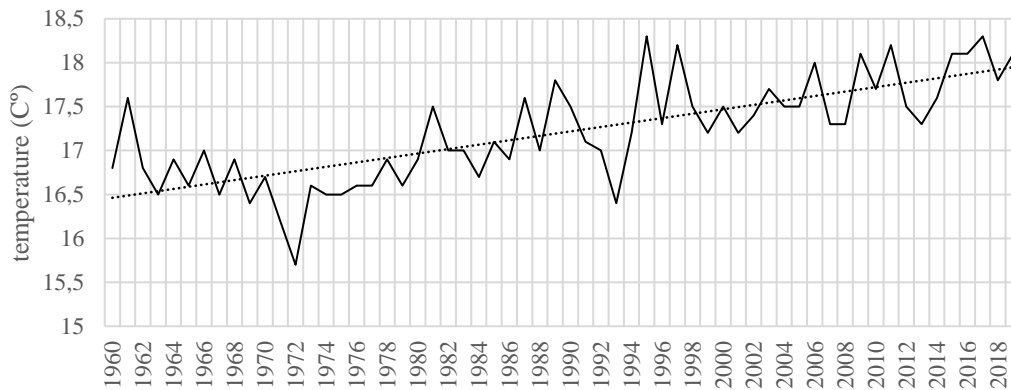


Figure 26- Evolution of the average yearly temperature in Lisbon [91]

Lisbon temperature’s evolution throughout the year is shown in Figure 27, according to the climate normal 1971-2000, where TA represents the average maximum temperature, TI the average minimum temperature and TMA and TMI represent the Highest and lowest temperature recorder, respectively.

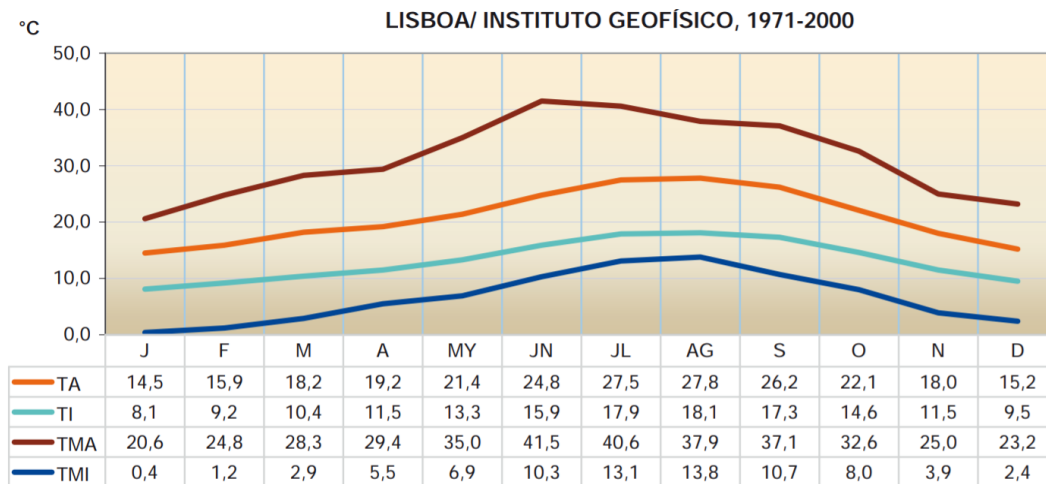


Figure 27- Climate normal values for air temperature in Portugal relating to the 1971-2000 time-frame; Instituto Geofísico [90]

Figure 28 and Figure 29 reveal the extreme temperature behaviour in Lisbon. Maximum temperatures range from 20°C to 40°C while minimum temperatures do not get below 0°C in peak Winter or 10°C during the Summertime.

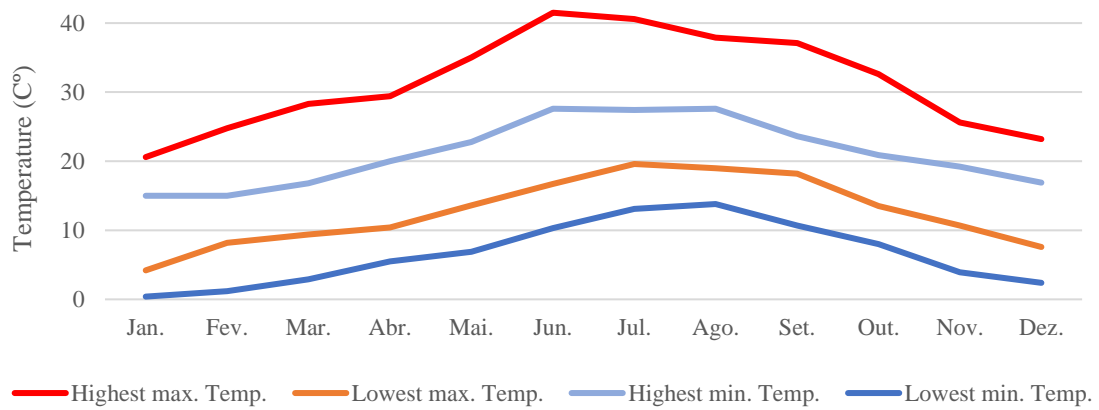


Figure 28- Extreme temperatures in Lisbon relating to the 1971-2000 time-frame [92]

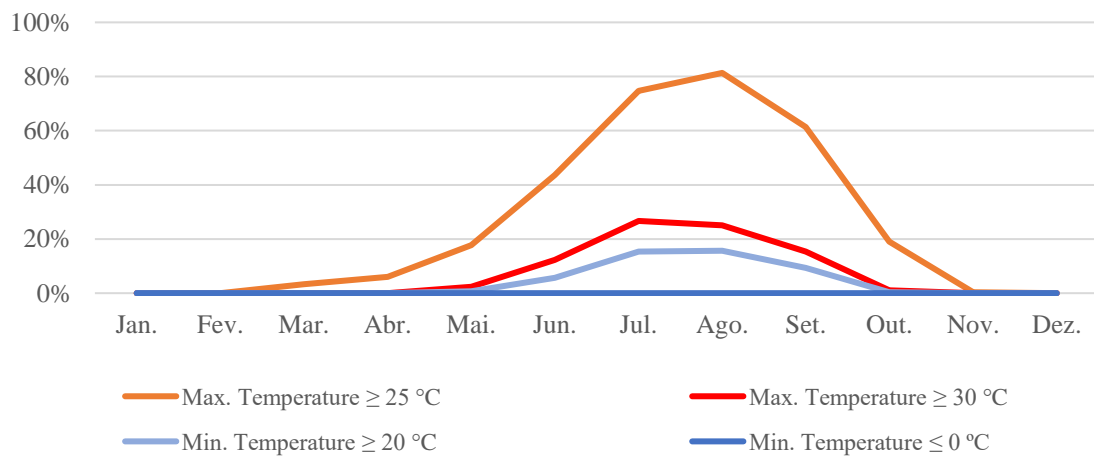


Figure 29-Percentage of days per month by range of temperature [92]

### 3.2.2. Weather file analysis

When it comes to select a weather file to use in a ventilation simulation, a quick analysis should be conducted to create a validation process. Although many sources of weather information are available, some can misrepresent the real situation due to data collection errors. For this study, four data sets were used:

- ipma-2020 Relógio weather station was obtained directly from IPMA and is a raw set of wind intensity and direction regarding the year 2020. This data was collected in the Relógio weather station in Lisbon.
- ipma-2020 GCD weather station was obtained directly from IPMA and is a raw set of wind intensity and direction regarding the year 2020. This data was collected in the weather station near Lisbon's Airport at a 6.4km distance to the São Cristovão's church.
- EnergyPlus is a recognized whole building energy simulation *software* that also provides weather data. In the case of Lisbon's data set, the values were developed by INETI and based on spatial interpolation of public climatic data published by Instituto de Meteorologia 1951-80 combined with INETI owned data and other freely available data sources.
- SNIRH provides through its website all data collected. In Lisbon's case, three weather stations are available for data retrieving but unfortunately there are significant gaps in the analyzed data due to equipment malfunction and lost information.

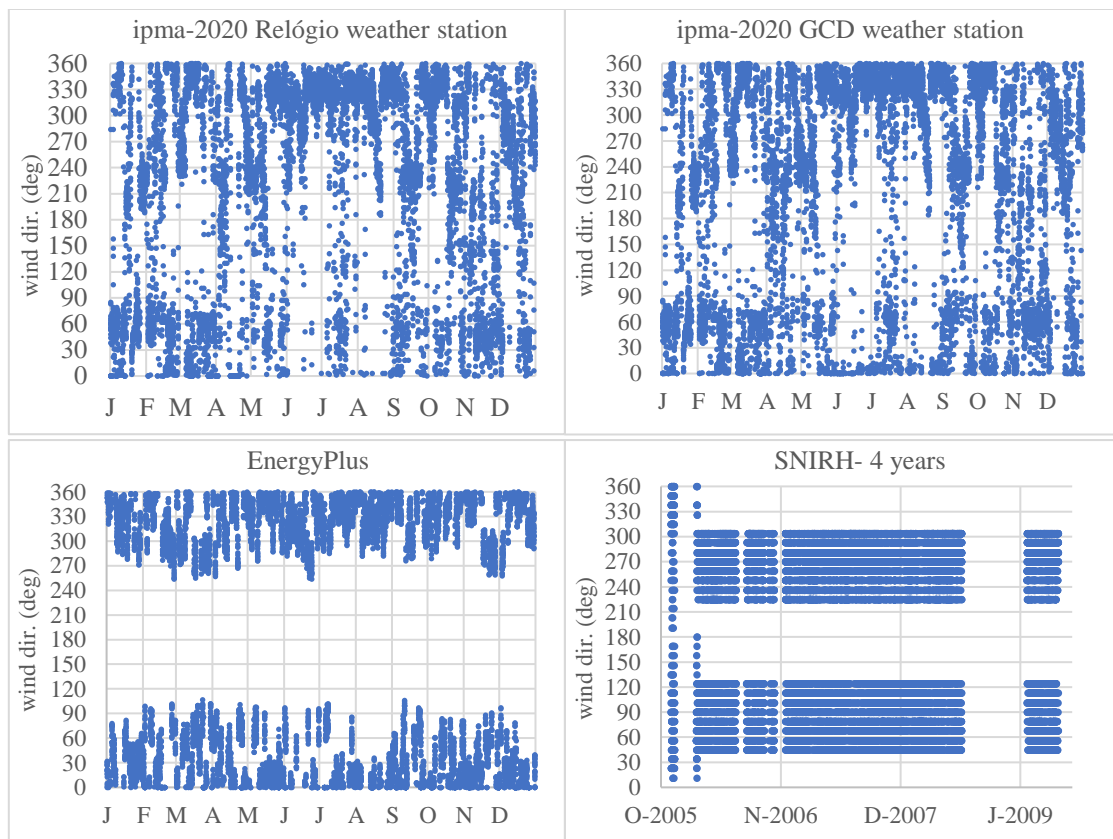


Figure 30- Wind direction of the four data sets

As easily perceived by the analysis of Figure 30 the SNIRH data is highly problematic as the wind direction is constant unlike IPMA's data and what is expected.

Regarding the EnergyPlus data, no wind direction entry is recorded to have direction from 120° to 240° which is also abnormal. As a file based on most common scenarios, EnergyPlus data set present the normal values for its parameters and as such, can differentiate from reality as reported by Coelho [78], specifically, EnergyPlus database attain a low goodness of fit for temperature and water-vapor pressure (56.5% and 40.1% respectively) when compared to on-site measurements taken on St Christopher church venue.

When comparing the wind roses from the four different databases in Figure 31 with others collected from different sources [93–96] two conclusions can be directly extrapolated. The first is related to the SNIRH data set and the prevalent West and East wind is an anomaly compared with all sets of data. The second is that the EnergyPlus rose wind shows, as mention in the previous sub-chapter, a 0% of Est, South and West wind occurrence, which, according to IPMA and references [93–96] is not the case. The figures in Annex B show the wind roses of the previous references.

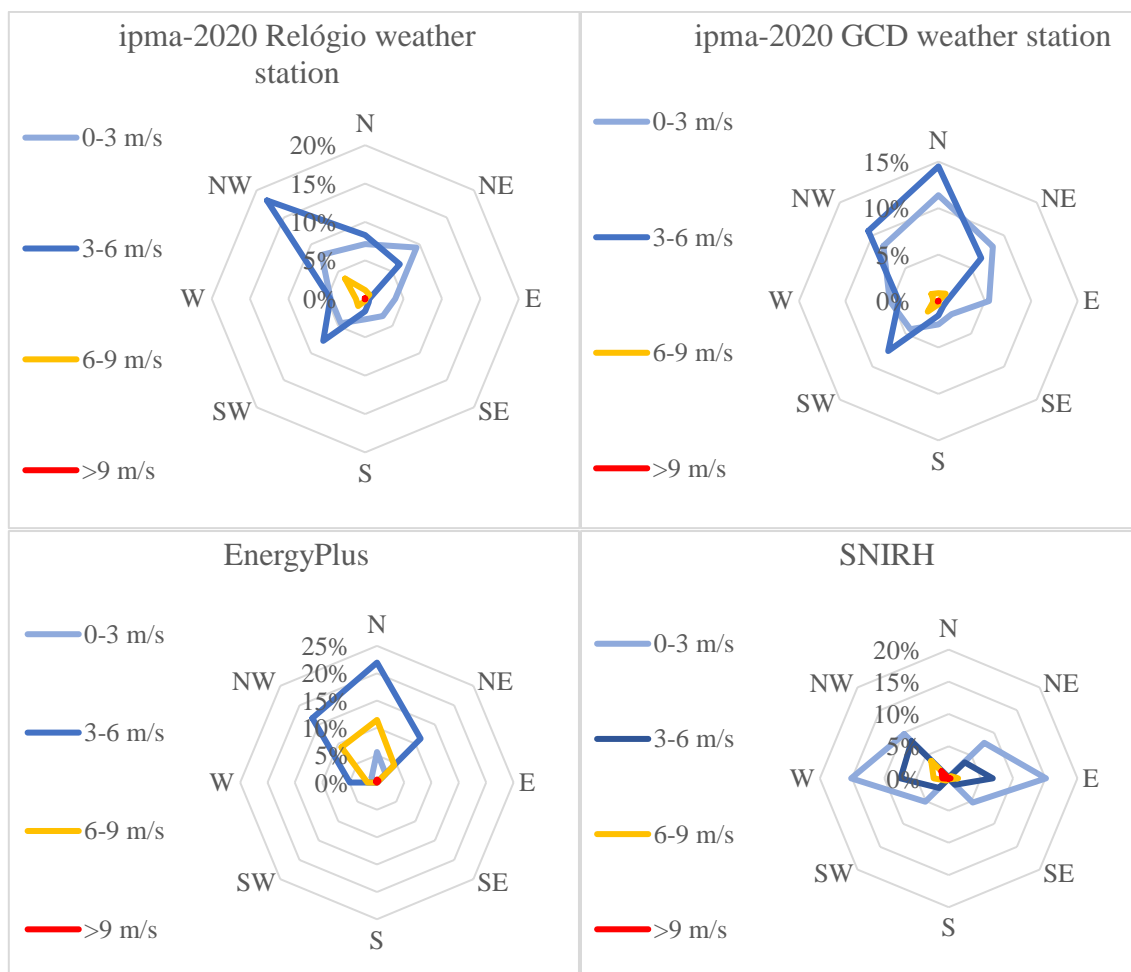


Figure 31- Wind rose diagram of the four data sets

Excluding the SNIRH dataset, all references examined show acceptable wind speed values (Figure 32). EnergyPlus, due to its synthetic nature referent to data collected in the 1951-1980-time frame reveals a more harmonized weekly average curve.

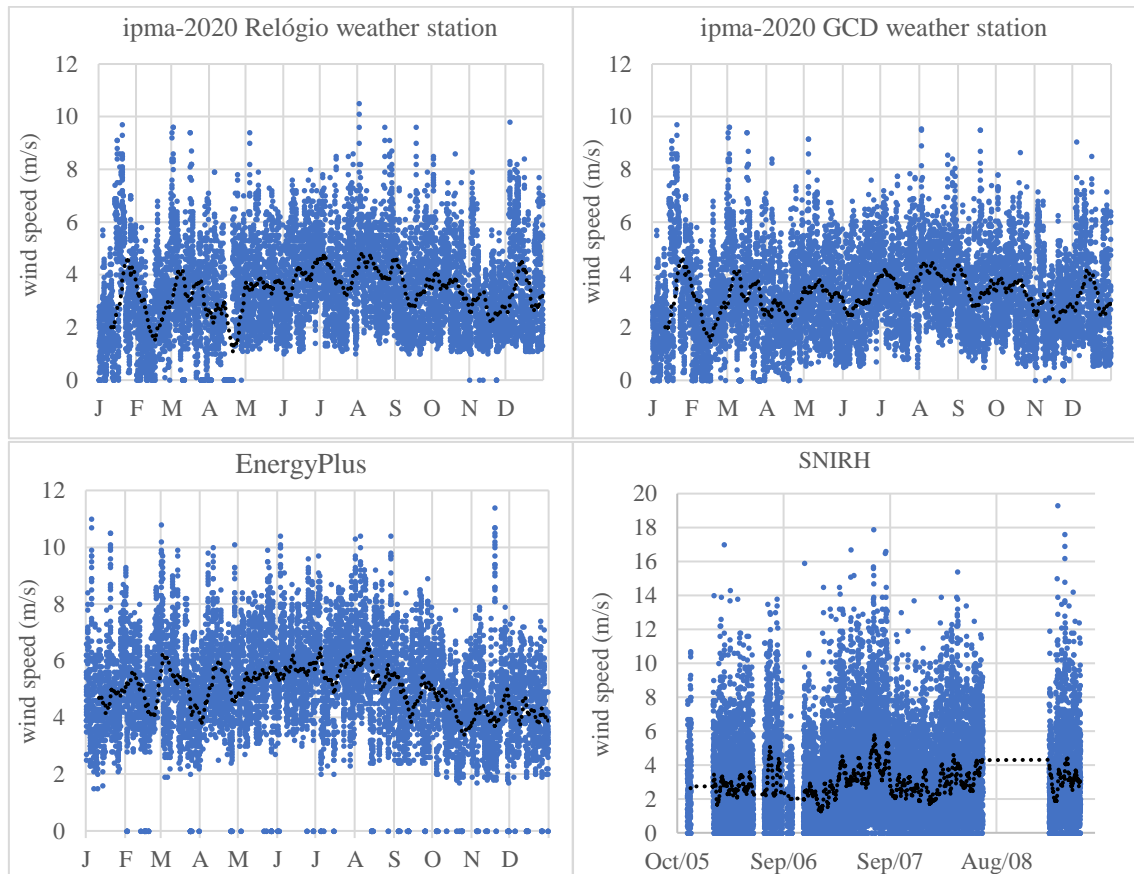


Figure 32- Wind speed of the four data sets; the black dotted line represents the weekly average.

At a primary stage of the construction of the model, 2 simulations were run to assess the implication of using IPMA and EnergyPlus databases. Because the definition of the most suited database is not the focus of this document, a simple analysis was conducted, regarding only the ACH results, to assess the consequence of utilizing either data sets (Table 9).

Table 10- Average ACH values for different weather databases

Analyzed period	Weather database	
	IPMA-2020 GCD	EnergyPlus
Open period	0.46	0.47
closed period	0.05	0.05
All year	0.14	0.15

As shown in Table 10 the results do not differ by a significant margin. This may be explained by:

1. The wind from SW that occurs in IPMA's database does not have a significant impact on the overall results as the North wind remains predominant in both databases.
2. The church site and surroundings are highly influential in the wind pressure registered on flow paths. The model's wind speed modifier, a combination of terrain and wind velocity constants, is low, as typical in urban environments, reflecting a mild response to the wind-induced ventilation when small variations are implemented. This modifier is explored in greater depth in the next chapter.

Although IPMA's database presents a bigger range of wind direction, the data it presents is referent to a single year, and as such, utilizing these values as a reference in the simulation may not reflect the typical conditions. Additionally, the use of typical weather and climate scenarios in buildings performance, energy efficiency and IAQ, is a complex theme that can induce wrong assumptions [97–99]. Global warming has created a more volatile climate and as such, predictions can be harder to pinpoint.

With all the information presented in this sub-chapter, a decision was made regarding which weather file to implement in the model that was created and discussed in sub-chapter 3.3.

For this reason, the selection of EnergyPlus database in detriment to the IPMA-2020 GCD database was not taken lightly and the variation on results that are expected are one more factor that contributes to the uncertainty of IAQ and ventilation analysis.

### 3.3. CONTAM- multizone IAQ and ventilation analysis software

*CONTAM* from *NIST* is a multizone IAQ and ventilation analysis *software* developed to help estimate airflows, contaminant concentrations and personal exposure for risk assessment activities [100] both in natural and mechanical ventilated buildings.

The *software* treats a building as a system of interconnected, well-mixed zones where air and contaminants flow thru. The *CONTAM software* and manual may be downloaded from [100].

The program can determine ACH, infiltration and exfiltration in buildings systems driven by wind pressure and thermal buoyancy. It also reproduces the effect of users and contaminant sources in the IAQ and its dispersion, although coupling another *software* is needed for this last analysis.

Due to its user-friendly graphical interface, and input flexibility, *CONTAM* has been used in multiple scientific papers [88, 101–104].

The first calculations made by *CONTAM* are the airflow rates between zones by solving a mass balance equation (eq.15).

$$\frac{dm_{\alpha,i}}{dt} = -R_{\alpha,i}C_{\alpha,i} - \sum_j F_{i,j} C_{\alpha,i} + \sum_j F_{j,i} (1 - \eta_{\alpha,j,i})C_{\alpha,j} + m_i \sum_j k_{\alpha,\beta} C_{\beta,i} + G_{\alpha,i} \quad (15)$$

where:

- $dm_{\alpha,i}$  is the mass of contaminant  $\alpha$  in zone  $i$  (kg);
- $R_{\alpha,i}$  is the removal coefficient for contaminant  $\alpha$  in zone  $i$  (kg/s)
- $C_{\alpha,i}$  is the concentration mass fraction of contaminant  $\alpha$  in zone  $i$  (kg/kg)
- $F_{i,j}$  is the rate of airflow from zone  $i$  to zone  $j$  (kg/s)
- $F_{j,i}$  is the rate of airflow from zone  $j$  to zone  $i$  (kg/s)
- $\eta_{\alpha,j,i}$  is the filter efficiency in the path from zone  $j$  to zone  $i$  (kg/kg)
- $C_{\alpha,j}$  is the concentration mass fraction of contaminant  $\alpha$  in zone  $j$  (kg/kg)
- $M_i$  is the mass of air in zone  $i$  (kg)
- $k_{\alpha,\beta}$  is the kinetic reaction coefficient in zone  $i$  between species  $\alpha$  and  $\beta$  (1/s)
- $C_{\beta,i}$  is the concentration mass fraction of contaminant  $\beta$  in zone  $i$  (kg/kg)
- $G_{\alpha,i}$  is the generation rate of contaminant  $\alpha$  in zone  $i$  (kg/kg)

Designers must supply data regarding airflow paths, contaminant source emission, removal rates, filters, and occupancy schedules.

In 2001, Persily and Ivy, NIST engineers, assembled a database containing leakage, wind pressure coefficients and ventilation system schedules to aid and expedite researchers and professionals in their model input parameters determination.

#### 3.3.1 Input parameters

To estimate an accurate representation of the IAQ and ventilation behaviour, trusted inputs must be adopted, and as such, this sub-chapter will present the input values and their origin in order to simplify the peer-review process.

An important characteristic that is not possible to implement in the simulations is the high thermal inertia that is typical of this type of building. *CONTAM* only allows for a static indoor temperature (set at 20°C) and therefore, the results that will be discussed do not reflect the thermic reality of the church.

### 3.3.1.1 Weather input

The weather-file used in the simulations is a synthetic data set based on spatial interpolation of public climatic data published by Instituto de Meteorologia 1951-80 and obtained from the EnergyPlus database, a National Renewable Energy Laboratory (NREL) managed institution.

The data in this file is a representation of average values collected across 30 years and can be downloaded thru the link: [105]

Ideally, the weather data utilized in a ventilation simulation is the one recorded on site. Interior and exterior temperatures as well as wind direction and intensity could reflect a more accurate status of the church’s air renewal behaviour. As these measurements are not possible to accomplish, the interior temperature was set to 20°C like the example models provided by NIST [106].

### 3.3.1.2 Contaminant sources and models

The only contaminant present in the simulations is CO<sub>2</sub> and was implemented with 44.01 g/mol and 400 PPM as default ambient value. Other properties such as mean diameter and specific heat were left blank because these characteristics are not necessary for the objective in sight, as shown by the case studies available at:[106]

*CONTAM* offers a variety of source models for the generation and dissemination rates of air contaminants. The table below is a summary of source models although other models are available in the literature [107].

As shown in Table 10, each model should be used for specific types of sources. In the case of the present work, since only CO<sub>2</sub> emissions are analyzed, and its emissions rates are fairly stable, the Constant Coefficient Model was chosen. To take into account the non-instantaneous character of the contaminant source, an incremental coefficient, and therefore, a trapezoidal schedule was applied to reflect the cumulative entry and exit of mass attendees (Figure 33).

*Table 11- Source models used to characterize source emission rates in CONTAM.*

Source Model Name	Equation	Example Uses
Constant Coefficient Model	$G$ <p>G= Genaration rate</p>	<ul style="list-style-type: none"> <li>• Dry VOC sources (e.g.linoleum)</li> <li>• Particles from cooking</li> </ul>

Source Model Name	Equation	Example Uses
Pressure Driven Model	$G \cdot \Delta P^n$ $\Delta P$ = pressure difference $n$ = pressure exponent	<ul style="list-style-type: none"> <li>Contaminated soil gas</li> </ul>
Decaying Model	$G_0 \exp(-t/t_c)$ $G_0$ = initial generation rate $t$ = time since start of emission $t_c$ = time constant	<ul style="list-style-type: none"> <li>Wet VOC sources (e.g., paint)</li> </ul>
Boundary Layer Diffusion Model	$hdA \left( C_i - \frac{C_s}{k} \right)$ $h$ = film mass transfer coefficient over sink $d$ = film density of air $A$ = surface area $C_i$ = concentration in air $C_s$ = concentration at surface of material $k$ = partition coefficient Burst	<ul style="list-style-type: none"> <li>Reversible sinks</li> </ul>
Burst Source Model	Fixed mass added to zone instantaneously	<ul style="list-style-type: none"> <li>Occupant activities (e.g., spraying an air freshener, changing kitty litter)</li> </ul>
Power Law Model	If $t < t_p$ , then “Dry” materials emissions $S(t) = at_p^{-b}$ Else $S(t) = at^b$ $t$ = time $a, b, t_p$ = empirical coefficients	<ul style="list-style-type: none"> <li>“Dry” materials emissions</li> </ul>
Peak Model	$S(t) = a \exp \left\{ -0.5 \left[ \frac{\ln(\frac{t}{t_p})}{b} \right]^2 \right\}$ $a, b, t_p$ = empirical coefficients	<ul style="list-style-type: none"> <li>“Wet” material emissions</li> </ul>

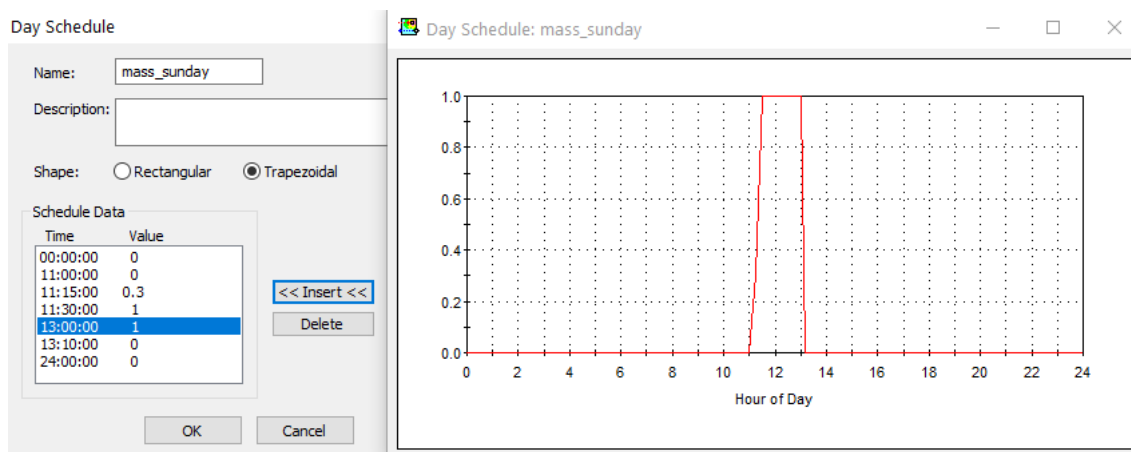


Figure 33- Sunday mass schedule and corrective factor of 0.3, 15 minutes before mass starts

Two sources were created to reflect both variables regarding CO<sub>2</sub> releases.

The first source is responsible to simulate the mass attendees entering the church, celebrating the mass, and exiting the building. A source was set to release 0.0046 L/s.person of CO<sub>2</sub>, corresponding to a typical human in “mass-like” conditions. This value was an extrapolation of table 4 from Persily et al. [108] where a met value of 1.3 was adopted, the male//female ratio set to 1 and ages ranging from 50 to 80. A factor of 40 was applied to reflect the number of attendees. An important fact to mention is that the number of mass attendees was referred by the mortuary employee that is a usual attendant of the religious service and therefore, no record is available.

The second source was implemented to simulate visitors’ effect on CO<sub>2</sub> emissions during the off-mass period. The church administration estimates 150 persons visiting during the Wintertime and 250 during the Summertime although no records were available. With these values as the basis for the subsequent analyses and considering:

- Daily and yearly constant distribution of visitors in the off-mass period.
- The church is opened 36 hours per week in an off-mass period.

An average of 5 persons per hour was considered and a source was set to release 0.0068 L/s.person of CO<sub>2</sub> reflecting visitors with 20 to 60 years old and an activity level equivalent to 2 met. Although a variable number of visitors should be implemented to better reflect the true nature of CO<sub>2</sub> emissions across seasons, the main factor in this analysis is the mass period that is regular throughout the year and much more influential on IAQ. Therefore, no repercussions should appear for this simplification.

The daily schedules implemented in the simulation are as shown in Table 12 and the weekly distribution of time for each of the church’s undertaken activities is presented in Figure 34.

Table 12- São Cristóvão church's schedule used in CONTAM

Weekday	CONTAM Day type	Church schedule				Mass schedule	
		Morning		Afternoon		beginning	end
Sunday	1	10:30	13:00			11:30	13:00
Monday	2	10:30	13:00				
Tuesday	3	10:30	13:00	14:00	19:00	18:15	19:00
Wednesday	4	10:30	13:00	14:00	19:00	18:15	19:00
Thursday	5	10:30	13:00	14:00	19:00	18:15	19:00
Friday	6	10:30	13:00	14:00	19:00	18:15	19:00
Saturday	7			17:00	19:00		

For the majority of the time, the church is closed and only 4% of the week is predicted to have a significant amount of occupants.

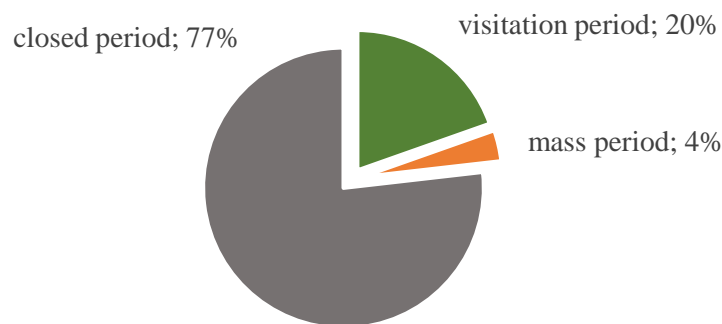


Figure 34- Weekly percentage of time for each church activity period

### 3.3.1.3 Model geometry

The model used in the simulation is a simplification of São Cristóvão's church.

Firstly, the volumes of the different compartments that compose the building are parallelepiped. This does not interfere with the *CONTAM* simulation results since only the volume and location of the flow paths are geometrical input parameters and the stratification of air is not in effect.

The walls of the church, due to their composition and thickness were considered leakless.

Five levels were created (Table 12). The first floor, floor 0 is under the main entrance level to the church and only has one compartment on the south side of the church, in the mortuary house. This room, not accessible to visitors and missing in all plans studied [109], [110] was considered by the author to connect to the upper floor.

On the ground floor, floor 1, is located the main and secondary entrances as well as the spans connecting the nave room to the sacristy and mortuary house. Exterior access to the sacristy is also present.

On the second floor, floor 2, although no connection between the nave and other rooms is considered, most of the windows are located here.

On the third floor, floor 3, some windows are connecting the nave and the exterior. The support building, sacristy and mortuary house roofs, are located at this level.

Floor 4 only has the bell towers with an assumed horizontal wooden hatch that gives access to the bells for maintenance.

Table 13- CONTAM floor height setting

	<b>Height (m)</b>
<b>Floor 0</b>	2.5
<b>Floor 1</b>	3.5
<b>Floor 2</b>	3.5
<b>Floor 3</b>	6
<b>Floor 4</b>	2

Although every compartment of the church was implemented in *CONTAM*, because visitors only have access to the main nave, the support rooms and accesses were not included in the whole building volume. In Figure 35, the highlighted area represents the space that is considered for the ACH calculation. This choice was made because not ignoring the bell towers and other compartments lead to a massive increase in the ventilation rate. In one simulation, considering the entire building, ACH values reached 20 air renewals. If these values were correct, they do not reflect the ventilation in the spaces where people are.

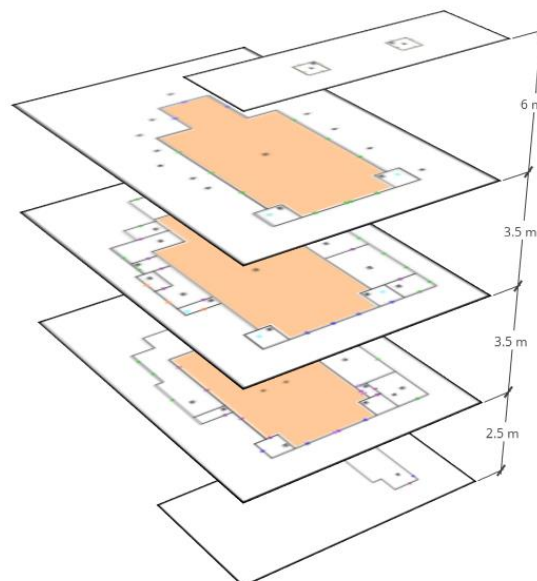


Figure 35- Schematic of São Cristóvão's church levels in CONTAM

### 3.3.1.4 Flow paths

One of the most critical factors in the simulation setup was the definition of existing flow paths in the church.

Due to the new Corona Virus pandemic, it was only possible to visit the inside of the church twice at the beginning of March 2020. As no permission was given by the church administration to take measurements on those days, they were only scouting tours to have a general idea of the building.

During the 2020 year, several visits were made to estimate the area of windows and doors from the outside.

The flow path information was, therefore, a combination of measurements taken on-site by the author, a set of the sacristy's renovation plans accessed from the São Cristóvão parish blog [109], a set of undated plans in pdf with low resolution [110], and a corrupted .dwg file with missing information that previous researchers have drawn.

A list of flow path types is available for consultation in Table 14.

A table of the flow path parameters and a *CONTAM* airflow elements layout is present in Appendix C.

Table 14- Flow path types identified at São Cristóvão's Church

Name	Description
<i>Door frame, masonry, uncaulked</i>	Frame of single side-hinged door connected to masonry wall, with cracks and crevices.
<i>Door, double, not weather-stripped</i>	Span with 2 doors, each door hinged from opposite sides without rubber foam weatherstrip tape.
<i>Door, single, not weather-stripped</i>	Single side-hinged door without rubber foam weatherstrip tape.
<i>General ceiling</i>	General ceiling infiltration.
<i>Window, single hung, not weather-stripped</i>	Hung window with the bottom half vertically slidable without rubber foam weatherstrip tape.
<i>Window framing, masonry, uncaulked</i>	Frame of window connected to masonry wall with cracks and crevices.
<i>Window, casement, not weather-stripped</i>	Single casement window with single side hinges without rubber foam weatherstrip tape.
<i>Window, double casement, not weather-stripped</i>	Span with 2 casement windows, each with single side hinges without rubber foam weatherstrip tape.

### 3.3.1.4 Result files

The *CONTAM* result files used in the analysis of the different simulations are the ACH, EBW, ECX and AGE files. ACH file display for each time-step the average air change rate per hour for the entire building; EBW files show pollutant concentrations in the areas with designated sensors; ECX files display the contaminant mass through each pathway; AGE files outputs the ages of air for the different compartments.



## 4. Simulation results

The presentation and discussion of the simulation results will be made in the present chapter and compared to EN 15251, EN 13779, CIBSE-Guide A and ASHRAE 61.2 prescribed ventilation rates for each simulation.

In sub-chapter 4.1. several attempts were made to create the most accurate model, reflecting the real on-site condition as close to reality as possible, refining the flow path parameters, bearing in mind that the points of comparison for this model are limited. Furthermore, only ACH results were analyzed in this sub-chapter as the goal is to improve the overall results and not to examine in-depth each iteration.

In sub-chapter 4.2. different strategies will be presented and analyzed to better suit the need of the different standards previously referenced.

### 4.1. Implementation and analysis of the start-off simulation and its refinements

For the simulations that serve the purpose of reaching a compatible ventilation performance in line with the literature, a trial-and-error methodology was approached as no on-site data collection was possible due to the limitations imposed by the COVID-19 restrictions.

Three simulations will be presented:

1. Sim\_00- Start-off simulation;
2. Sim\_01- First refinement to the model;
3. Sim\_02- Second refinement to the model;

Two church attendance statuses were evaluated. The first is the open-doors period that reflects the hours in which visitors can enter the church and mass attendees can celebrate religious service. For the present chapter, no distinction was made between the mass period and the visitation period.

#### 4.1.1. Simulation 00

For the first simulation, the flow path values selected were directly extracted from the AIVC Guide 5. Although some authors reflect on the lack of information regarding the values there presented by ASHRAE and AIVC [111], such as the condition of testing (*in situ*) [112], they do not present results that differ from the proposed ones. Furthermore, AIVC Guide 5 (Table 14) expresses average values that tend to translate fairly accurate results in typical cases. However, when degradation of the materials that compose a building is in play, these values may not reflect the true air infiltration and ventilation performance expected.

The start-off simulation, *Sim\_00*, was based on the following conditions and assumptions:

- AIVC- guide 5 ELA values were directly applied to pathways (Table 15).
- The main door was set to open according to the Table 12 church schedule and all other doors and windows remain closed.

- Mass attendees were set to 40 persons and uniform distribution of 5 visitors per hour when the church is open.

Table 15- AIVC Guide 5: ELA values

AIVC-code	description	ELA			discharge coefficient (Cd)	$\Delta Pa$
		cm <sup>2</sup> /item	cm <sup>2</sup> /m	cm <sup>2</sup> /m <sup>2</sup>		
CE_RAV	General ceiling - best estimate.	0	0	1,8	0.65	4
DRDBNW_RAV	Door. double. not weatherstripped	0	0	11	0.65	4
DRSINW_RAV	Door. single. not weatherstripped. best estimate	21	0	0	0.65	4
FRDRMAUC_RAV	Door frame. masonry. not caulked. best estimate	0	0	5	0.65	4
FRWNMAUC_RMX	Window framing. masonry. uncaulked. maximum	0	0	10.3	0.65	4
WNCASENW_RAV	Window. casement. not weatherstripped. best estimate	0	0.28	0	0.65	4
WNSISHWE_RMX	Single Hung windows: Window. single hung. weatherstripped. maximum	0	1.24	0	0.65	4

Results were analyzed and compared to the literature.

As foreseeable, the average ACH values for the open hours were superior to the closed hours with 0.47 and 0.05, respectively and a weighted average of 0.15 considering the open/closed hours in a year time. The standard deviation is also greater for the open doors period with a value of 0.14 versus the 0.007 of the closed doors periods. Table 16 provides a compilation of ACH values during the heating and cooling season, and the church open and closed hours.

Table 16- Sim\_00 Average ACH values vs Coelho et al.

		Coelho et al. [78]	Sim_00
<b>Cooling season</b>	<b>Open</b>		0.44
	<b>Closed</b>		0.04
	<b>All-season</b>		0.13
<b>Heating season</b>	<b>Open</b>		0.51
	<b>Closed</b>		0.07
	<b>All-season</b>		0.17
<b>1 year</b>	<b>Open</b>	0.70	0.47
	<b>Closed</b>	0.28	0.05
	<b>All year</b>	0.34	0.15

The bigger airflow rates, shown in Figure 36 and Figure 37, occur in the Summer and Winter time. This can be explained by two reasons.

In the Summertime, in Lisbon, the average wind speed is greater than throughout the rest of the year, and as such, the pressure difference in the pathways is increased. During the Winter, the temperature differential increases and so the temperature-driven ventilation.

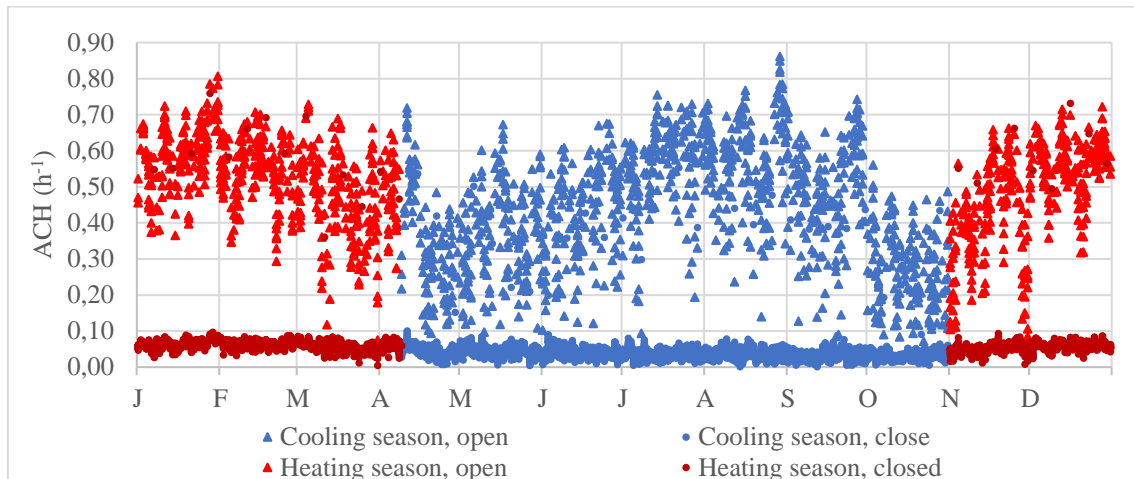


Figure 36 – Sim\_00 hourly ACH throughout 1 year, considering open and closed doors intervals

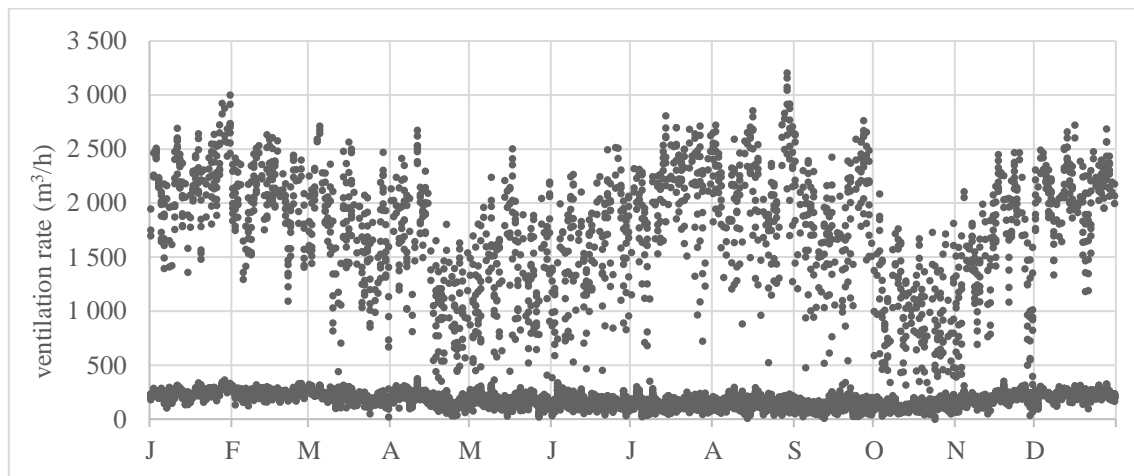


Figure 37- Sim\_00 hourly ventilation rates in  $m^3/h$

Throughout April, May and June, lower ventilation rates were identified. This is justified by an increase in exterior temperature, getting closer to the indoor temperature.

October is the month where the lowest ACH values are recorded. A combination of low windspeeds and similar inside and outside temperatures are responsible for lower fresh air exchange as the volume in the analysis is subjected to a constant 20 C°.

Considering the first three months of the year, by a quick study of Table 17, it is possible to assess that given the similar wind speed in this time frame, the ACH variations visible in Figure 38 and Figure 39 are caused by the increase of the exterior temperature.

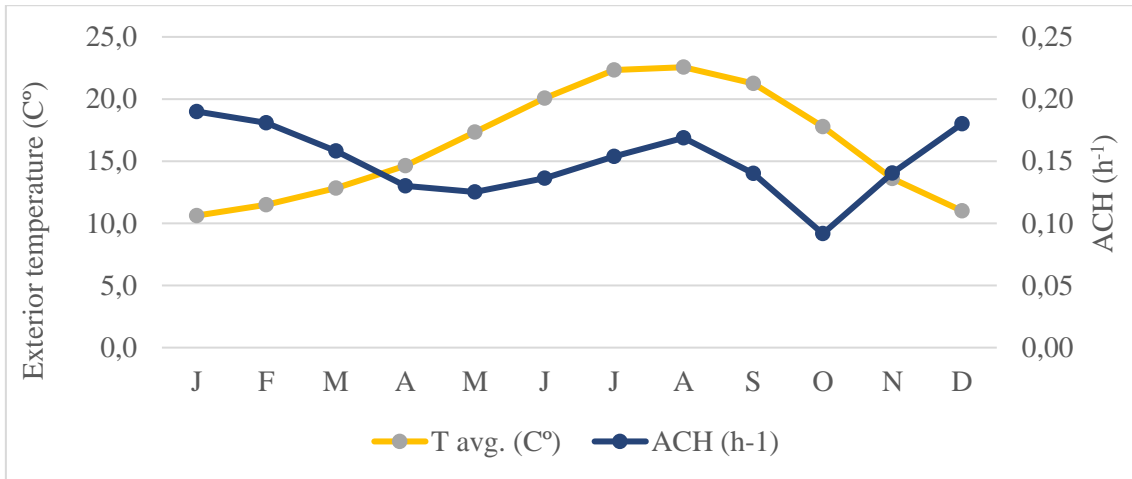


Figure 38- Exterior temperature monthly average vs ACH monthly average

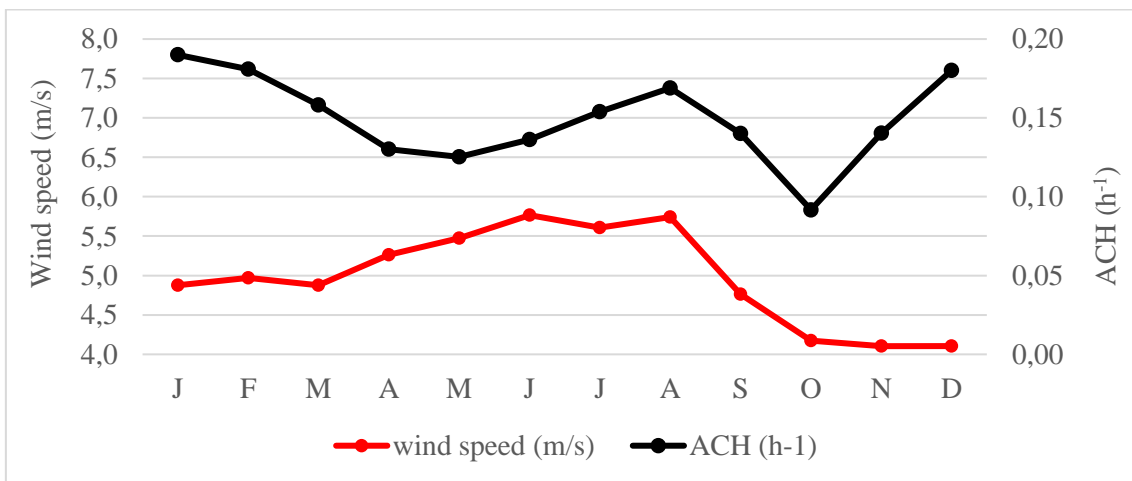


Figure 39- Wind speed monthly average vs ACH monthly average

Table 17- Average temperature, and wind speed by month

Month	T avg. (C°)	Stdev. (C°)	wind speed (m/s)
Jan	10.6	2.6	4.9
Feb	11.5	2.7	5.0
Mar	12.8	3.2	4.9
Apr	14.6	3.8	5.3
May	17.3	4.6	5.5
Jun	20.1	4.6	5.8
Jul	22.3	5.1	5.6
Aug	22.6	5.1	5.7
Sep	21.3	4.6	4.8
Oct	17.8	3.2	4.2
Nov	13.6	2.7	4.1
Dec	11.0	2.4	4.1

To better defend the choices done to refine the model, some information should be presented. According to Mleczkowska et al.[73] the RPH for a closed brick church in Tarnow, Poland, is situated between  $0.12\text{--}0.8\text{ h}^{-1}$  and according to Schellen [75], a church with stone vaults registered  $0.08$  to  $0.12\text{ h}^{-1}$ . Coelho et al. [78] estimated a mean ACH ranging  $0.28\text{--}0.7\text{h}^{-1}$  and averaging  $0.32\text{ h}^{-1}$  for the São Cristóvão's Church.

Although the measurements are taken by Coelho et al. [78] only reflect 3 days, the sensitivity study subsequently conducted showed the accuracy of the ACH estimation and therefore, the information extracted from AIVC- guide 5 and utilized in the first simulation to define the pathways parameters must be corrected as the church windows and doors are in very poor condition and broken windows can be seen around the church. The degradation of these elements cannot be taken lightly when a ventilation analysis is being conducted as they may reveal themselves highly influential in the results obtained.

With the results presented in mind, some conclusions can be reached:

1. The ACH during the closed doors hours is significantly inferior to that estimated by Coelho et al. [78] ( $0.05$  to  $0.28$ ).
2. The ACH during the open doors hours is around  $1/2$  of what Coelho et al. [78] estimated ( $0.47$  to  $0.7$ ).

These differences can be justified by several reasons. Considering the same volumes were applied in both cases, the main reason for the disparity in the results is the flow path parameters used in the simulation.

A blower door test should have been able to provide some accurate information regarding the leakage characteristics of certain doors and windows. Such test did not occur and therefore, the effective leakage area of windows and doors was boosted from the original AIVC- guide 5 values until a more accurate representation was reached.

#### **4.1.2. Simulation 01**

For a second simulation, the following parameter was applied:

- AIVC- guide 5 values of ELA were boosted by a factor of 2, reflecting the degradation of the pathways (Table 18).
- The main door was set to open according to the Table 12 church schedule and all other doors and windows remain closed.
- Mass attendees were set to 40 persons and a uniform distribution of 5 visitors per hour when the church is open.

This simulation will be referred from this point on as *sim\_01*.

Table 18- AIVC Guide 5: Equivalent leakage values factored by 2

AIVC-code	Description	ELA			discharge coefficient (Cd)	$\Delta Pa$
		cm2/item	cm2/m	cm2/m2		
CE_RAV	General ceiling - best estimate.	0	0	3.6	0,65	4
DRDBNW_RAV	Door, double, not weatherstripped	0	0	22	0.65	4
DRSINW_RAV	Door. single. not weatherstripped. best estimate	42	0	0	0.65	4
FRDRMAUC_RAV	Door frame. masonry. not caulked. best estimate	0	0	10	0.65	4
FRWNMAUC_RMX	Window framing. masonry. uncaulked. maximum	0	0	20.6	0.65	4
WNCASENW_RAV	Window. casement. not weatherstripped. best estimate	0	0.56	0	0.65	4
WNSISHWE_RMX	Single Hung windows: Window. single hung. weatherstripped. maximum	0	2.48	0	0.65	4

Comparing *Sim\_01* to *Sim\_00*, (Table 19) the ACH yearly average for the open doors period doubled and surpassed the value proposed by Coelho et al [78] of 0.7 by 0.05. The closed-door period, even dough greater than the previous simulation, still does not come close to 0.28, value that is also mentioned by Coelho et al.

Table 19- *Sim\_01* Average ACH values vs other simulations

		Coelho et al. [78]	<i>Sim_00</i>	<i>Sim_01</i>
<b>Cooling season</b>	<b>Open</b>		0.44	0.69
	<b>Closed</b>		0.04	0.09
	<b>All-season</b>		0.13	0.23
<b>Heating season</b>	<b>Open</b>		0.51	0.81
	<b>Closed</b>		0.07	0.13
	<b>All-season</b>		0.17	0.29
<b>1 year</b>	<b>Open</b>	0.70	0.47	0.75
	<b>Closed</b>	0.28	0.05	0.11
	<b>All year</b>	0.34	0.15	0.25

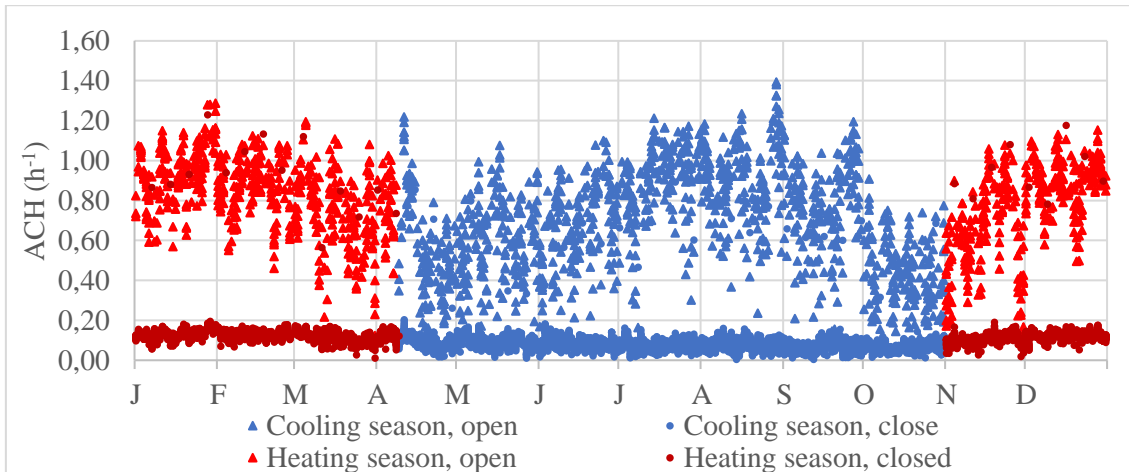


Figure 40- Sim\_01 hourly ACH throughout 1 year, considering open and closed doors intervals

Figure 41 is presented to simplify the conversion from ach (Figure 40) to  $m^3/h$ .

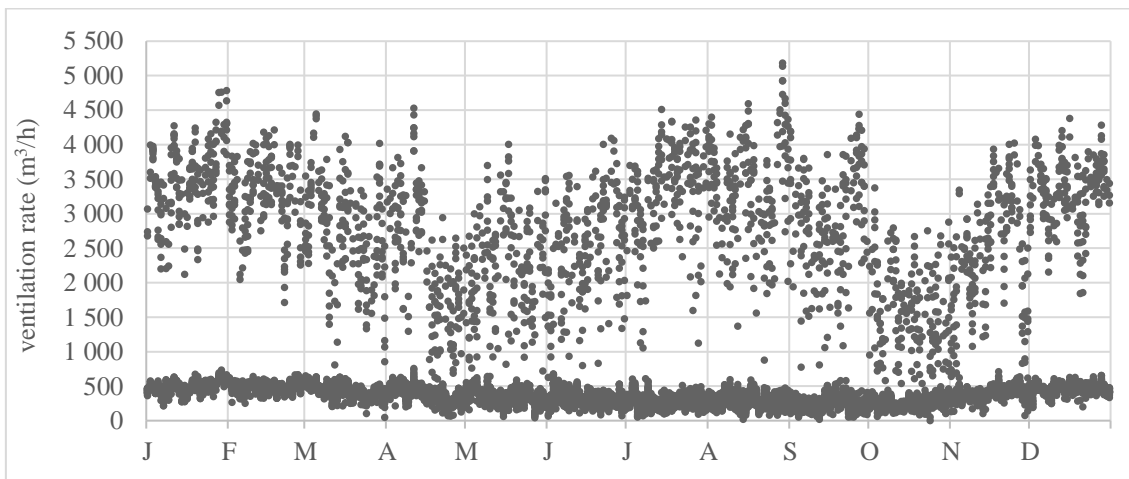


Figure 41- Sim\_01 hourly ventilation rates in  $m^3/h$

Given Sim\_01 results, a major conclusion was reached.

The ventilation rate attributed to the leakage of the model is lower than the proposed by Coelho et al. For the reason that during the closed-doors period doors and windows are closed, all air exchange between the interior and the exterior occurs due to the presence of cracks, fissures, imperfections, and gaps in the windows and doorframes. Even more, the broken windows are not yet employed in the model and they should be a factor with some weight in the entire building ACH.

#### 4.1.3. Simulation 02

If for the third iteration was to be applied an increase in the flow path's ELA and implemented the broken windows to augment the closed-door period ACH, both the open-door and closed-door period ACH would increase, and has portrayed in Table 19, this value is already acceptable. Another factor that dissuades the increase of flow path's ELA is the lack of a scientific base for such. The Sim\_01 ELA values are already doubled

from the average and some maximum recommended leakage areas. Consequently, Sim\_02 will have the following conditions:

- AIVC- guide 5 values of ELA were boosted by a factor of 1.5, reflecting the degradation of the pathways.
- The main door was set to open according to the Table 12 church schedule and all other doors and windows remain closed.
- Mass attendees were set to 40 persons and a uniform distribution of 5 visitors per hour when the church is open.
- Broken windows were implemented in the simulation by creating orifices with different dimensions. On the 3rd floor, 10 windows were considered broken and a one-way air flow path with  $0.01\text{m}^2$  was implemented per window.
- The main door size was reduced by 10%. This measure was implemented to combat the drastic increase of open-doors period ACH that would result.

These latest results, seen in Table 20, show the efficacy of implementing the broken windows paths. The open-door period is acceptably close to that obtained by Coelho et al. and all year ACH average is also similar. The difference between the Sim\_02 close door ACH and Coelho et al. close door ACH can be justified by the different schedules used in both studies, weather database, among other factors. For the scope of this study, the values attained were deemed acceptable and in line with the consulted references. Therefore, Sim\_02 will reflect the actual ventilation state in São Cristóvão's church taken into account the unattainable variables that compose the simulation.

Table 20- Sim\_02 Average ACH values vs other simulations

		Coelho et al. [78]	Sim_00	Sim_01	Sim_02
<b>Cooling season</b>	<b>Open</b>		0,44	0.69	0.71
	<b>Close</b>		0.04	0.09	0.14
	<b>All-season</b>		0.13	0.23	0.27
<b>Heating season</b>	<b>Open</b>		0.51	0.81	0.81
	<b>Close</b>		0.07	0.13	0.18
	<b>All-season</b>		0.17	0.29	0.33
<b>1 year</b>	<b>Open</b>	0.70	0.47	0.75	0.75
	<b>Close</b>	0.28	0.05	0.11	0.15
	<b>All year</b>	0.34	0.15	0.25	0.30

Figure 42 and Figure 43 represent the hourly ach throughout the year.

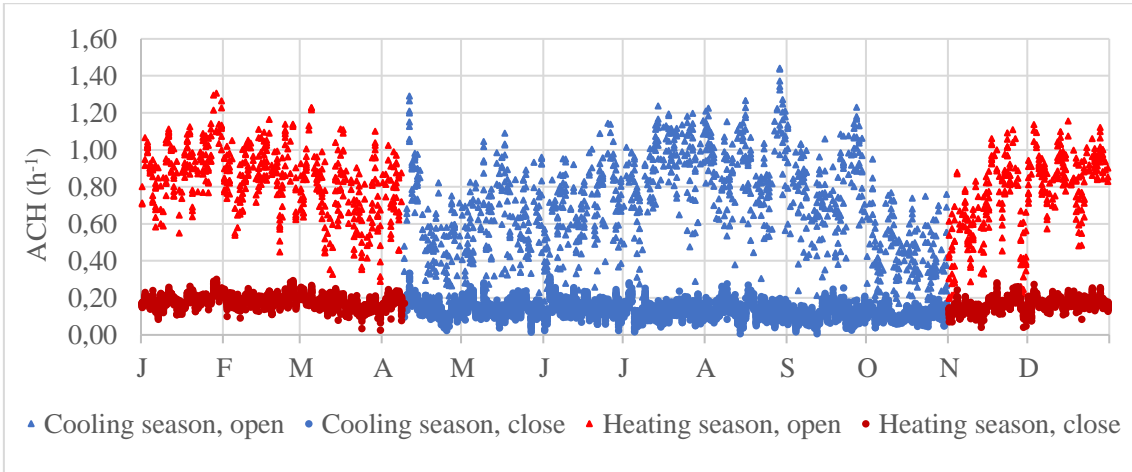


Figure 42- Sim\_02 hourly ACH throughout 1 year, considering open and closed doors intervals

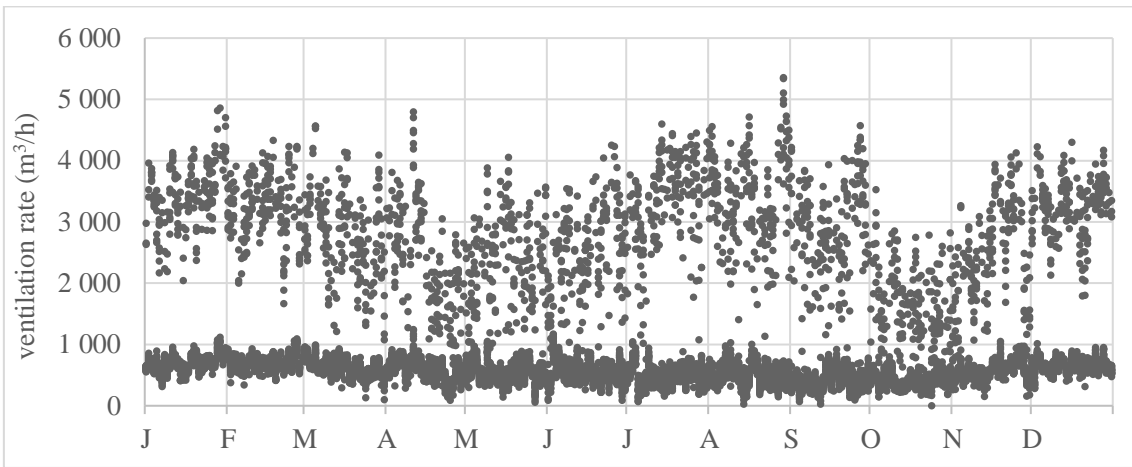


Figure 43- Sim\_02 hourly ventilation rates in  $\text{m}^3/\text{h}$

## 4.2. Ventilation strategies

As stated in the previous sub-chapter, this section will firstly explain the conditions and assumptions chosen and implemented in the simulations followed by an in-depth analysis based on the most used standards, EN15251, EN 13779, CIBSE-Guide A and ASHRAE 61.2. Finally, a comparison between the different standards for each simulation will be produced as well as an evaluation of the different ventilation strategies.

Three ventilation strategies were implemented in the *software* and examined.

- *Sim\_1* reproduces the scenario in which the church is closed, and no visitors are admitted. For this simulation, some standards and guidelines are not applicable since fresh air intake is directly linked to the number of the space/compartment users. Because the church was closed during its renovation works and again during the Covid-19 pandemic, some information about the ventilation status throughout these periods can be useful for future analysis of extended closed-doors periods and their impact on the São Cristóvão church's art body.

- *Sim\_2* reflects the opening of the bell tower's top floor hatch and access doors on the main floor of the church during the Spring and Autumn season. This strategy aims to take advantage of the chimney effect created by the two towers. Such approach is hardly accomplished due to rain entering the bell towers, possibly damaging the wall, and unreliable human factors. It is unlikely to expect the church priest to climb up and down the stair that gives access to the bells every time the hatches need to be open or closed. Even so, this simulation can gauge the influence of the stack effect on the overall ACH.

- *Sim\_3* is the easier strategy to implement. Taking advantage of cross ventilation combined with stack effect, some windows and doors will be opened on opposite sides of the building. Two simulations were conducted in order to test different options being *Sim\_3.1* and *Sim\_3.2*.

- *Sim\_4* will represent the increase of tourism that is estimated by the Portuguese Government in the "Tourism Strategy 2027" report [113]. With a 6.1% annual increase of tourists in Lisbon, it is speculated that by 2027 the São Cristóvão's Church will be occupied uniformly by 10 visitors per hour and mass attendees will reach 70. Although the increase in tourism does not directly apply to mass service attendees, for the purpose of this document it will be considered as a high number of occupants is a relevant analysis.

For all cases, the building polluting level was set to very low polluting as prescribed in EN 15251.

Although in sub-chapter 4.1 the main distinction of the year was made between heating and cooling season, major differences can be found when smaller time frames are used. For this reason, the seasons (Winter, Spring, Summer, and Autumn) are applied when further detail is needed to analyze average values and time-sensitive fluctuation.

Three different times of the day were examined as the number of people inside the church oscillate. The first church attendance status reflects the period when the church is open, but no mass service is being conducted, called *visitation*. The second attendance status occurs when the mass service is happening, called *mass*. The third and final attendance status occurs when the church is closed, called *closed*.

### 4.2.1. Ventilation strategies: Sim\_02

Sim\_02, although briefly discussed in Chapter 4.1.3, will be further examined to establish the base condition for future comparisons.

#### 4.2.1.1. Sim\_02: General information

For this simulation, the main church door, as well as the doors that connect the nave and mortuary house, are open during the visitation and mass attendance status, marked in the shaded areas of Figure 44. The shaded area with dotted lines in the same picture marks the door connecting the nave to the sacristy that is opened when mass begins and closed once it's finished. All windows are closed for the entirety of the simulation.

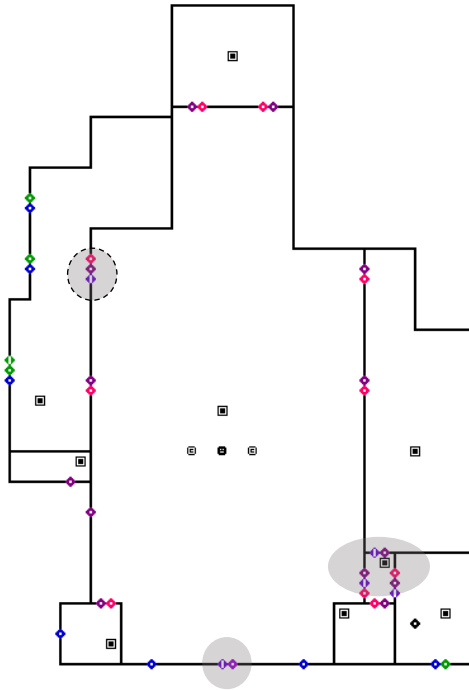


Figure 44- Sim\_02: floor 1 open/closed spans schematic

Monthly average ACH values fluctuate throughout the year (Figure 45 and Figure 46) with the highest values recorded during peak Summer and Winter, reaching 0.36 and 0.33 respectively. During Spring and Autumn, these values drop to 0.27 and 0.19 respectively.

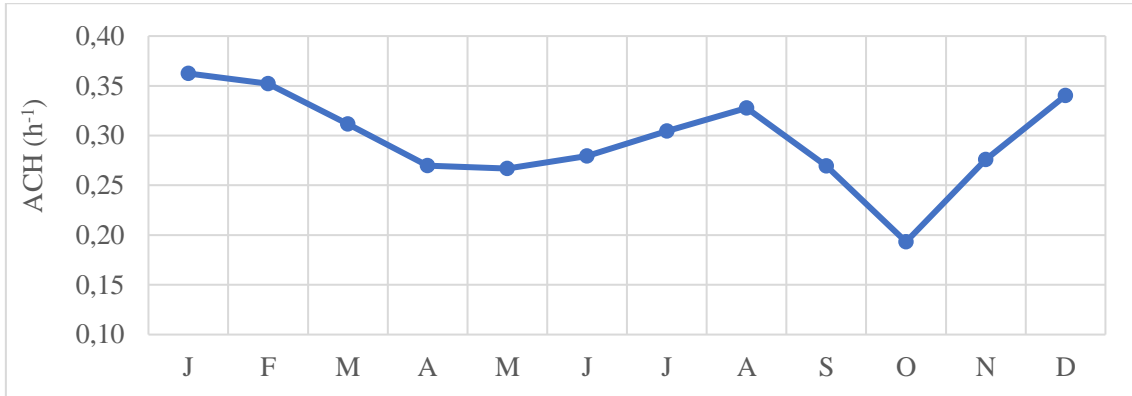


Figure 45- Sim\_02: Monthly average ACH

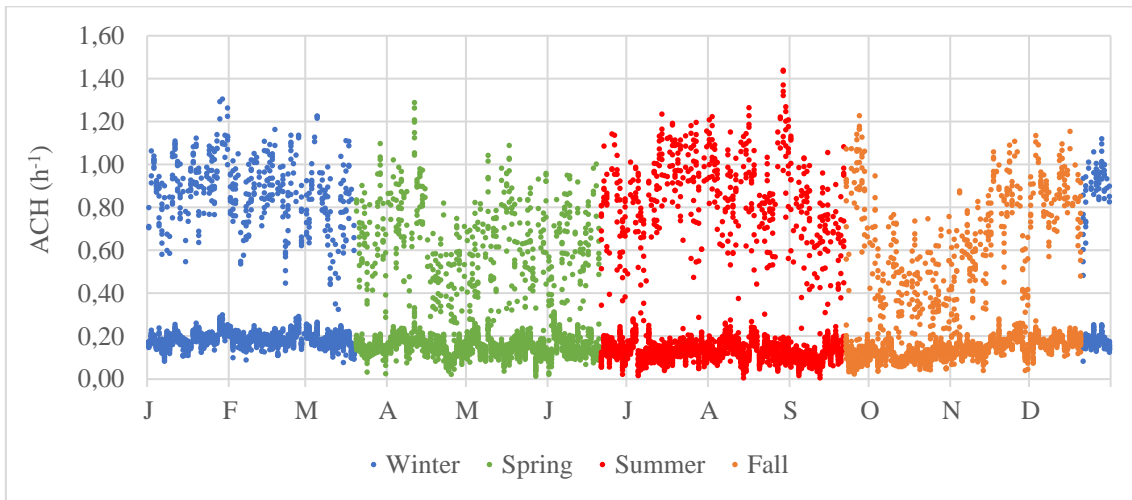


Figure 46- Sim\_02: ACH values for each season throughout the year

The ACH yearly average in São Cristóvão’s church is 0.30 and the seasonal ventilation rates can be consulted in Table 21.

Table 21- Sim\_02: ACH values for each season and church attendance status throughout the year

Church attendance status	Season				All year
	Winter	Spring	Summer	Autumn	
visitation period	0.87	0.63	0.87	0.64	0.75
mass period	0.93	0.64	0.68	0.70	0.74
closed period	0.19	0.16	0.13	0.14	0.15

Note worth, an visible in Figure 47, is the fact that during Winter, as the door connecting the sacristy and nave is open for the mass service, combined with the highest inside/outside temperature difference, ventilation rates are the highest recorded, reaching 0.87 ach. During Summer, although the doors and windows have the same schedule as through the Wintertime, due to the low  $\Delta T$  registered upon the mass period, ventilation rates drop to 0.68 ach.

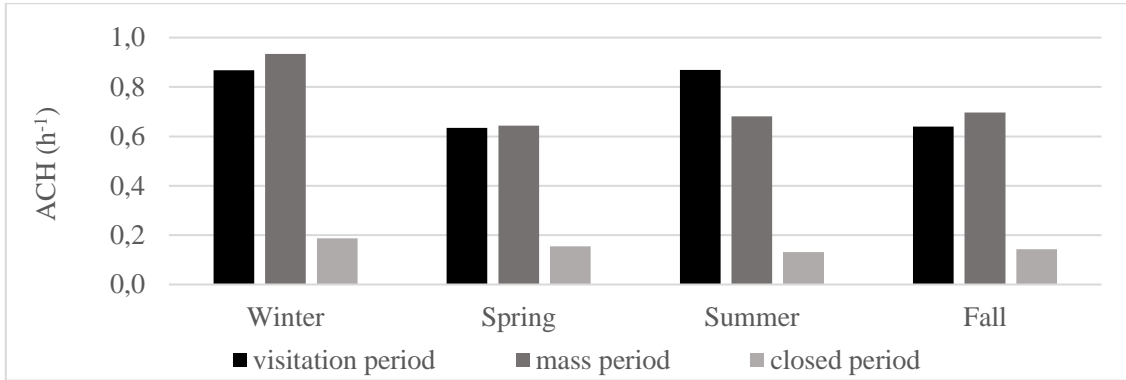


Figure 47- Sim\_02: Average ACH and standard deviation values for each church attendance status by season

#### 4.2.1.2. Sim\_02: EN 15251

Being one of the main objectives of this document, a comparison to EN15251 prescribed ventilation rates was conducted for the three different church attendance status.

Because EN 15251's prescribed fresh air rates factors in the analyzed compartment area and the number of occupants, once the mass period is over, the occupant's part of the equation drastically diminishes. The recommended airflow rates for each category drop circa 2/3 when moving from the mass attendance status to visitation attendance status and circa 3/4 when moving from the mass attendance status to closed attendance status. This can be seen in Figure 48 and Table 22.

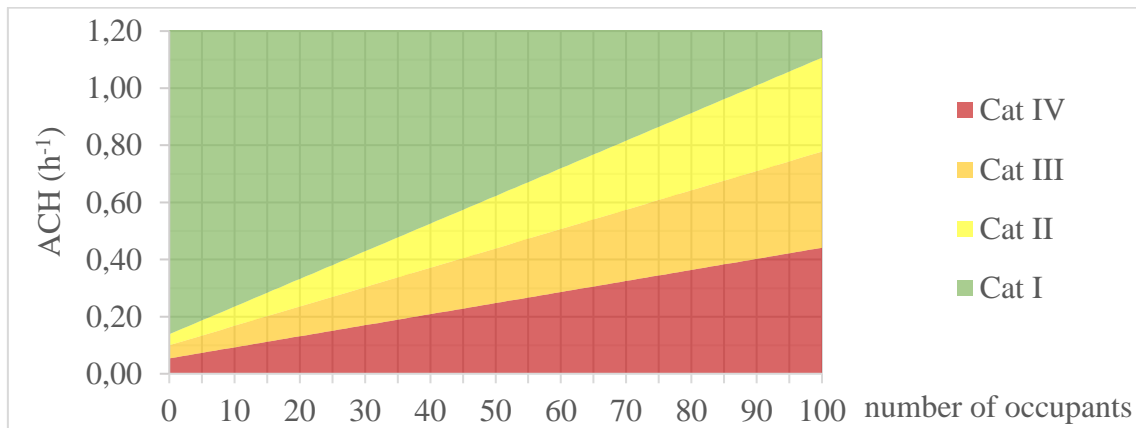


Figure 48- EN 15251 prescribed airflow rates for São Cristóvão's church by number of occupants

Table 22- Sim\_02: EN 15251 prescribed ACH rates for each attendance status

Category	Percentage of dissatisfied people [%]	Minimum church ACH needs		
		mass period	visitation period	Closed period
Category I	15	0.53	0.19	0.14
Category II	20	0.37	0.13	0.10
Category III	30	0.21	0.07	0.05
Category IV	>30	<0.21	<0.07	<0.05

From Figure 49 to Figure 52, the green shade area symbolizes the airflow that respects the prescribed airflow rates in category I of EN 15251 values, in yellow the category II, in orange the category III and finally, in red, the values that fall in category IV.

Throughout the mass period (Figure 49), 79% of the time is spent complying with the recommended ventilation rates of category I, 12% of time complying with category II and the remaining time inserted in category III and IV. For a non-controlled air supply building, the ACH is mostly acceptable and in some cases, too high from an art conservation standpoint. However, this thematic is not going to be discussed in this document.

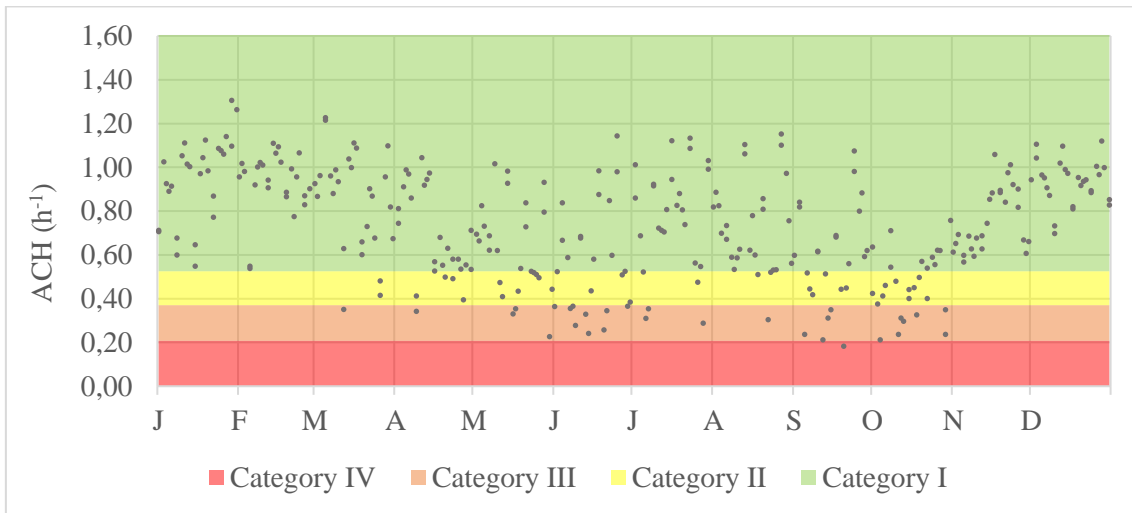


Figure 49- Sim\_02: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period

During the visitation period (Figure 50), 99% of the time is spent in category I as the number of occupants is relatively low (5) and the main door is open. Although no windows are open, the large size of the door in combination with the broken windows and general span leakage is capable of both supplying and extracting big amounts of air as visible in Figure 51.

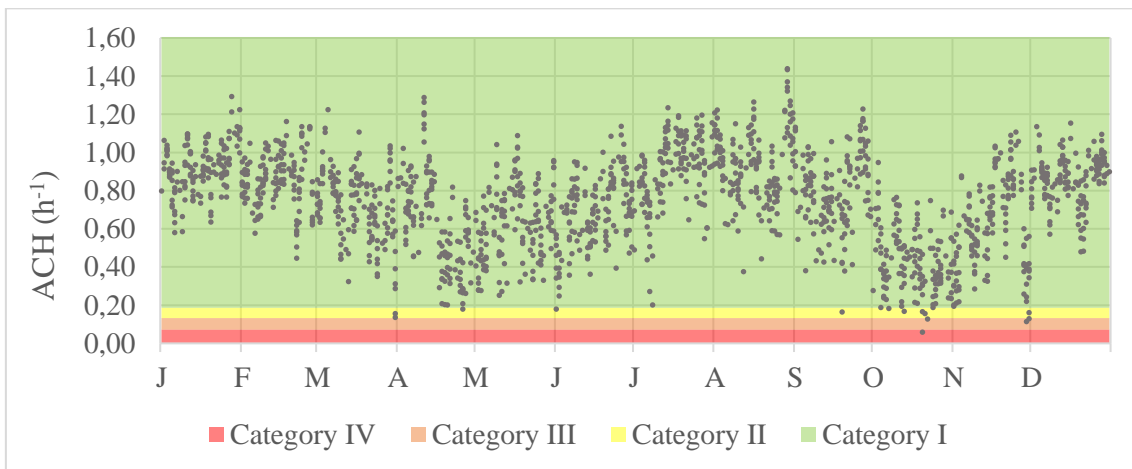


Figure 50- Sim\_02: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period

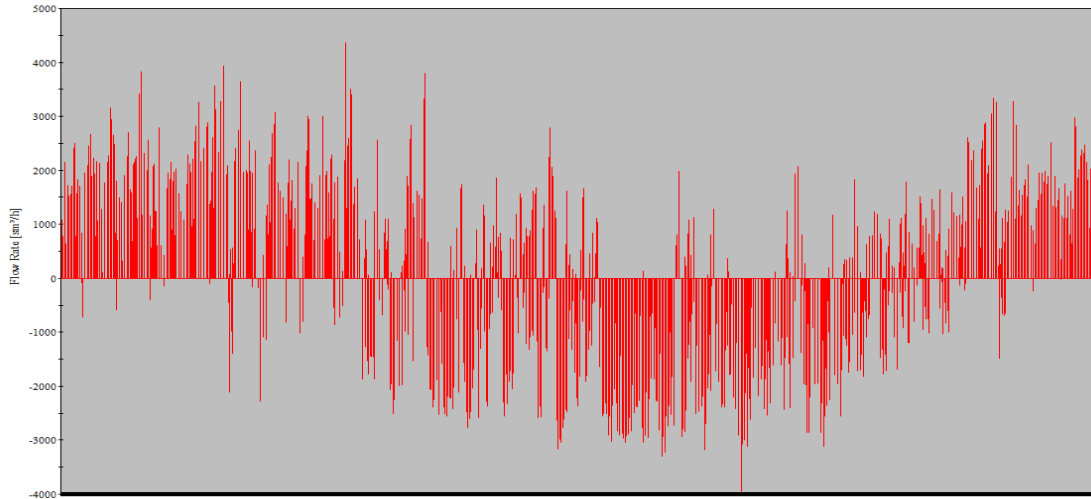


Figure 51- Sim\_02: Main door hourly airflow balance throughout the year

For the closed period, since no occupants are contemplated, only the area factor of the ventilation rate equation is considered. Although the prescribed ventilation rate for this time frame is circa 1/4 of the mass attendance status, because no windows or doors are open, all ventilation is generated by the envelope leakage leading to low ACH values.

According to the data examined and presented in Figure 52, 64% of the time spent in the closed attendance status was spent in category I and 23% in category II.

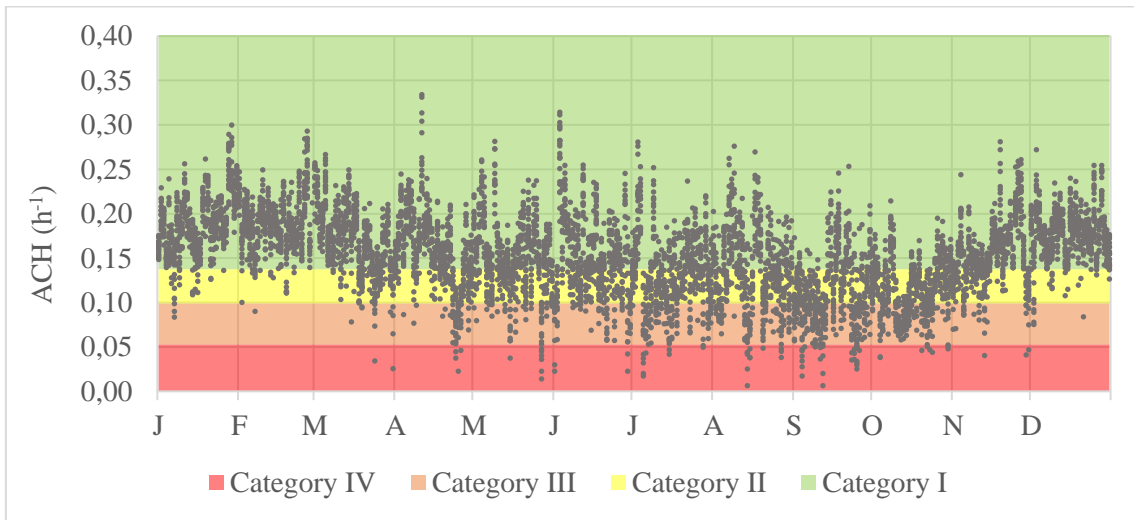


Figure 52- Sim\_02: ventilation rates vs EN 15251 hourly prescribed ventilation rates: closed period

For easier interpretation of the results, Table 23 and Figure 53 were made in order to summarize the information regarding EN 15251's ventilation rates and the amount of time spent in each category and attendance status.

Table 23- Sim\_02 EN 15251 Category based on ACH values

EN 15251 Category based on ACH values	number of hours in category			% of time spent in category per year			% of time spent in category per attendance status		
	visitation period	mass period	closed period	visitation period	mass period	closed period	visitation period	mass period	closed period
Category I	1754	247	4271	20.03%	2.82%	48.76%	99.2%	78.7%	64.0%
Category II	10	37	1557	0.11%	0.42%	17.78%	0.6%	11.8%	23.3%
Category III	3	29	768	0.03%	0.33%	8.77%	0.2%	9.2%	11.5%
Category IV	2	1	80	0.02%	0.01%	0.91%	0.1%	0.3%	1.2%
TOTAL	1769	314	6676	20.2%	3.6%	76.2%	100%	100%	100%

Given the low number of occupants (5 people) during the visitation period combined with a high amount of fresh air entering the main door, 99% of the time is spent in category I. Throughout the mass attendance status, 79% is spent in category I, 12% in category II and the remaining time spent in category III and IV.

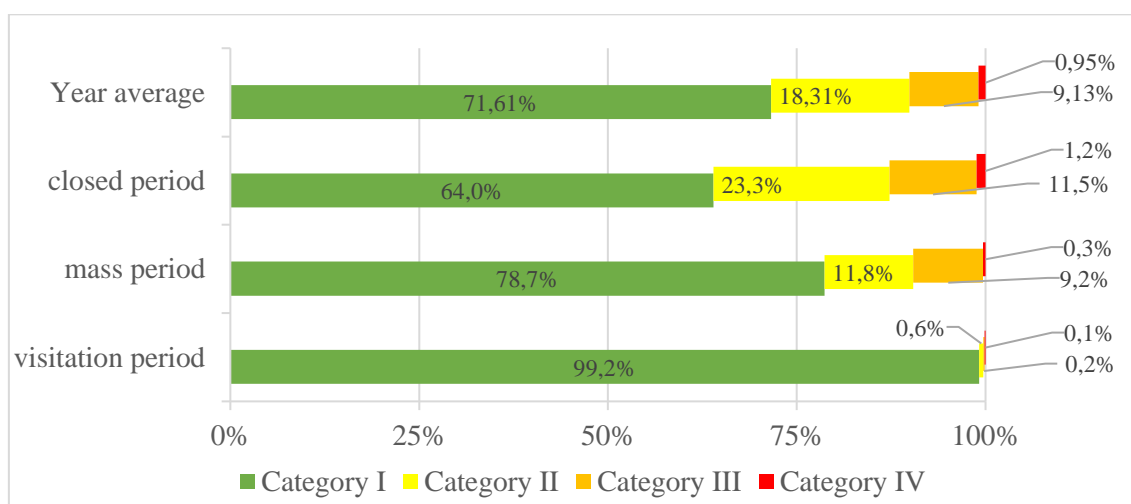


Figure 53- Sim\_02: Percentage of time spent in each EN 15251 category per church attendance status

#### 4.2.1.3. Sim\_02: EN 13779

EN 13779, which sets the CO<sub>2</sub> concentration limits and prescribes fresh air rates for smoking and non-smoking areas was applied to the model and the results evaluated. The standard offers two methods of attaining prescribed airflows, one for non-human occupancy compartments (air m<sup>3</sup>/h.m<sup>2</sup>) and one for expected human occupancy (m<sup>3</sup>/h.person). Since the latter will be used in the analyses, the closed period will not be looked upon as no occupants are expected to be in the church.

In Sim\_02, the church presents a good response in the renewal of used air and CO<sub>2</sub> concentrations never exceed the IDA 1 superior limit (Figure 54). Even during the months

in which ventilation is reduced, due to the small number of occupants considered, the contaminant considered never reaches 300ppm above outdoor concentration.

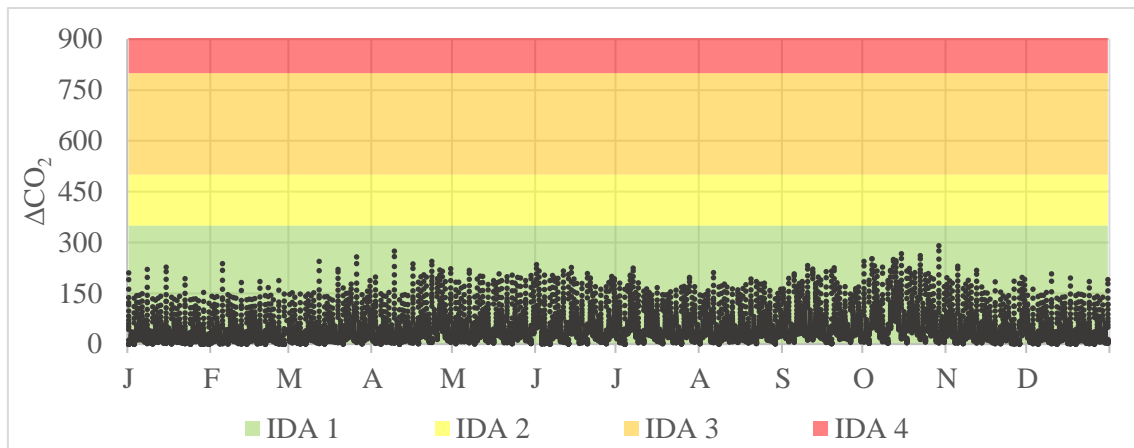


Figure 54- Sim\_02: CO<sub>2</sub> levels in São Cristóvão's main nave (units in ppm above outdoor concentration)

The most significant period in terms of CO<sub>2</sub> discharges is the mass attendance status as the most occupants are in the church.

Figure 55 shows one of the weeks in the simulation where the ACH was amongst the lowest values recorded and CO<sub>2</sub> measurements, on the other hand, the highest. The first spike in the same figure is relative to the Sunday mass where CO<sub>2</sub> values reach circa 240 ppm above the outdoor concentration. The amount of time between the end of Sunday mass and the next visitation period on Monday is sufficient to balance the in/outdoor carbon dioxide concentration. The same cannot be said for the remaining days of the week as the augment of the open hours and a constant flux of occupants raises CO<sub>2</sub> levels and the ventilation is not capable of restoring the balance during the close hours. This is due to the mass service being conducted at the end of the day, “trapping” the CO<sub>2</sub> particles inside the church, leaving the air renewal to ventilation by leakage.

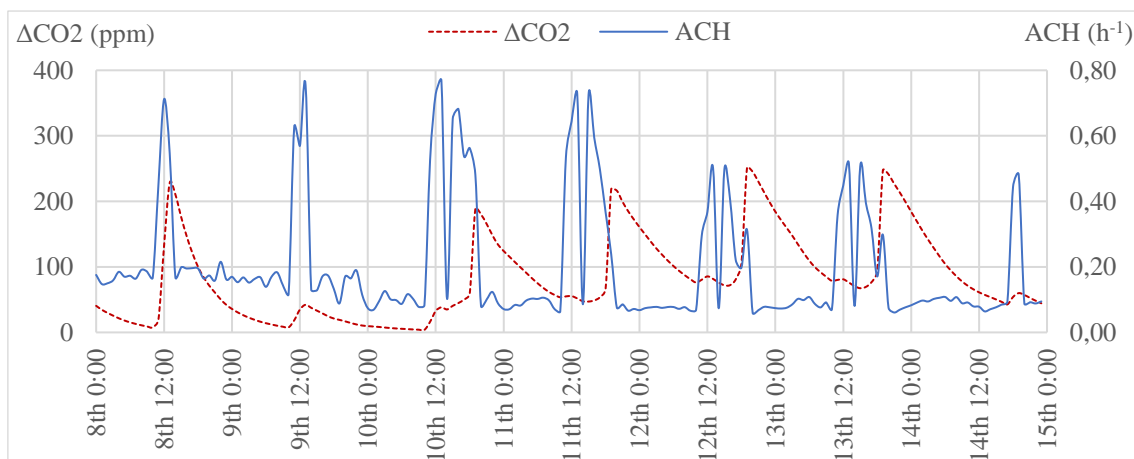


Figure 55- Sim\_02: CO<sub>2</sub> concentration levels and ACH values recorded in the church nave from October 08<sup>th</sup> to October 14<sup>th</sup>. The 8<sup>th</sup> of October represents a day type 1(Sunday)

For average day-type values of CO<sub>2</sub>, a season distinction was made to understand the implications of wind and temperature-induced ventilation throughout the week. The

combination of the higher temperature difference and higher wind speeds contribute to lower CO<sub>2</sub> concentrations during Winter as seen in Figure 56. Also, after Sunday mass, the rate of air renewal is higher compared to the other seasons. For the remaining of the year peak values, that are recorded at the end of mass service, are similar as for the ventilation capacity to substitute the used air.

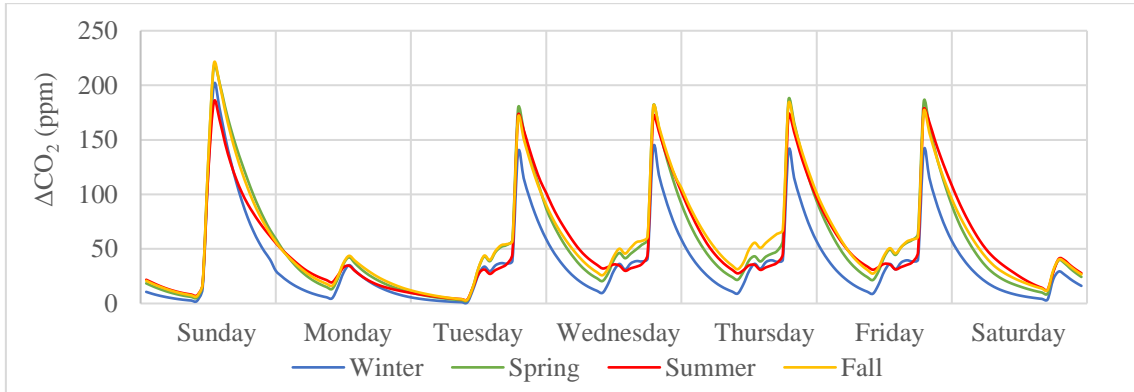


Figure 56- Sim\_02: CO<sub>2</sub> hourly average concentration levels by day of the week and season

Figure 57 shows the average hourly ach and CO<sub>2</sub> concentration per day type and season.

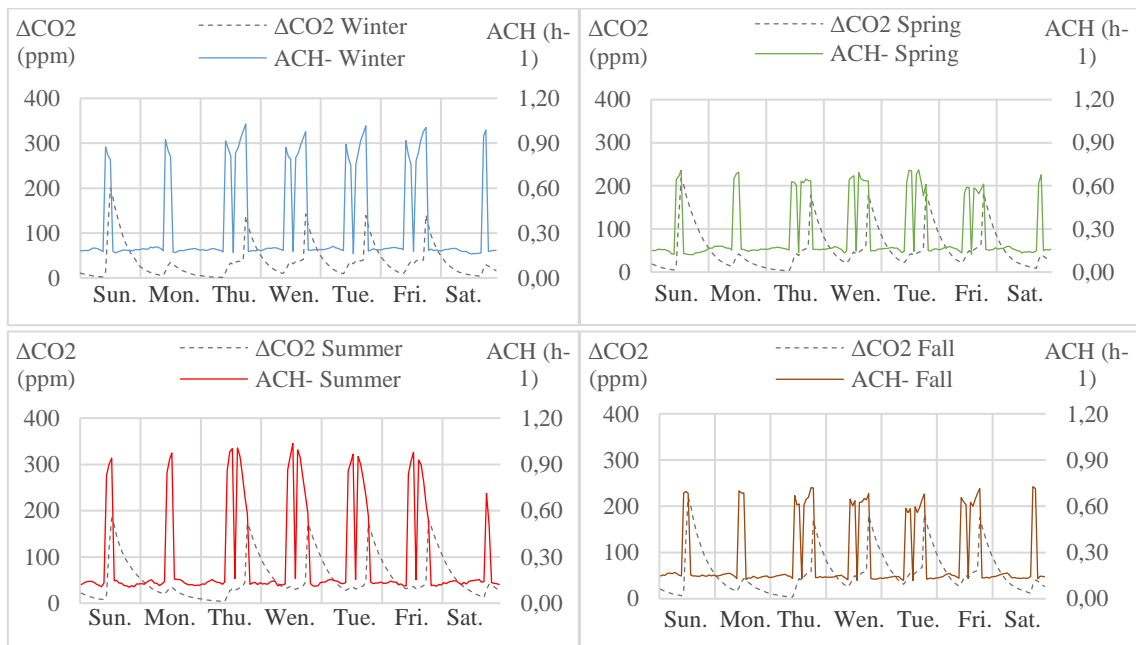


Figure 57- ΔCO<sub>2</sub> levels and ACH average per day of the week and by Season

Table 24 synthesize the amount of time in compliance with EN 13779 ventilation rates for each IDA category for the year that was simulated in *Contam*.

Table 24- Sim\_02: IDA Category based on CO2 levels and prescribed airflows verification

IDA Category	CO2 level above outdoor air (ppm-default value)	Airflow per person [m3/(h.person)]	% of time spent in IDA Category		% of time spent in IDA Category and respecting prescribed ACH values	
			visitation period	mass period	visitation period	mass period
IDA 1	350	72	100%	100%	100%	47%
IDA 2	500	45	0	0	-	-
IDA 3	800	29	0	0	-	-
IDA 4	1200	18	0	0	-	-

#### 4.2.1.4. Sim\_02: ASHRAE 62.1

Ashrae 62.1 although having the same methodology as EN 15251 when it comes to determining airflow rates, conjugating an area related ventilation and an occupancy related rate, the main difference lays in the notion that ASHRAE 62.1 only divides IAQ into 2 categories, acceptable and not acceptable, giving rise to a binary analysis. ASHRAE's prescribed values applied to this case can be seen in Table 25

Table 25- ASHRAE 62.1 Recommended airflow rates

Compartment type	r <sub>p</sub> - Airflow per person [m3/(h.person)]	r <sub>a</sub> - Airflow per floor area [m3/(h.m2)]	church airflow needs (ACH)		
			visitation period	mass period	closed period
museums	13.7	1.08	0.102	0.230	
churches	9	1.08	0.095	0.180	0.083

Because the church in question hosts several pieces of art that are on display, and given the superior prescribed airflow rates, a decision was made to consider the São Cristóvão's church as a museum for this study.

Throughout the visitation attendance status (Figure 58), flow rates are satisfying, not respecting the target 1 time.

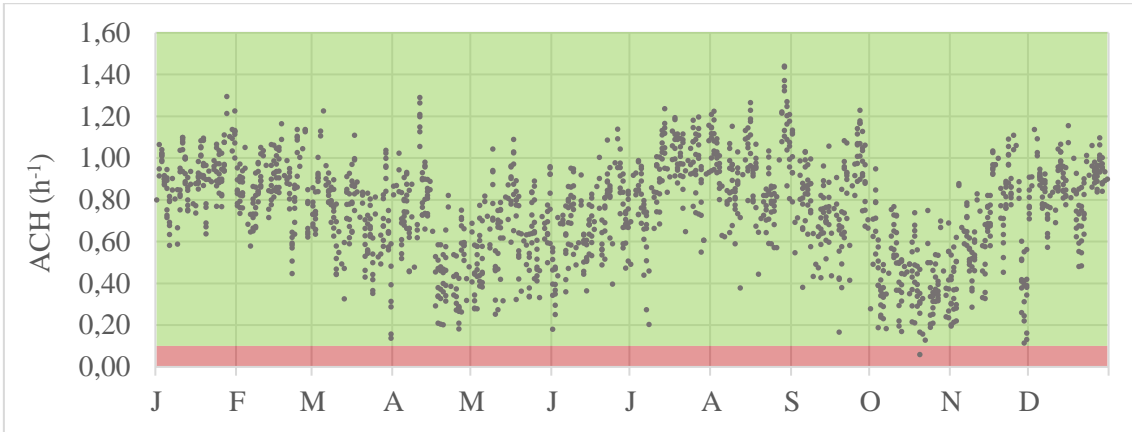


Figure 58- Sim\_02: ASHRAE 62.1 prescribed ACH for visitation attendance status

As seen on EN 15251 analysis for the mass attendance status (Figure 59), the lower values are registered during late Spring and early Autumn. However, the binomial IAQ system leads to an increase in the percentage of time respecting prescribed ventilation rates, only dipping below the threshold 6 times.

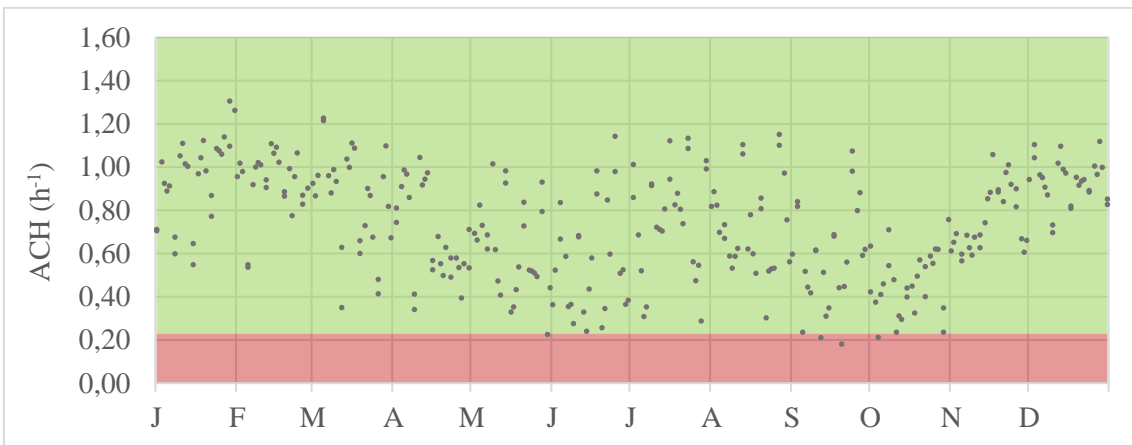


Figure 59- Sim\_02: Ashrae 62.1 prescribed ACH for mass attendance status

The ACH for 7% of the time spent under the closed attendance status did not reach the acceptable threshold, as seen in Figure 60.

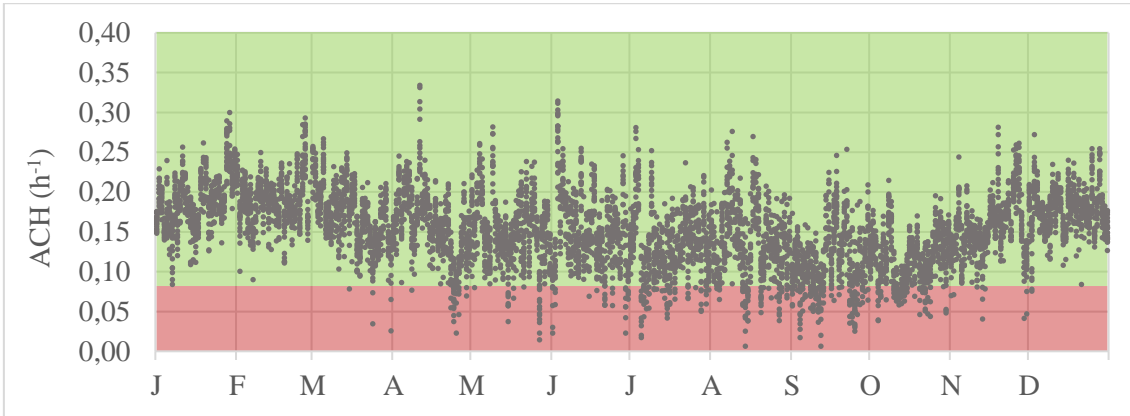


Figure 60- Sim\_02: Ashrae 62.1 prescribed ACH for closed attendance status

Table 26 presents the percentage of time complying with recommended ventilation rates for each visitation status.

Table 26- Sim\_02: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status

attendance status	Number of hours in accordance with airflow prescribed values	% of time respecting prescribed ACH values per year	% of time respecting prescribed ACH values per attendance status
visitation period	1767	20.2%	100%
mass period	310	3.5%	99%
closed period	6242	71.3%	93%

#### 4.2.1.5. Sim\_02: CIBSE Guide A

Cibse guide A establishes for the church particular case a  $0.05h^{-1}$  and  $0.39h^{-1}$  for the visitation (Figure 61) and mass attendance status (Figure 62), respectively. No analysis will be made for the closed period as no occupants are meant to be in the studied compartment.

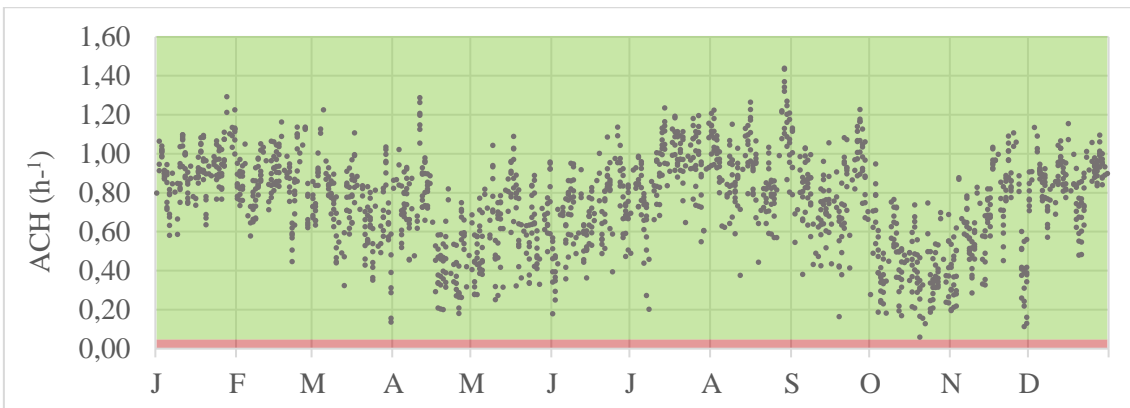


Figure 61- Sim\_02: CIBSE guide A prescribed ACH for visitation attendance status

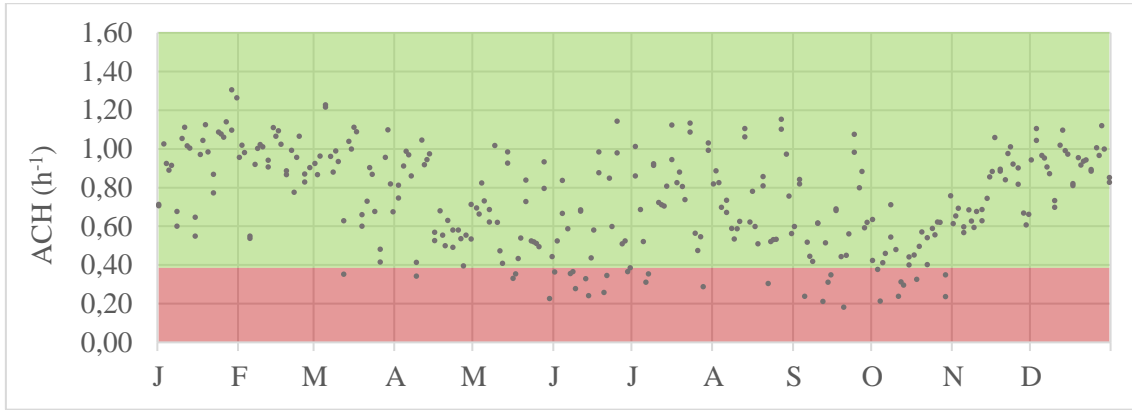


Figure 62- Sim\_02: CIBSE guide A prescribed ACH for mass attendance status

Information gathered from Figure 62 and presented in Table 27 shows the 10% of the time ventilation rates are inferior to the recommended ones, for the mass attendance status.

Table 27- Sim\_02: Percentage of time respecting CIBSE Guide A prescribed ventilation rates

Building/room type:	Number of hours in accordance with airflow prescribed values		% of time spent complying with recommended air rates per attendance status	
	visitation period	mass period	visitation period	mass period
Churches/Museums and art galleries	1768	282	100%	90%

## 4.2.2. Ventilation strategies: Sim\_1

### 4.2.2.1. Sim\_1: General information

As mentioned previously, Sim\_1 represents the situation where the church is closed all year. For the purpose of this document, comparing this simulation with others may not be relevant as the main focus is to study different ventilation strategies. However, given the Covid-19 pandemic and the ramifications of the restrictions imposed on churches and museums, it may be relevant to future works that may study the impact of closing spaces to the public that don't have climatization systems.

Because EN 13779 and Cibse Guide A applicable ventilation rates are based on the number of occupants, for this simulation these standards will not be mentioned.

Predictably, monthly average ACH values, showed in Figure 64, are low compared to Sim\_02 logging a maximum of 0.19 in the Winter season during January and February. constantly decreasing until the minimum of 0.11 in October. During November and December, ACH values augment until reaching the January values.

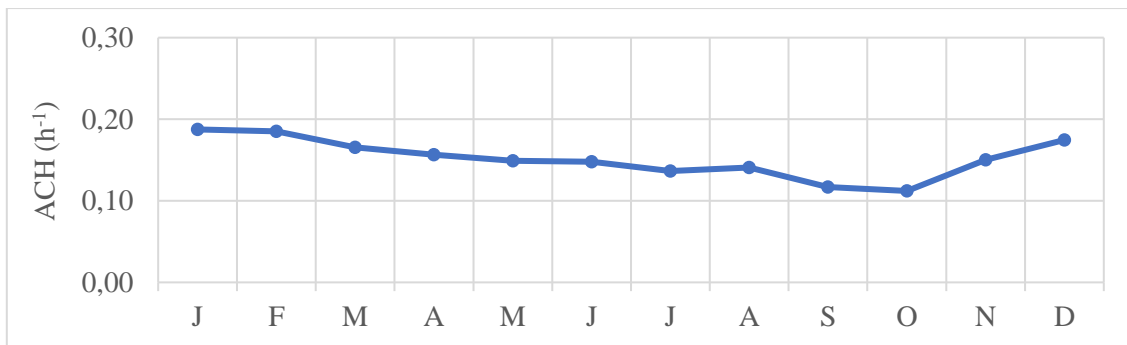


Figure 63- Sim\_1: Monthly average ACH

Figure 64 shows the recorder ach through the simulated year. The highest value happens on April 11<sup>th</sup>.

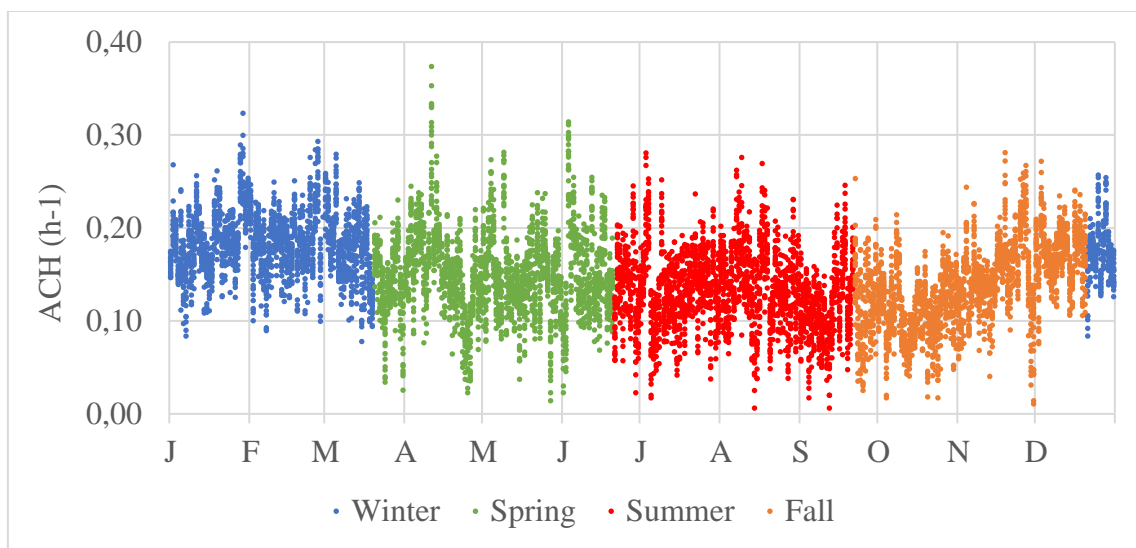


Figure 64- Sim\_1: ACH values for each season throughout the year

The variations in ventilation rates are due to the building leakage and an average of 0.15 ach was recorded with a standard deviation of 0.05.

Table 28 shows the average ach values per season.

Table 28- Sim\_1: Average ACH values by season

Church attendance status	Season			
	Winter	Spring	Summer	Autumn
closed period	0.18	0.15	0.13	0.14

#### 4.2.2.2. Sim\_1: EN 15251

Affecting EN 15251 to the present simulation, only the closed attendance status is relevant to examine. The prescribed airflow rate (Table 29) for the entire year is static due to the constant visitor number “0” and although the standard categories are based on the percentage of satisfied people, only the ach values prescribed will be acknowledged for this simulation.

Table 29- Sim\_1: EN 15251 prescribed ACH rates

Category	Minimum church ACH needs
	Closed period
Category I	>0.14
Category II	0.10
Category III	0.05
Category IV	<0.05

Present in Figure 65 and summarized in Figure 66 are the ACH value variation throughout the year and the percentage of time spent in each category.

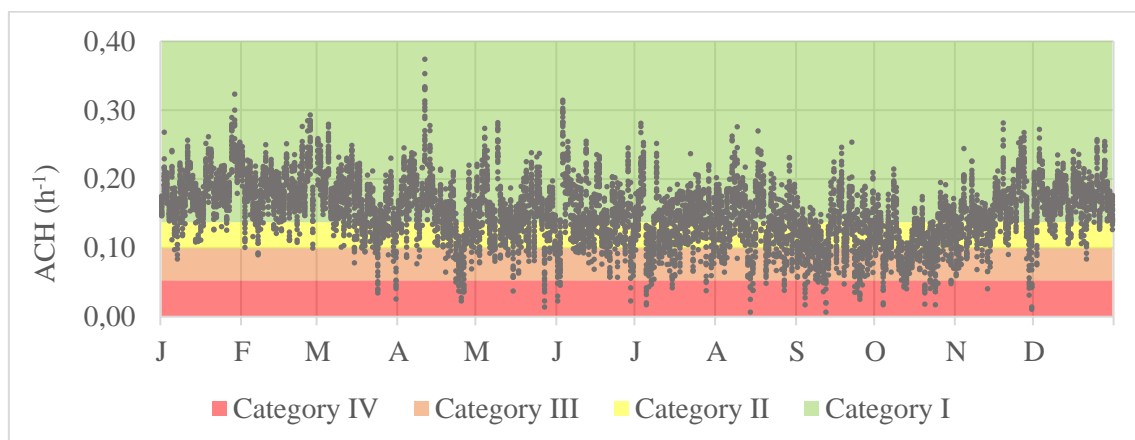


Figure 65- Sim\_1: ventilation rates vs EN 15251 hourly prescribed ventilation rates

According to the simulation results, 85% of the time, the IAQ falls in category I and II and 15% in category III and IV, as displayed in Figure 66.

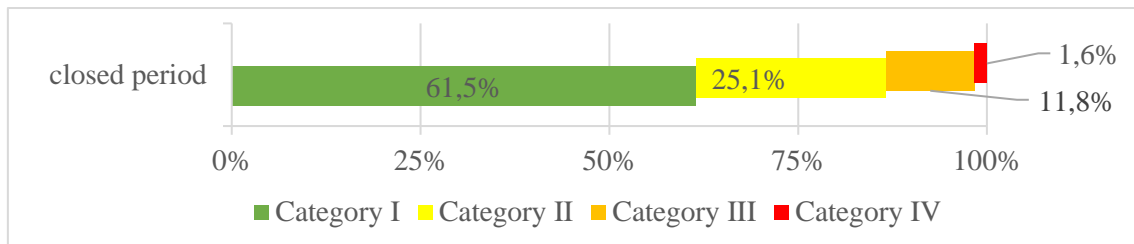


Figure 66- Sim\_1: Percentage of time spent in each EN 15251

#### 4.2.2.2. Sim\_1: ASHRAE 62.1

When analyzing the results through the ASHRAE 62.1 lens, only the area factor of the prescribed airflow equation is present in this case, as no occupants are accounted for.

Due to the laxer restrictions of this standard compared with its European counterparts, ventilation rates and therefore IAQ is deemed acceptable circa 93% of the time. This can be seen in Figure 67 and in Table 30.

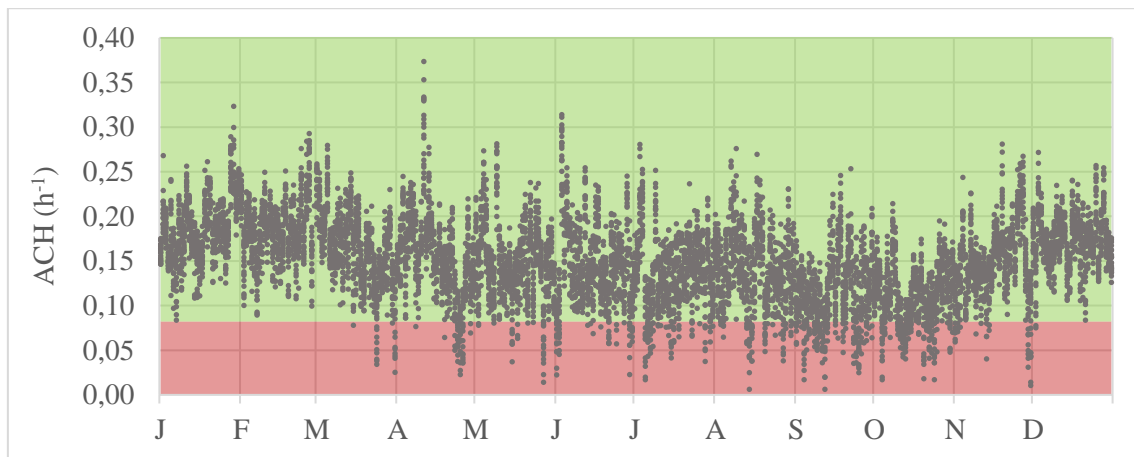


Figure 67- Sim\_1: ASHRAE 62.1 prescribed ACH for visitation attendance status

Table 30- Sim\_1: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates

Compartment type	Church airflow needs ACH (h <sup>-1</sup> )	Number of hours in accordance with airflow prescribed values	% of time respecting prescribed ACH values per year
museums	0,083	8138	92.9%

### 4.2.3. Ventilation strategies: Sim\_2

#### 4.2.3.1. General information

In *sim\_2*, throughout Spring and Autumn, where the lowest ACH values were recorded in previously presented simulations, the bell tower's upper hatch, two 0.25m<sup>2</sup> holes, and 1<sup>st</sup>-floor access doors were set to open during the time when the church is open for visitation and mass service.

The shaded and dotted-line areas in Figure 68 symbolizes spans that are open during the mass service and the shaded areas represent doors that are open throughout the church open hours schedule. Throughout the visitation attendance status, the same conditions of *Sim\_02* were applied to all other spans.

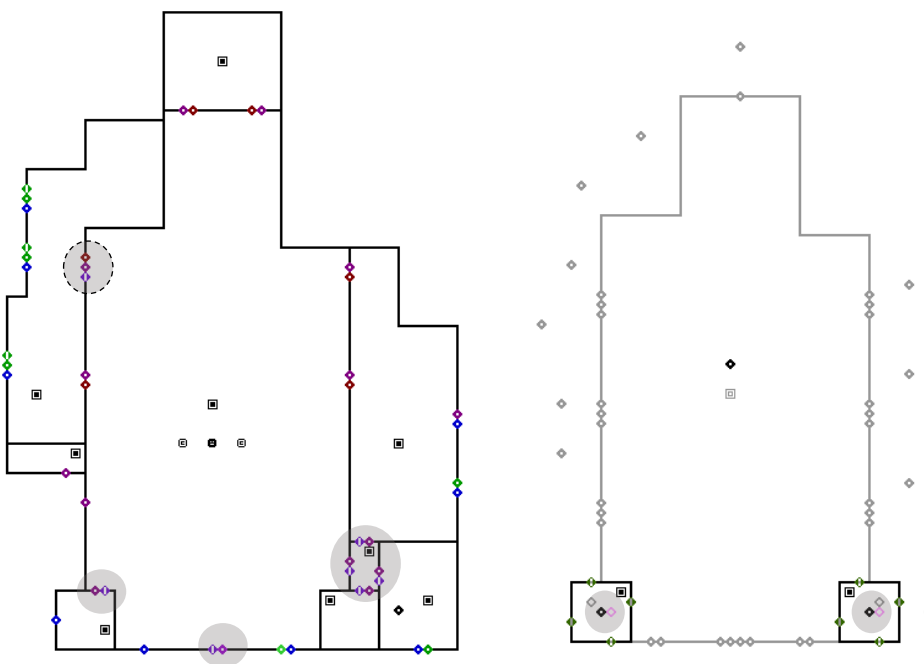


Figure 68 *Sim\_2*: 1<sup>st</sup> floor and 4<sup>th</sup> floor open span schematic (light grey walls and airflow paths represent the floor below)

As mentioned in sub-chapter 4.2, this particular ventilation strategy has some practical issues. Any strategy that depends on human intervention to open or close airflow paths has a higher probability of success and even higher probability when the activity is physically taxing, as the daily climb of the bell towers are. Even more, the fact that the activation of this strategy is seasonal can be difficult to implement. However, for the academic purpose of this document, it is an interesting option to study.

The opening of the bell towers hatches and access doors increase significantly the average monthly ach values during Spring and Autumn (Figure 69). Wind induce ventilation is the most influential mean of air replacement inside the church during these seasons due to the negative pressure that is present immediately on top of the hatches. This strategy is highly dependent on wind speeds due to the low temperature differences recorded.

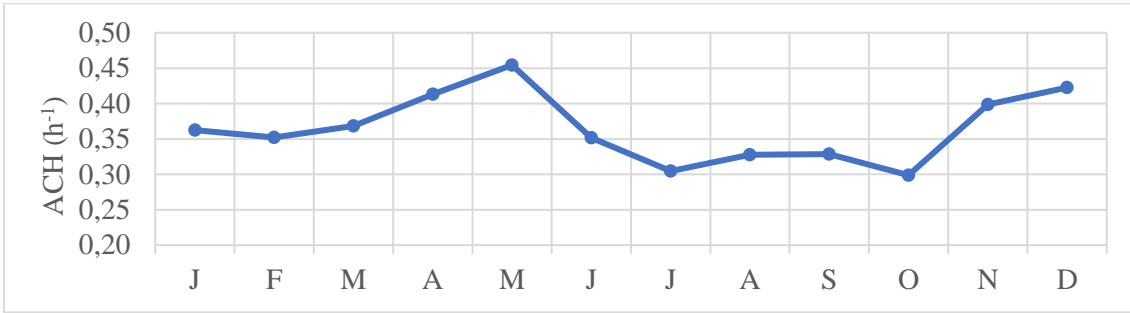


Figure 69- Sim\_2: Monthly average ACH

As visible in Figure 70 and consultable in Table 31, ventilation rates simulated during the time the hatches are open reach as high as 3 ach. Although not in the scope of this document the rapid movement of air can be prejudicial to the artwork roosted inside the church.

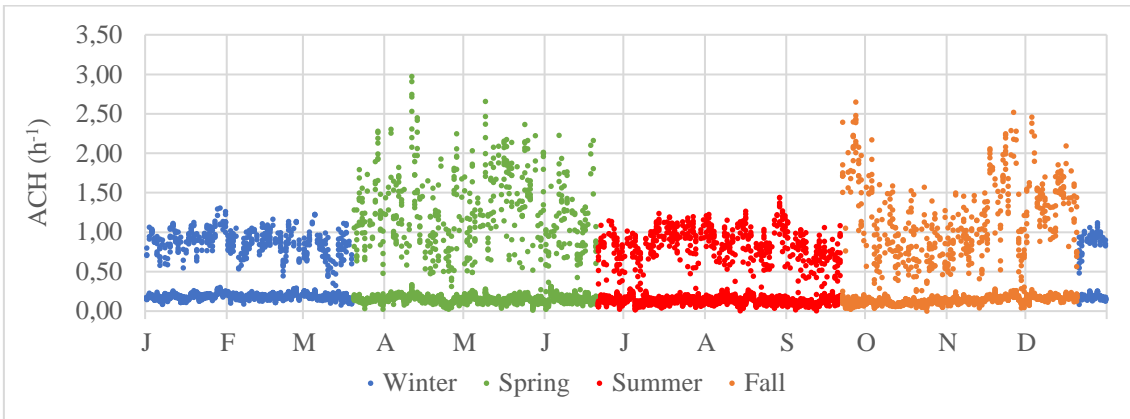


Figure 70- Sim\_2: ACH values for each season throughout the year

Table 31- Sim\_2: ACH average values for each season and church attendance status throughout the year

Church attendance status	Season							
	Winter		Spring		Summer		Autumn	
	avg	stdev	avg	stdev	avg	stdev	avg	stdev
visitation period	0.87	0.15	1.28	0.51	0.87	0.20	1.16	0.51
mass period	0.93	0.18	1.23	0.48	0.68	0.25	1.26	0.46
closed period	0.19	0.03	0.16	0.04	0.13	0.04	0.14	0.04

The standard deviations presented in Table 31 show the irregularity of this strategy. Comparing the mass periods during Spring and Summer seasons. ach average values are 1.23 and 0.68, respectively, with standard deviation of 0.48 and 0.25 also respectively. The difference in the stdev. doubled. ACH average values can be seen in Figure 71.

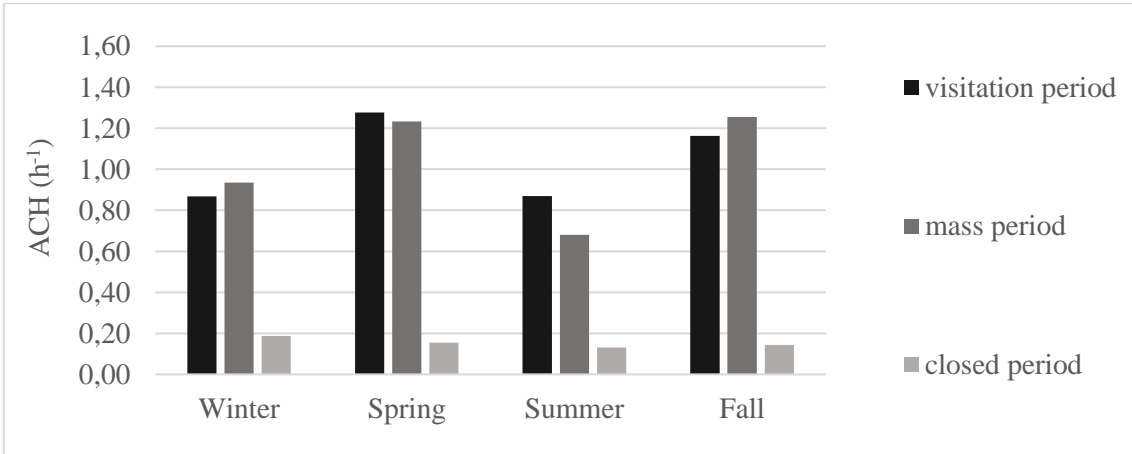


Figure 71- Sim\_2: Average ACH and standard deviation values for each church attendance status by season

#### 4.2.3.2. Sim\_2: EN 15251

When applying EN 15251 to sim\_2 the following results were attained. During the mass attendance status (Figure 72), 91% of the time is spent in category I, and only 0.3% (1 hour) in category IV where prescribed ventilation rates are low and only suitable for a limited part of the year. The remaining time is spent in categories II and III, 14 and 13 hours, respectively.

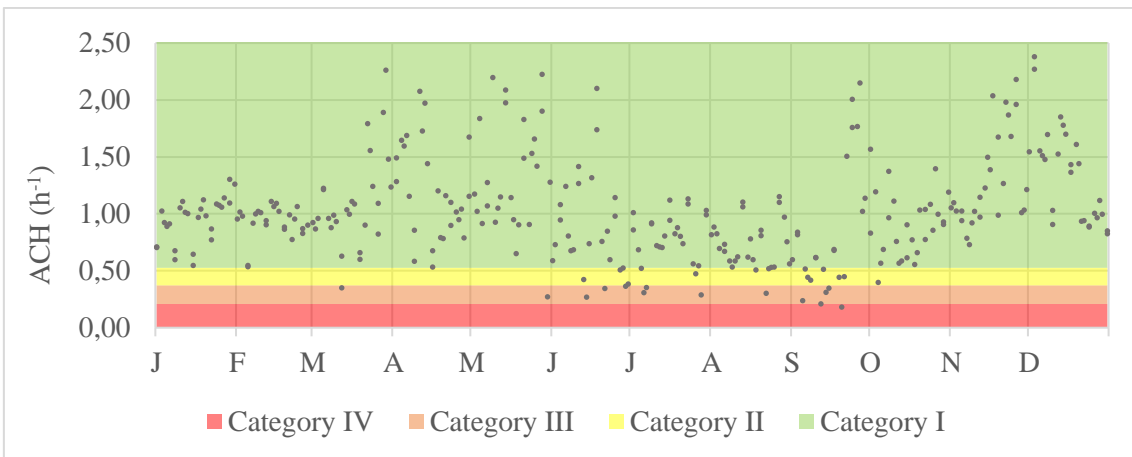


Figure 72- Sim\_2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period

Focusing solely on the visitation period, 99.9% of the time is spent in category I, as graphically displayed in Figure 73.

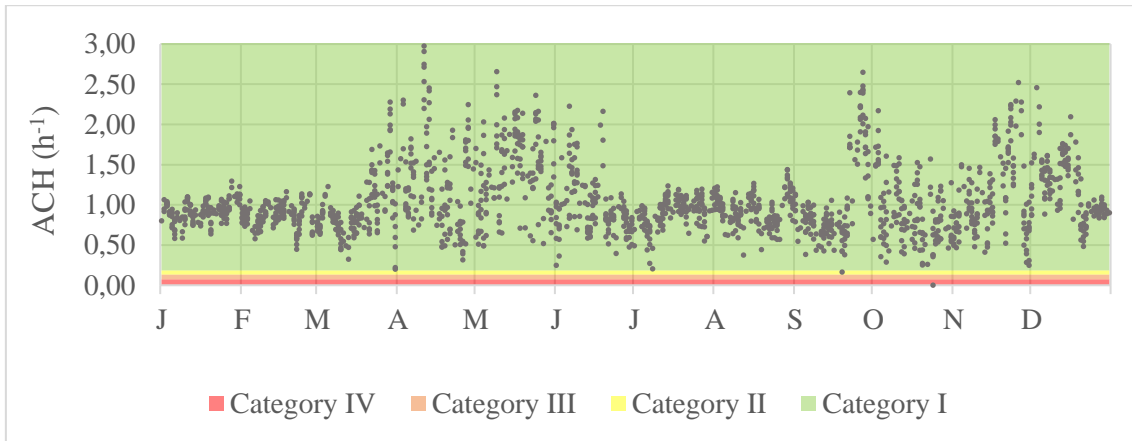


Figure 73- Sim\_2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period

According to the data, 48.8% of the closed period is spent in compliance with the category I ventilation rates, 17.8% with category II, and 8.8% with category III (Figure 74). 80 hours of the simulation showed ventilation rates that are inferior to the lowest prescribed value and therefore corresponding to category IV.

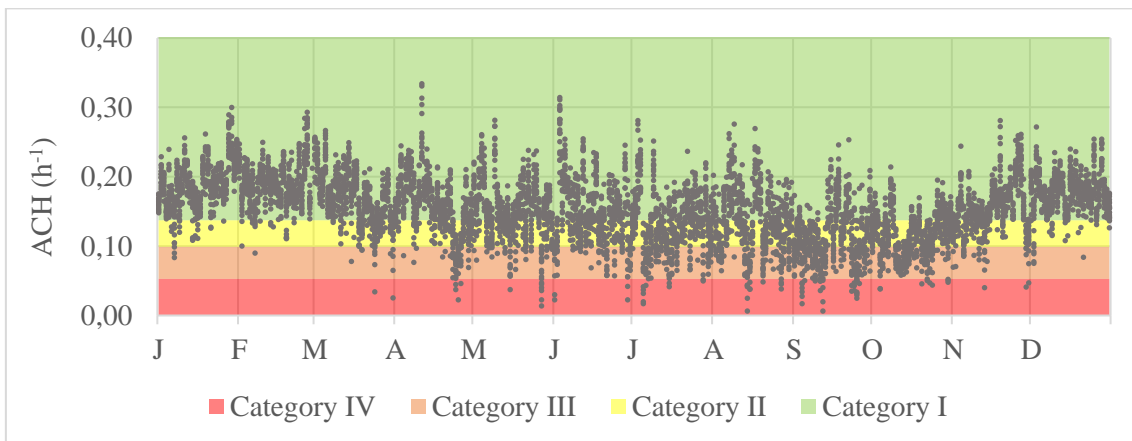


Figure 74- Sim\_2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: closed period

Figure 75 and Table 32 combine all the information gathered that is relevant to the application of EN 15251.

Table 32- Sim\_2: EN 15251 Category based on ACH values

EN 15251 Category based on ACH values	number of hours in category			% of time spent in category per year			% of time spent in category per attendance status		
	visitation period	mass period	closed period	visitation period	mass period	closed period	visitation period	mass period	closed period
Category I	1767	286	4271	20,2%	3,3%	48,8%	99,9%	91,1%	64,0%
Category II	1	14	1557	0,0%	0,2%	17,8%	0,1%	4,5%	23,3%
Category III	0	13	768	0,0%	0,1%	8,8%	0,0%	4,1%	11,5%
Category IV	1	1	80	0,0%	0,0%	0,9%	0,1%	0,3%	1,2%
TOTAL	1769	314	6676	20,2%	3,6%	76,2%	100%	100%	100%

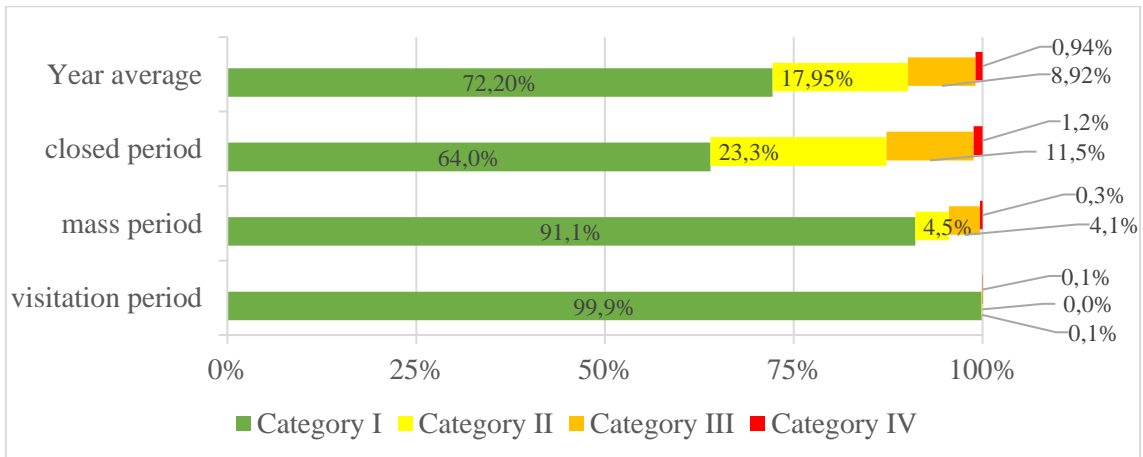


Figure 75- Sim\_2: Percentage of time spent in each EN 15251 category per church attendance status

#### 4.2.3.3. Sim\_2: EN 13779

Carbon dioxide levels throughout the year are inferior to the 350 ppm above outdoor concentration, and therefore, inserted in IDA I (Figure 76).

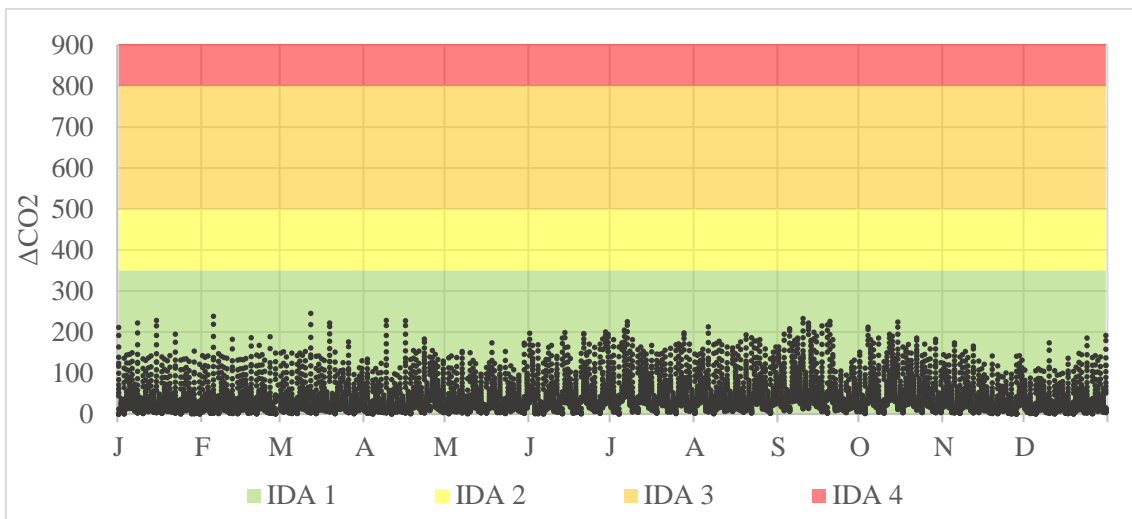


Figure 76- Sim\_2: CO<sub>2</sub> levels in São Cristóvão's main nave (units in ppm above outdoor concentration)

The maximum value is registered on the 12<sup>th</sup> of march (246ppm) at 13:00. The ventilation rates that are present after this measurement, even lower than the average, are sufficient to replace 99% of the CO<sub>2</sub> particles before the church is open to the public the next morning. This singular case is presented in Figure 77.

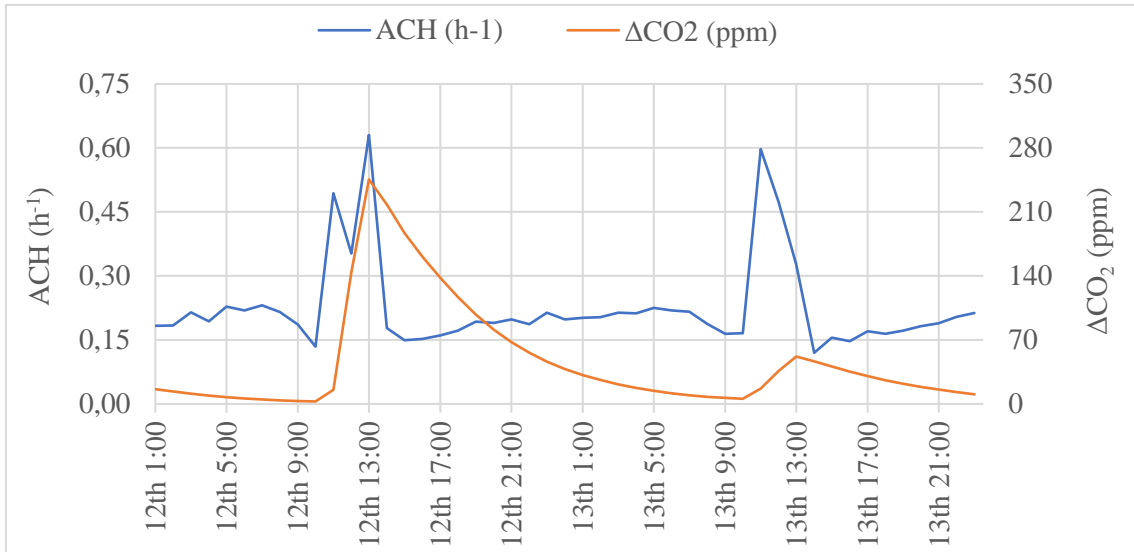


Figure 77- Sim\_2: CO<sub>2</sub> concentration levels and ACH values recorded in the church nave from March 12<sup>th</sup> to March 14<sup>th</sup>. The 12<sup>th</sup> of March represents a day type 1 (Sunday)

During Winter, the mass service on Sunday produces the highest CO<sub>2</sub> concentrations even if throughout the other days of the week peak values are lower, compared to the other seasons. Also, circa 25% decrease in CO<sub>2</sub> average concentrations can be observed during Sunday mass when this strategy is implemented and comparing Winter and Summer to Spring and Autumn.

The CO<sub>2</sub> hourly average concentration by season is displayed in Figure 78.

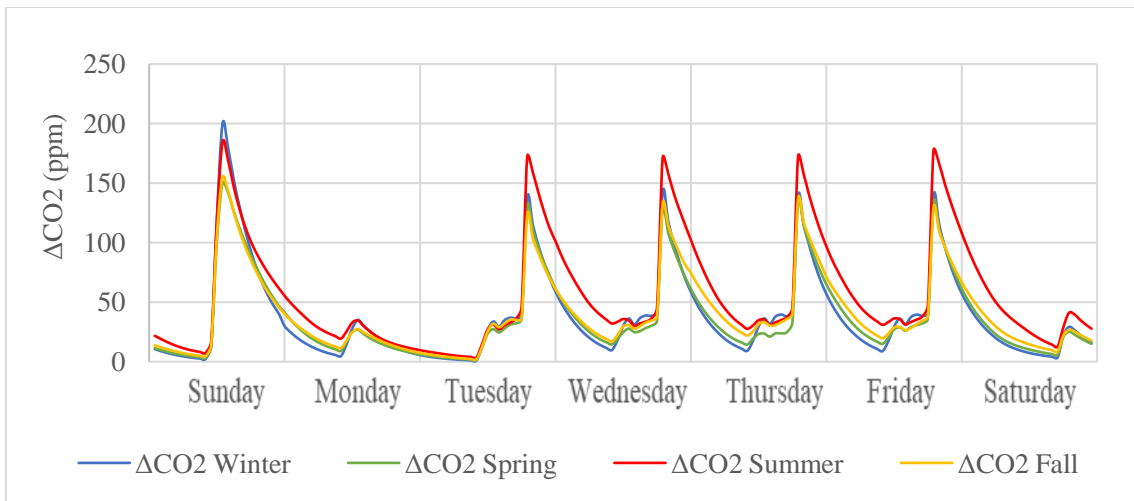


Figure 78- Sim\_2: CO<sub>2</sub> hourly average concentration levels by day of the week and season

Figure 79 shows the CO<sub>2</sub> hourly average concentration and the ACH hourly average combined. This analysis allows a better visual representation of the effectiveness regarding contaminants removal rates.

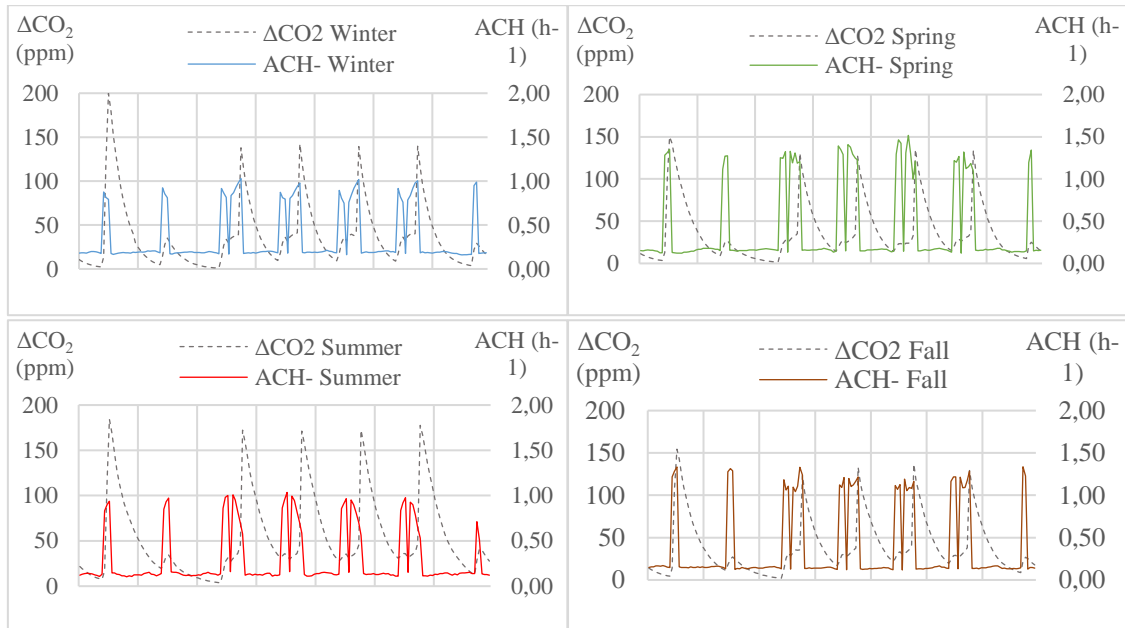


Figure 79- Sim\_2:  $\Delta\text{CO}_2$  levels and ACH average per day of the week and by Season

Prescribed ventilation rates were achieved virtually the entire year for the visitation attendance status but only 72% for the mass period (Table 33). Regarding this second attendance status, during the Summer and Winter were recorded 80% of the hours where ventilation rates did not comply with does prescribed.

Table 33- Sim\_2: IDA Category based on  $\text{CO}_2$  levels and prescribed airflows compliance

IDA Category	CO2 level above outdoor air (ppm-default value)	Airflow per person [m3/(h.person)]	% of time spent in IDA Category		% of time spent in IDA Category and respecting prescribed ACH values	
			visitation period	mass period	visitation period	mass period
IDA 1	350	72	100%	100%	99.9%	72.3%
IDA 2	500	45	0	0	-	-
IDA 3	800	29	0	0	-	-
IDA 4	1200	18	0	0	-	-

#### 4.2.3.4. Sim\_2: ASHRAE 62.1

ASHRAE’s prescribed ventilation rates were met 99.9% of the time, and the lowest percentage of acceptable air exchange was seen in the closed period due to the 1.08 m<sup>3</sup>/h.m<sup>2</sup> recommended value.

Table 34- Sim\_2: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status

attendance status	Number of hours in accordance with airflow prescribed values	% of time respecting prescribed ACH values per year	% of time respecting prescribed ACH values per attendance status
visitation period	1768	20.2%	99.9%
mass period	312	3.6%	99.4%
closed period	6203	70.8%	92.9%

Figure 80 through Figure 82 shows the simulated hourly ach and prescribed ventilation rate for the visitation, mass, and closed attendance status, by this order.

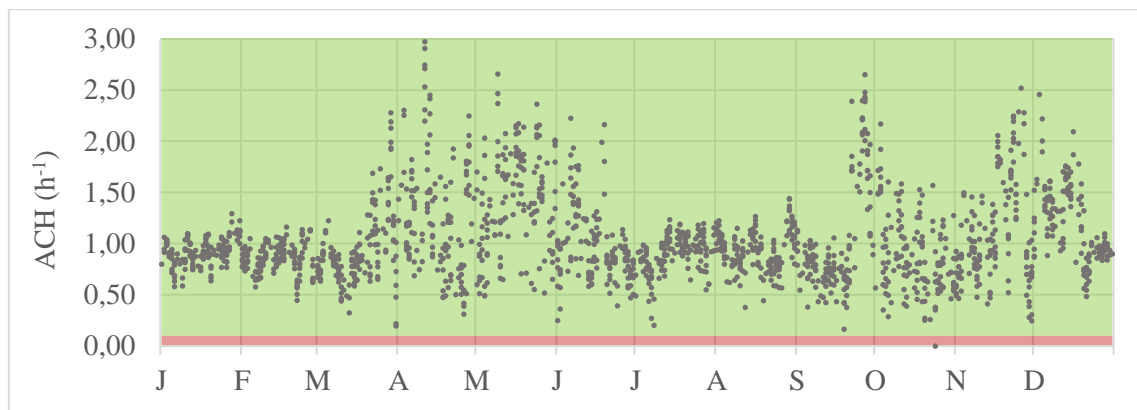


Figure 80- Sim\_2: ASHRAE 62.1 prescribed ACH for visitation attendance status

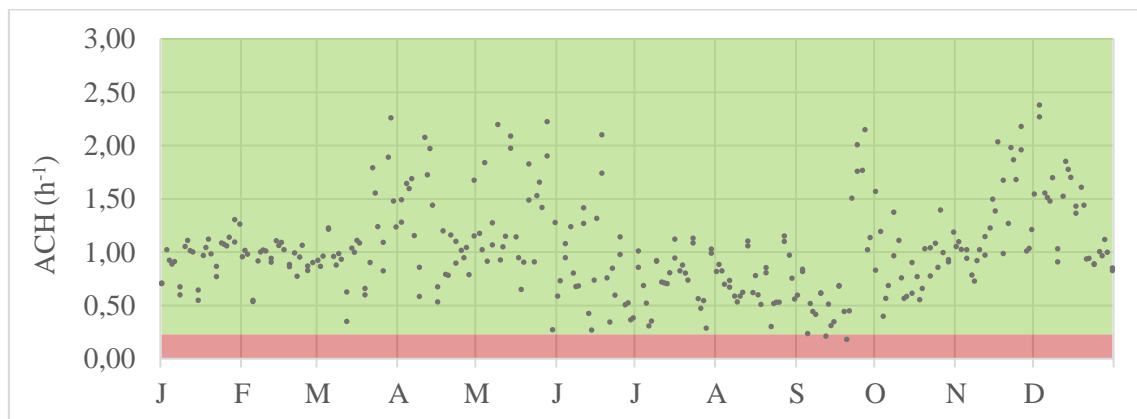


Figure 81- Sim\_2: ASHRAE 62.1 prescribed ACH for mass attendance status

Both the visitation and mass periods have acceptable ventilation rates in de order of 99% of the time and the closed period has 93% of the time RPH above the recommended ones.

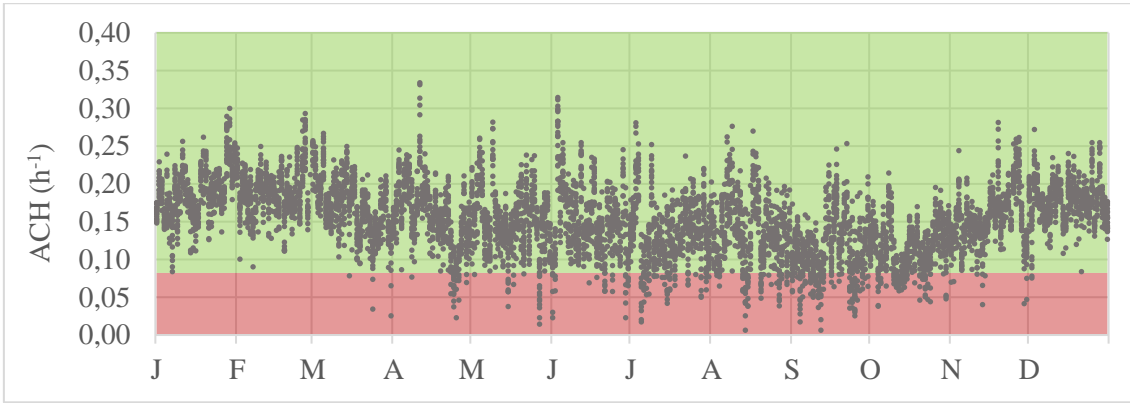


Figure 82- Sim\_2: ASHRAE 62.1 prescribed ACH for closed attendance status

A visual comparison was made with all the attendance status and the yearly average and presented in Figure 83.

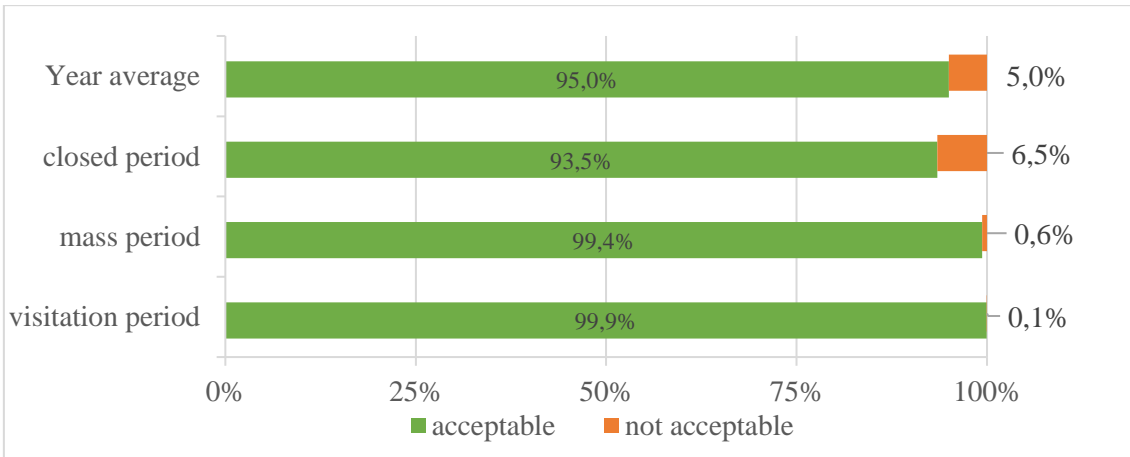


Figure 83- Sim\_2: Percentage of time in compliance with ASHRAE 62.1 ventilation rates per church attendance status

#### 4.2.3.5. Sim\_2: CIBSE Guide A

CIBSE Guide A application on sim\_2 revealed 99.9% of the time complying with prescribed ventilation rates for the visitation period (Figure 84), and 95.2% when looking only at the mass period (Figure 85).

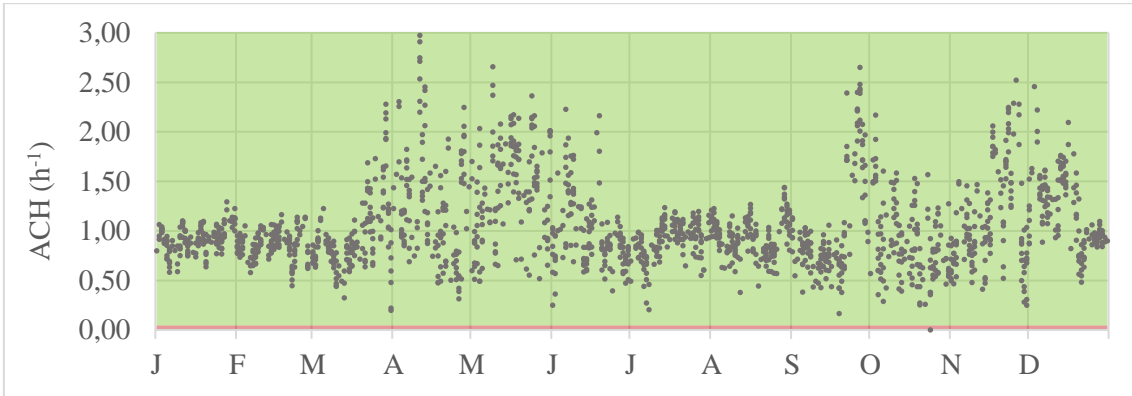


Figure 84- Sim\_2: CIBSE guide A prescribed ACH for visitation attendance status

The hours in which ventilation rates are inferior to those recommended happen mainly during the Summertime, in late June, July, August and, more recurrently, in September.

Only one of the 14 hours (4.5% of the mass period) that miss the suggested air substitution rate happened outside the Summer period, occurred in March and by a small 0.05 ACH difference.

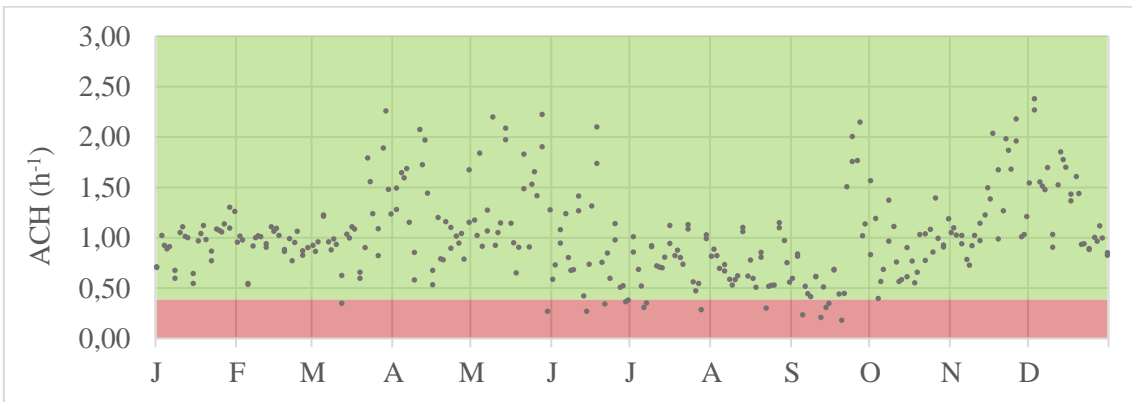


Figure 85- Sim\_2: CIBSE guide A prescribed ACH for mass attendance status

Figure 86 shows the percentage of time each attendance status is complying with the prescribed ventilation rates.

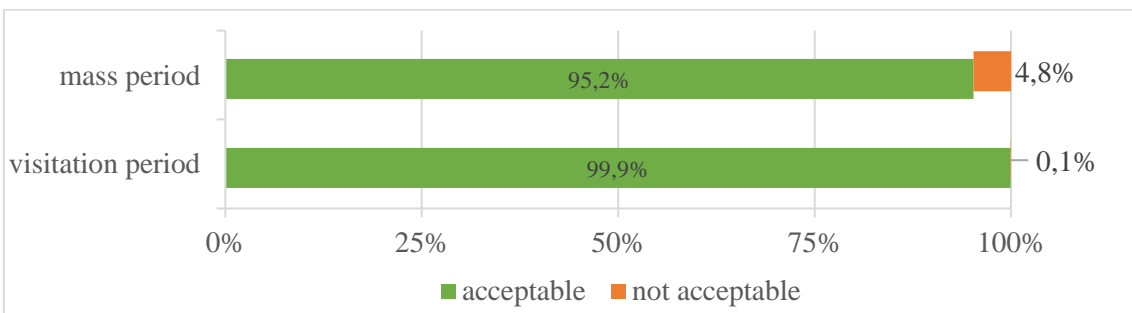


Figure 86- Sim\_2: Percentage of time respecting CIBSE guide A acceptable ventilation rates for visitation and mass attendance status

#### 4.2.4. Ventilation strategies: Sim\_3

The next set of simulations aim to study the most effective way to replace used air using a cross-ventilation strategy (Figure 87). For Sim\_3.1 some windows on the North and South facades on the 1<sup>st</sup> floor are open during mass service as well as the doors that connect the mortuary and sacristy areas to the nave. Throughout the visitation attendance status, the same conditions of Sim\_02 were applied to all other spans. This strategy will take advantage of the predominant North wind and increase ACH values.

Sim\_3.2 most eastern windows on the 1<sup>st</sup> floor and the doors that connect the altar and the nave's annex are set to open during mass service. Throughout the visitation attendance status, the same conditions of Sim\_02 were applied to all other spans.

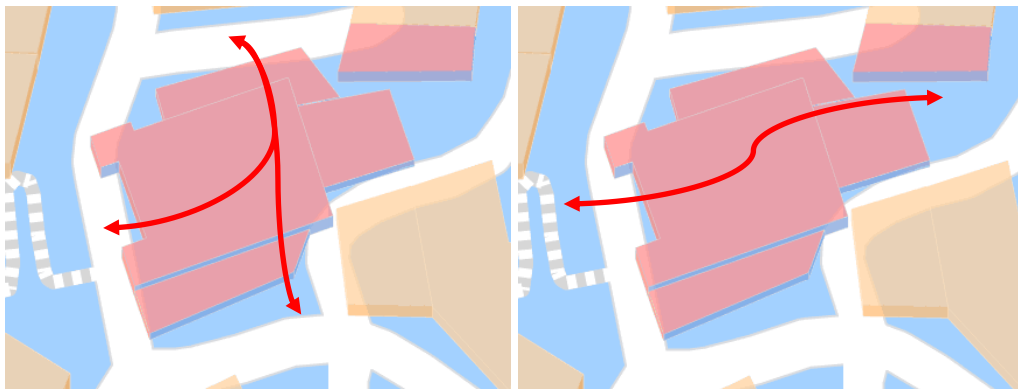


Figure 87- Sim\_3.1 and Sim\_3.2 implemented cross ventilation strategies

#### 4.2.4.1. Ventilation strategies: Sim\_3.1

##### 4.2.4.1.1. Sim\_3.1: General information

Simulation 3.1 intends to habitate the church with a cross ventilation strategy. Some spans are set to open during the mass service to increase the amount of air flowing from the north side to the south side of the church (left to right in the figure below).

The shaded and dotted-line areas in Figure 88 symbolizes spans that are open during the mass service and the shaded areas represent doors that are open throughout the church open hours schedule. Every non-highlighted span is set to the conditions of Sim\_02, the base simulation.

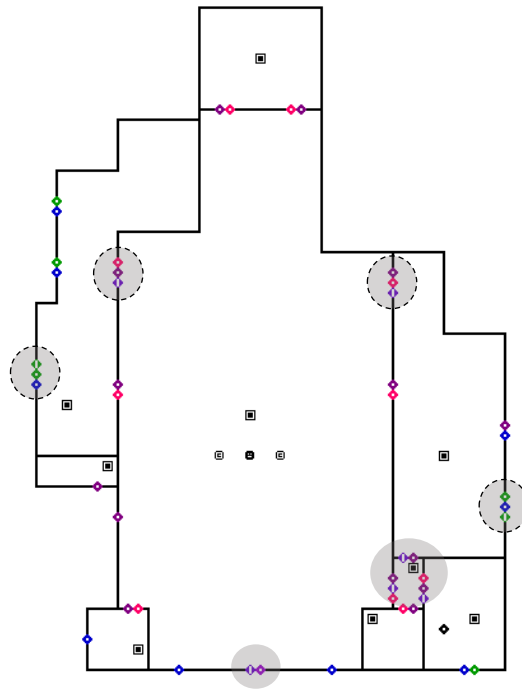


Figure 88 Sim\_3.1: floor 1 open spans schematic

The highest monthly average ach values were recorded during January and August; 0.38 and 0.36, respectively; and the lowest in April and October; 0.29 and 0.21, respectively; average ach values can be seen in Figure 89 and hourly ach values can be seen in Figure 90.

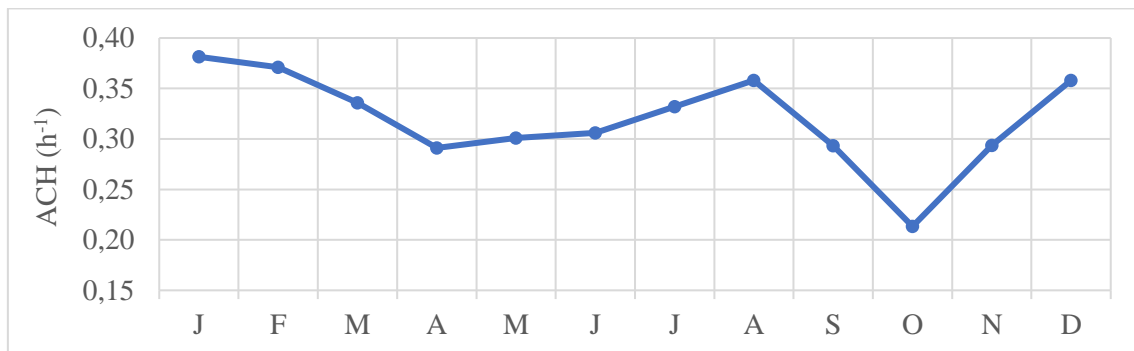


Figure 89- Sim\_3.1: Monthly average ACH

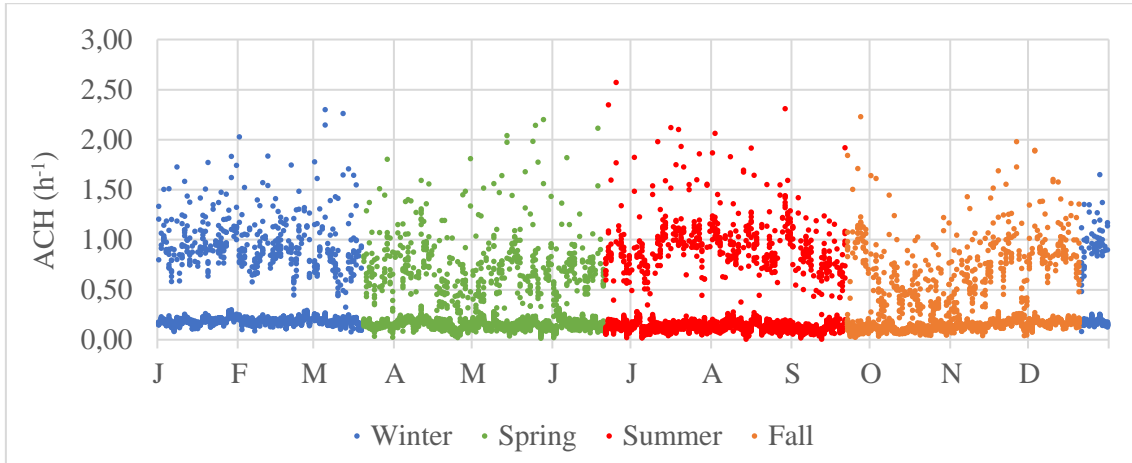


Figure 90 Sim\_3.1: ACH values for each season throughout the year

Seasonal average ach values can be consulted in Table 35 and graphically analyzed in Figure 91.

Table 35- Sim\_3.1: ACH values for each season and church attendance status throughout the year

Church attendance status	Season							
	Winter		Spring		Summer		Autumn	
	avg	stdev	avg	stdev	avg	stdev	avg	stdev
<b>closed period</b>	0.19	0.03	0.16	0.04	0.13	0.04	0.14	0.04
<b>visitation period</b>	0.88	0.16	0.65	0.21	0.89	0.2	0.65	0.26
<b>mass period</b>	1.41	0.28	1.25	0.39	1.34	0.47	1.17	0.37

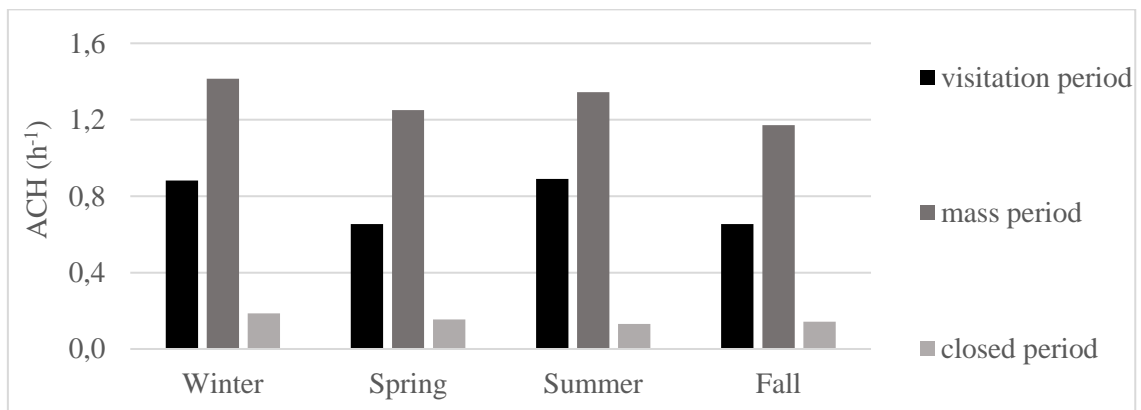


Figure 91- Sim\_3.1: Average ACH and standard deviation values for each church attendance status by season

#### 4.2.4.1.2. Sim\_3.1: EN 15251

Both the mass (Figure 92) and visitation attendance status (Figure 93) presented an extremely high percentage of time spent in category I of EN 15251. During the mass period, only 5 hours in the year are identified with a ventilation rate lower than the category I threshold. Of these 5, 2 hours are in category III and the remaining of the time is in line with category II ventilation rates.

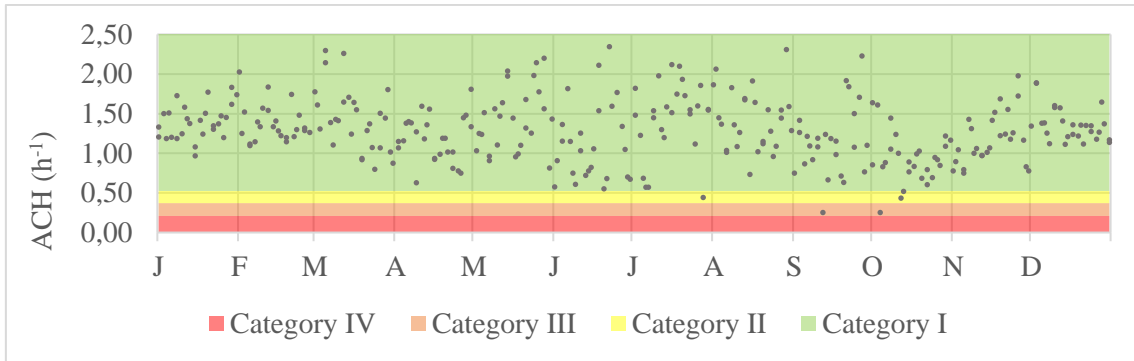


Figure 92- Sim\_3.1: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period

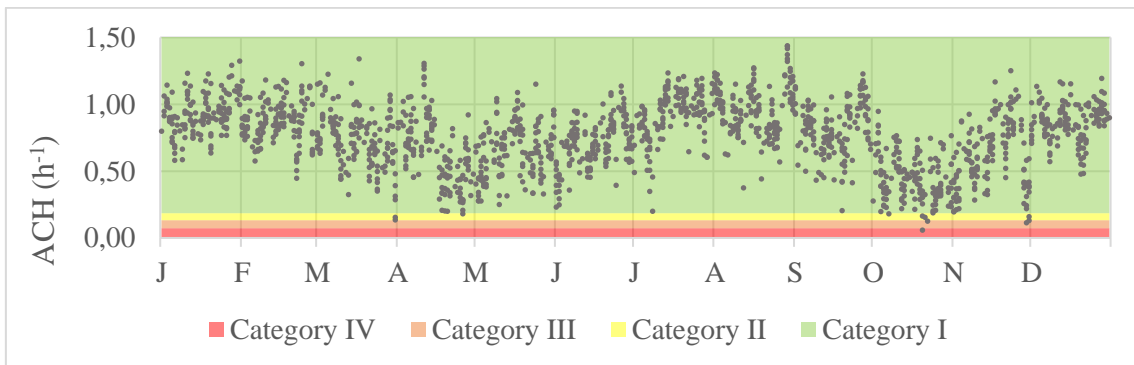


Figure 93- Sim\_3.1: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period

Studying the closed period (Figure 94), category I ventilation rates categories throughout the year represent 64% of the time, category II, 23.3%, category III 11.5% and ultimately, category IV that characterize 1.2% of the simulated year.

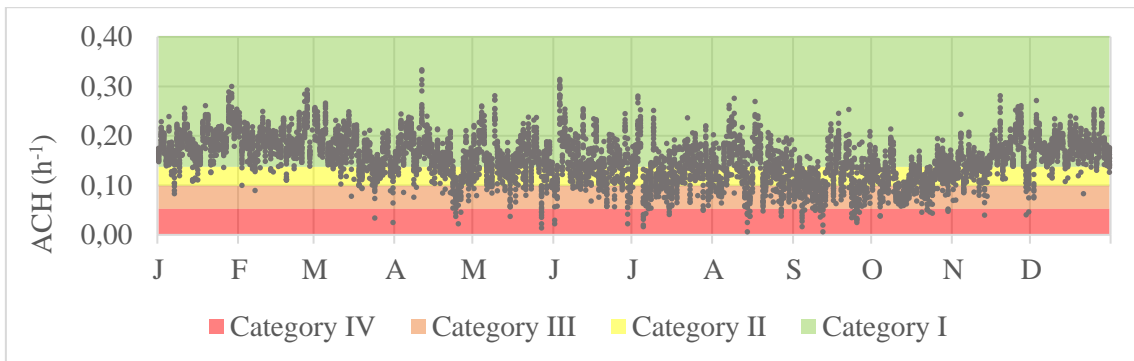


Figure 94- Sim\_3.1: ventilation rates vs EN 15251 hourly prescribed ventilation rates: closed period

A compilation of relevant data to the EN 15251 application can be consulted in Table 36 and Figure 95.

Table 36- Sim\_3.1: EN 15251 Category based on ACH values

EN 15251 Category based on ACH values	number of hours in category			% of time spent in category per year			% of time spent in category per attendance status		
	visitation period	mass period	closed period	visitation period	mass period	closed period	visitation period	mass period	closed period
Category I	1757	309	4271	20.06%	3.53%	48.76%	99.3%	98.4%	64.0%
Category II	7	3	1557	0.08%	0.03%	17.78%	0.4%	1.0%	23.3%
Category III	3	2	768	0.03%	0.02%	8.77%	0.2%	0.6%	11.5%
Category IV	2	0	80	0.02%	0.00%	0.91%	0.1%	0.0%	1.2%
TOTAL	1769	314	6676	20.2%	3.6%	76.2%	100%	100%	100%

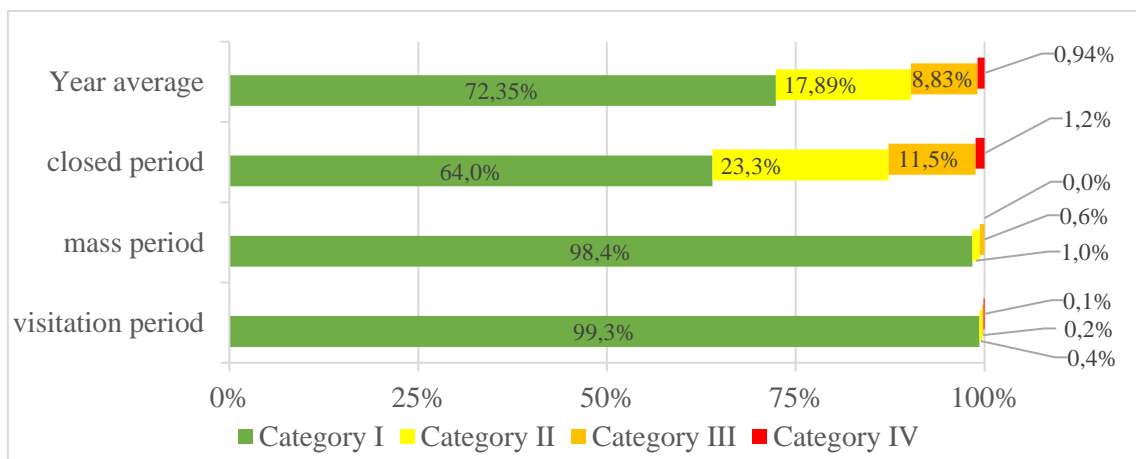


Figure 95- Sim\_3.1: Percentage of time spent in each EN 15251 category per church attendance status

#### 4.2.4.1.3. Sim\_3.1: EN 13779

CO<sub>2</sub> levels remain in IDA 1 (Figure 96) category throughout the year when EN 13779 is applied.

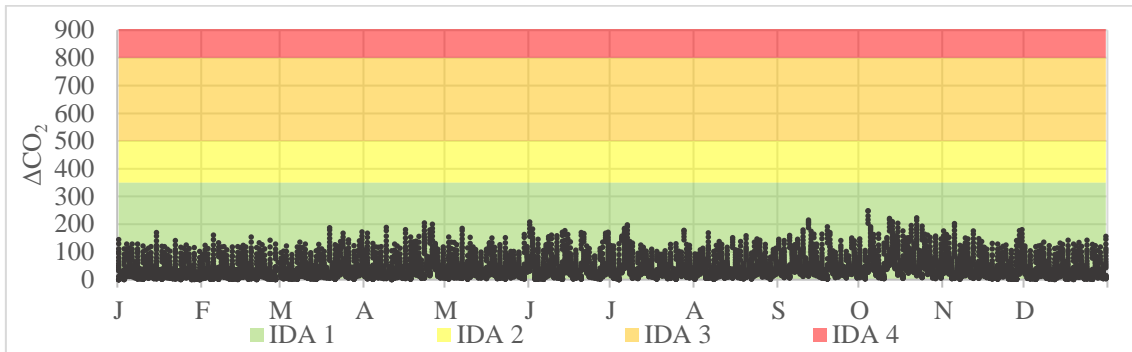


Figure 96- Sim\_3.1: CO<sub>2</sub> levels in São Cristovão's main nave (units in ppm above outdoor concentration)

Seen in Figure 97 is the average hourly  $\Delta\text{CO}_2$  per day of the week and season. It is possible to identify a faster air substitution in the Wintertime as the concentration decline at a more rapid pace. During Spring and Autumn, as ventilation rates are inferior, CO<sub>2</sub> levels peak at slightly higher values.

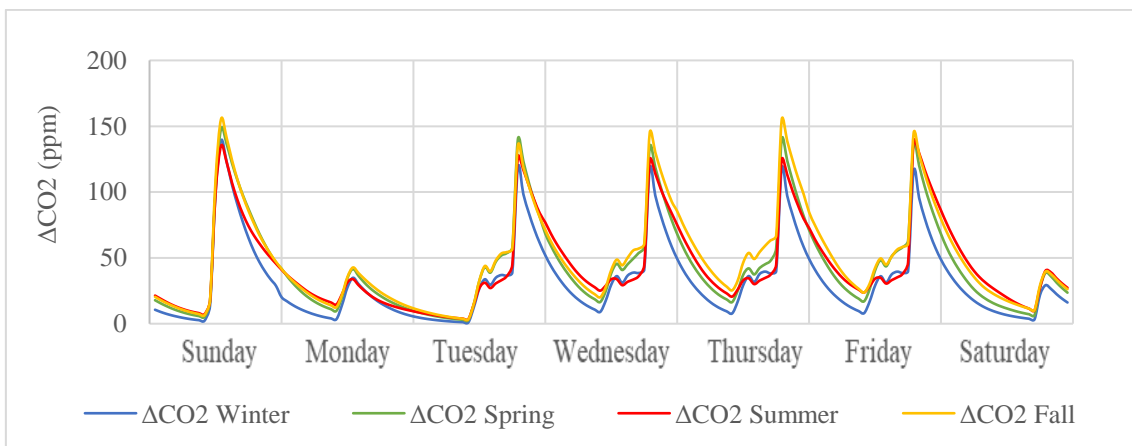


Figure 97- Sim\_3.1:  $\Delta\text{CO}_2$  average levels per day of the week and by Season

With higher ventilation rates during Winter and Summer, CO<sub>2</sub> levels are lower when comparing to the other seasons. Figure 98 depicts this.

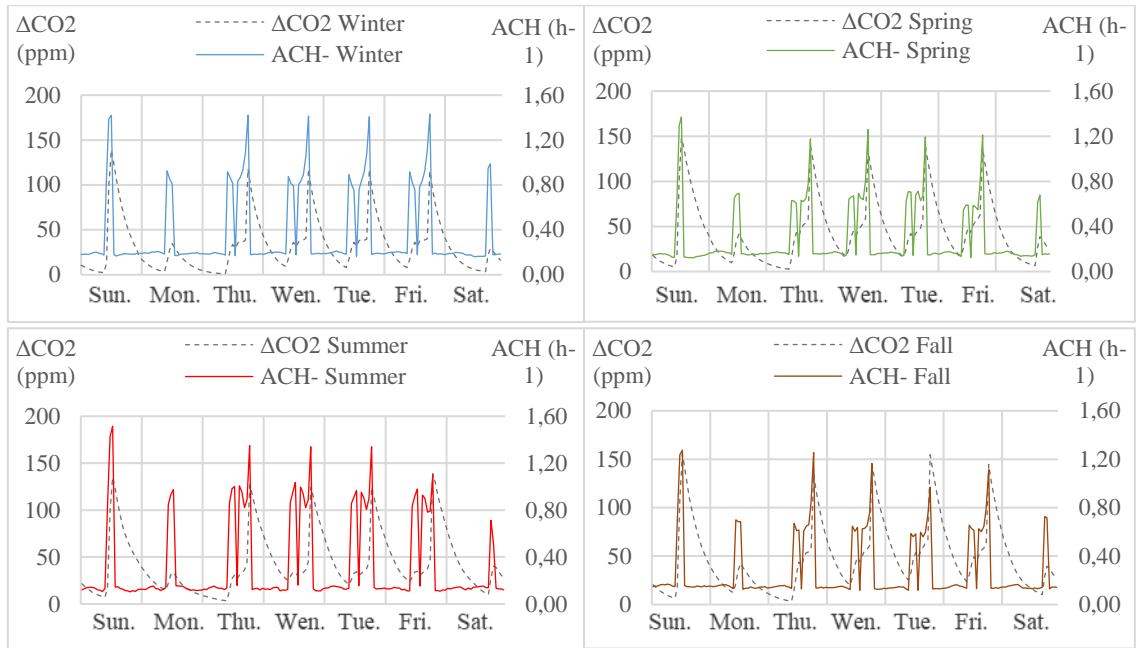


Figure 98- Sim\_3.1:  $\Delta CO_2$  levels and ACH average per day of the week and by Season

Table 47 presents the acceptable results of this ventilation strategy through the EN 13779 lens. Throughout the entire visitation period but 2 hours, the ventilation rates are greater than the prescribed one of  $72 \text{ m}^3/(\text{h}\cdot\text{person})$  for IDA 1, and, during the mass period, 90% of the time is spent in compliance with IDA I ventilation rate.

Table 37- Sim\_3.1: IDA Category based on  $CO_2$  levels and prescribed airflows verification

IDA Category	CO2 level above outdoor air (ppm-default value)	Airflow per person [m <sup>3</sup> /(h.person)]	% of time spent in IDA Category		% of time spent in IDA Category and respecting prescribed ACH values	
			visitation period	mass period	visitation period	mass period
IDA 1	350	72	100.0%	100.0%	99.9%	90.8%
IDA 2	500	45	0.0%	0.0%	-	-
IDA 3	800	29	0.0%	0.0%	-	-
IDA 4	1200	18	0.0%	0.0%	-	-

#### 4.2.4.1.4. Sim\_3.1: ASHRAE 62.1

Throughout the visitation attendance status flow rates are satisfying, not respecting the target 1 time, as seen in Figure 99.

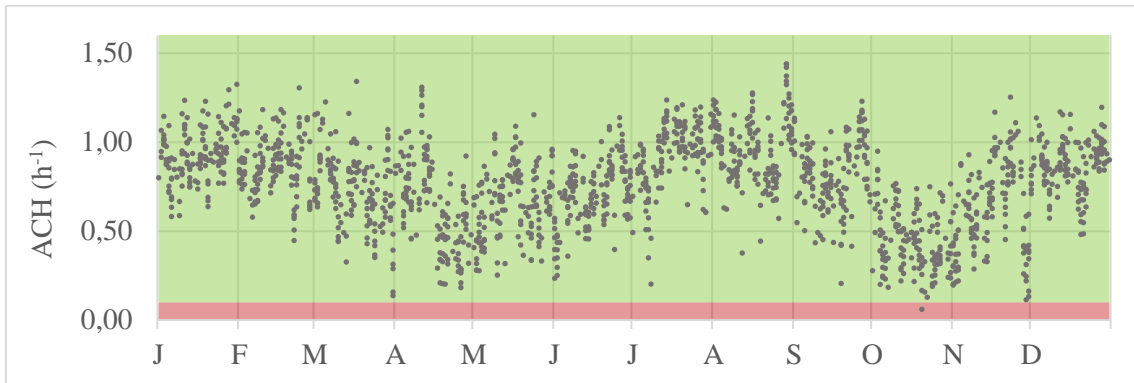


Figure 99- Sim\_3.1: ASHRAE 62.1 prescribed ACH for visitation attendance status

Throughout the mass attendance status (Figure 100), flow rates are satisfying, respecting the target ach all year.

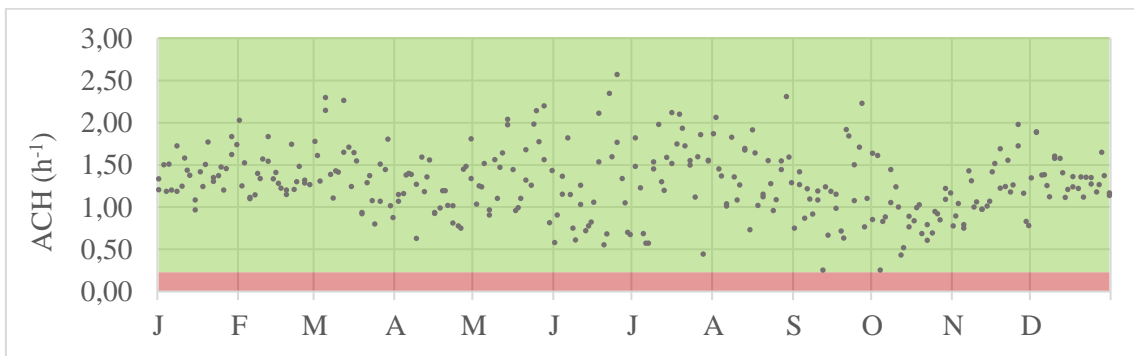


Figure 100- Sim\_3.1: ASHRAE 62.1 prescribed ACH for mass attendance status

During the close period (Figure 101), 93.5% of the time is spent complying with prescribed ventilation rates.

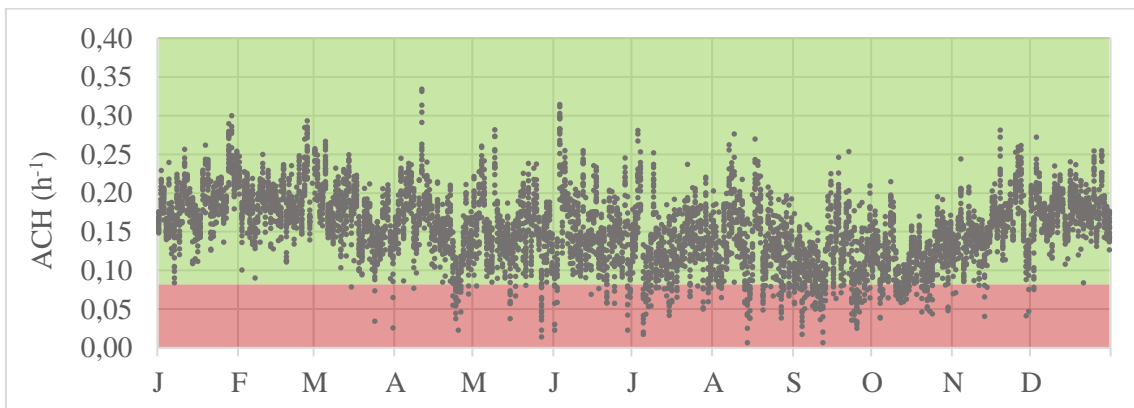


Figure 101- Sim\_3.1: ASHRAE 62.1 prescribed ACH for closed attendance status

Table 38 and Figure 102 summarize the information previously present.

Table 38- Sim\_3.1: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status

attendance status	Number of hours in accordance with airflow prescribed values	% of time respecting prescribed ACH values per year	% of time respecting prescribed ACH values per attendance status
visitation period	1767	20.2%	99.9%
mass period	314	3.6%	100.0%
closed period	6242	71.3%	93.5%

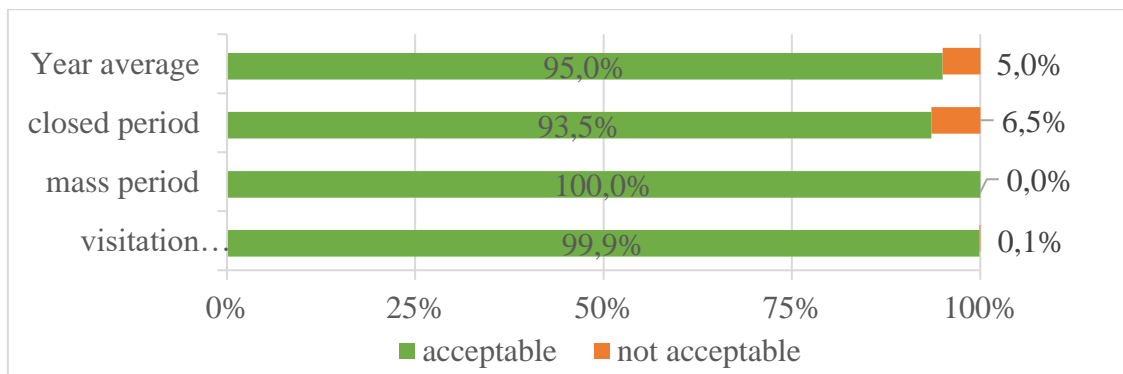


Figure 102- Sim\_3.1: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates

#### 4.2.4.1.5. Sim\_3.1: CIBSE Guide A

During the visitation period (Figure 104Figure 103) of sim\_3.1, only 1 hour was recorded under the prescribed value of  $0.048\text{m}^3/\text{h}$ .

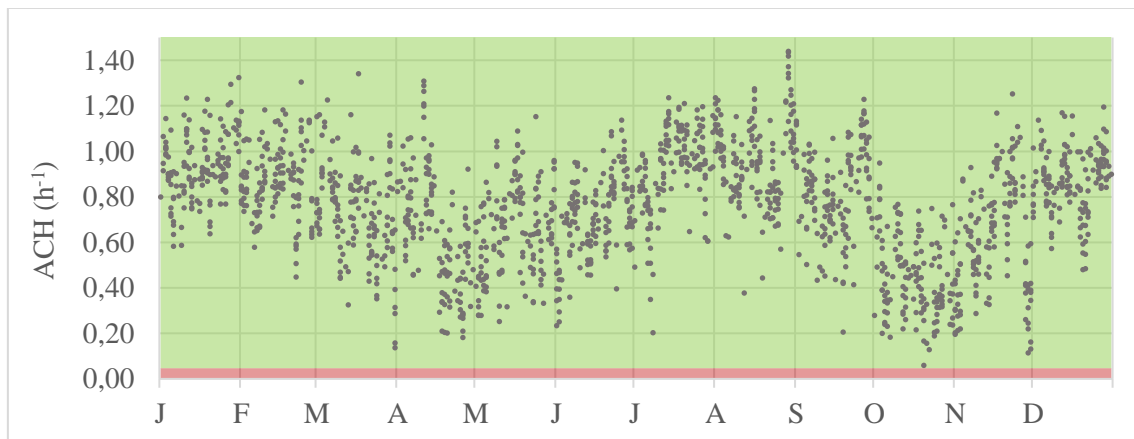


Figure 103- Sim\_3.1: CIBSE guide A prescribed ACH for visitation attendance status

Throughout the mass period (Figure 104), the natural ventilation of the church was not able to comply with the prescribed values for 2 hours.

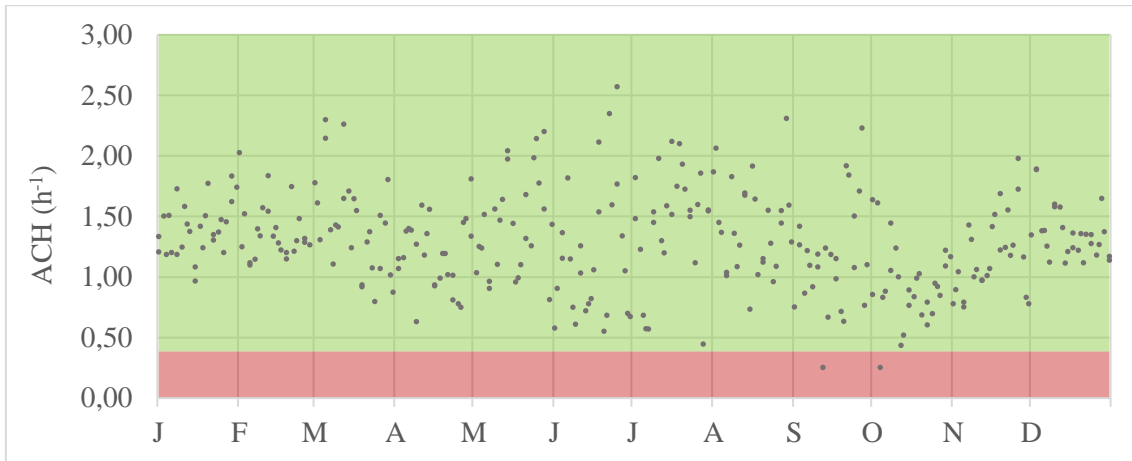


Figure 104- Sim\_3.1: CIBSE guide A prescribed ACH for mass attendance status

Both church attendance statuses examined revealed an extremely high IAQ by this standard as seen in Figure 105.

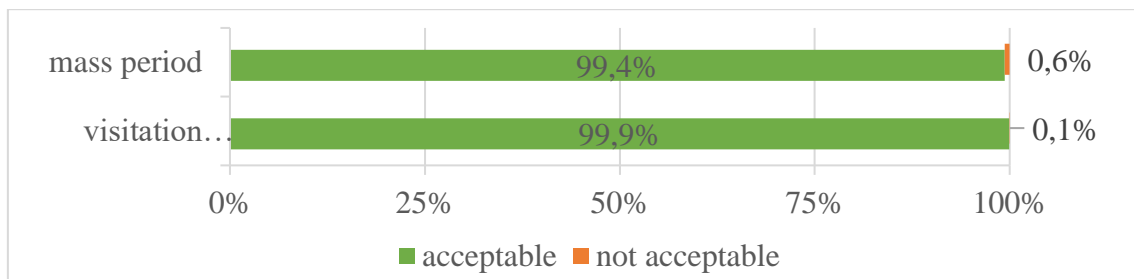


Figure 105- Sim\_3.2: Percentage of time respecting CIBSE guide A acceptable ventilation rates for visitation and mass attendance status

As mentioned previously, the church interior temperature is fixed at 20°C, which can be misleading when assuming the veracity of the results attained. The thermal inertia factor of the church can not be implemented in these simulations, and as such, the ventilation by thermal difference isn't probably translating into true values.

If the interior temperature of an indoor climate simulation starts at 20°C and the ventilation rates are increased during Summer days, as they were, comparing Sim\_02 to Sim\_3.1, the following are likely to transpire:

- The interior temperature will slowly increase, as hotter air is entering the church through doors windows and cracks.
- RH will decrease as hotter air circulates through the church. The velocity at which these changes occur, although undetermined, is speculated to be slow.

In some cases, the absolute values of the climate parameters, such as Temperature and RH are not a problem by them selfs on the art displayed in structures that are not built for the purpose. Drastic or extreme variation can cause irreversible damage to some objects, especially do they are a combination of materials that have different responses to climatic inputs [53].

In contrast, if ventilation rates are increased during Winter nights, the interior temperature will slowly decrease, and RH will increase. Even more, the combination of high levels of outdoor humidity, with an increase in the number of occupants may create the ideal conditions for the growth and proliferation of different species of mycelium., leading to the degradation of the collections.

The safeguard of the artwork displayed in São Cristovão's church from climate conditions, although studied by Silva et al. [54], is not directly examined in this document. As such, any changes in the ventilation performance of the church that impacts the overall hygrothermal response should be carefully analyzed so the conservation of the collections is not compromised.

#### 4.2.4.2. Ventilation strategies: Sim\_3.2

##### 4.2.4.2.1. Sim\_3.2: General information

The intent of this simulation is to habilitate the church with a cross ventilation strategy, different from the previous one. This strategy only needs the opening of the two small single side-hung windows on the Eastern side of the church, in the annex behind the altar.

In Figure 106, the shaded and dotted-line areas symbolize spans that are open during the mass service and the shaded areas represent doors that are open throughout the church open hours schedule.

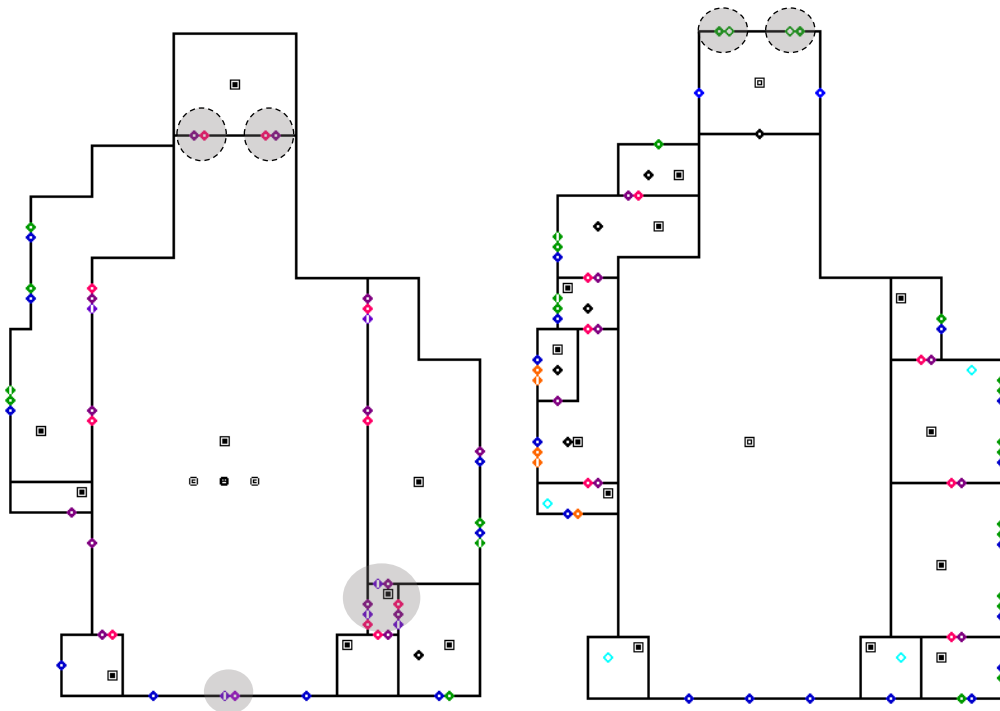


Figure 106 Sim\_3.2: 1<sup>st</sup> floor and 2<sup>nd</sup> floor open span schematic

During the cold months of December, January, February and March, average ACH values go from 0.30 to 0.37. After this period, ach values drop to 0.27 and peaks again in August. The decrease visible in Figure 107 stops in October at 0.20 ach.

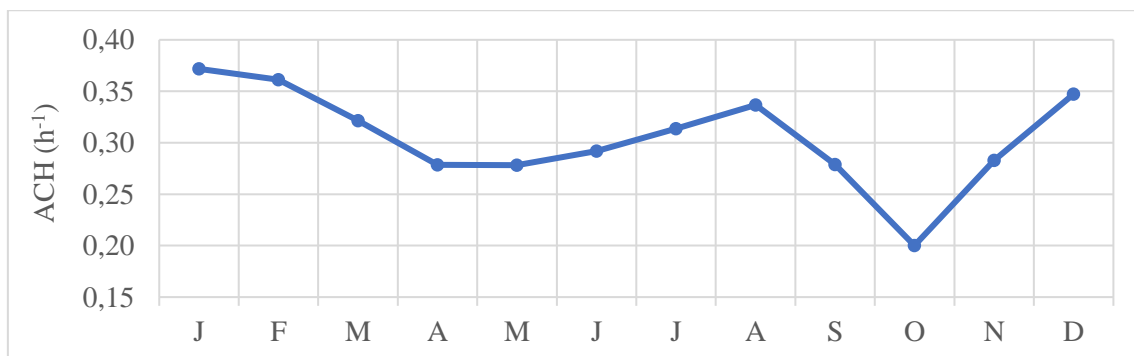


Figure 107- Sim\_3.2: Monthly average ACH

These simulation results show a bigger ventilation variation. Instead of the steady increase in the ventilation rates, as seen in Sim\_3.1, this strategy has a more dispersed set of results, as Figure 108 shows. Average ach and its standard deviations by season can be consulted in Table 39.

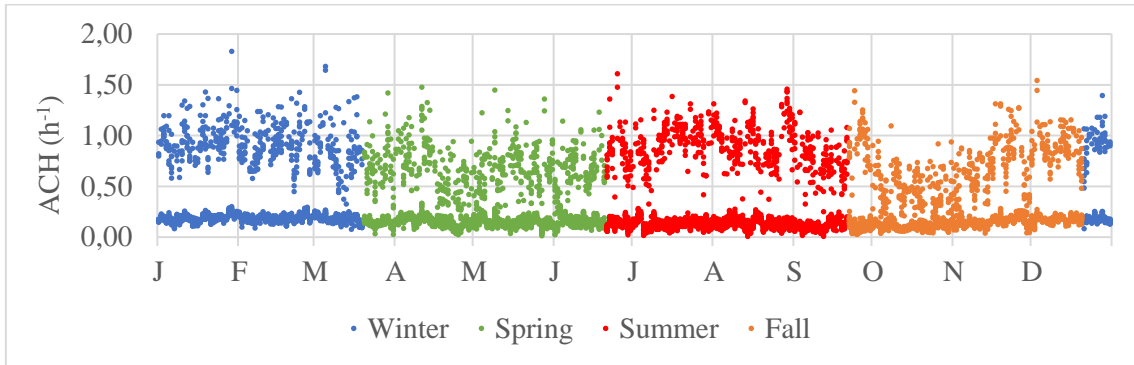


Figure 108 Sim\_3.2: ACH values for each season throughout the year

Table 39- Sim\_3.2: ACH values for each season and church attendance status throughout the year

Church attendance status	Season							
	Winter		Spring		Summer		Autumn	
	avg	stdev	avg	stdev	avg	stdev	avg	stdev
<b>closed period</b>	0,19	0.03	0.16	0.04	0.13	0.04	0.14	0.04
<b>visitation period</b>	0.87	0.16	0.64	0.21	0.88	0.19	0.64	0.26
<b>mass period</b>	1.15	0.23	0.89	0.25	0.92	0.30	0.87	0.29

Ach values, presented in Figure 109, during Winter and Summer, are higher than those recorded during the Spring and Autumn for all church attendance statuses considered.

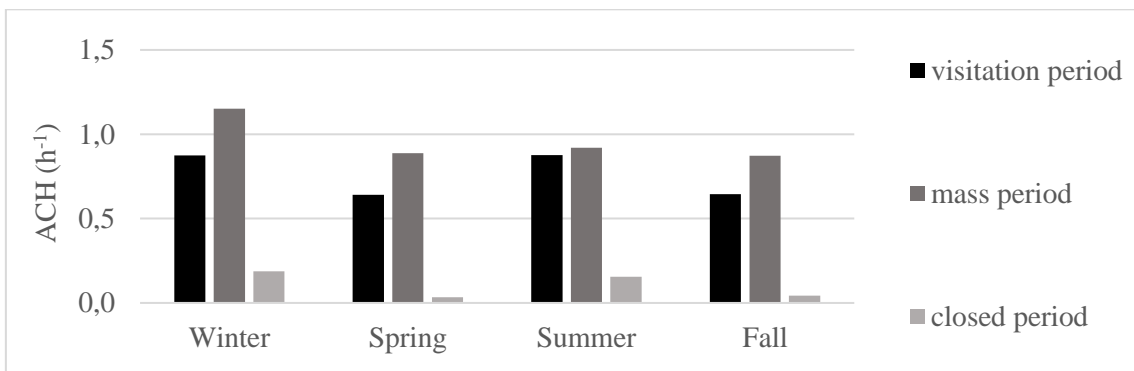


Figure 109- Sim\_3.2: Average ACH values for each church attendance status by season

#### 4.2.4.2.2. Sim\_3.2: EN 15251

Throughout the mass period (Figure 110), the most critical time-step evaluated, only 18 hours were spent outside category I. However, no data point is set on category IV.

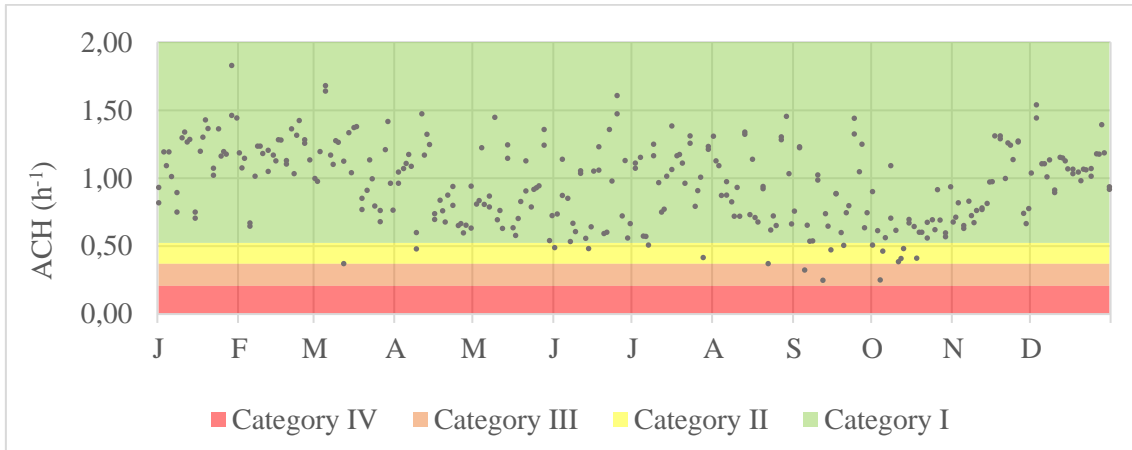


Figure 110- Sim\_3.2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period

During the visitation attendance status (Figure 111), even better results were seen as just 12 hours were spent outside category I. Unlike the previously discussed period, 2 hours were spent in Category IV.

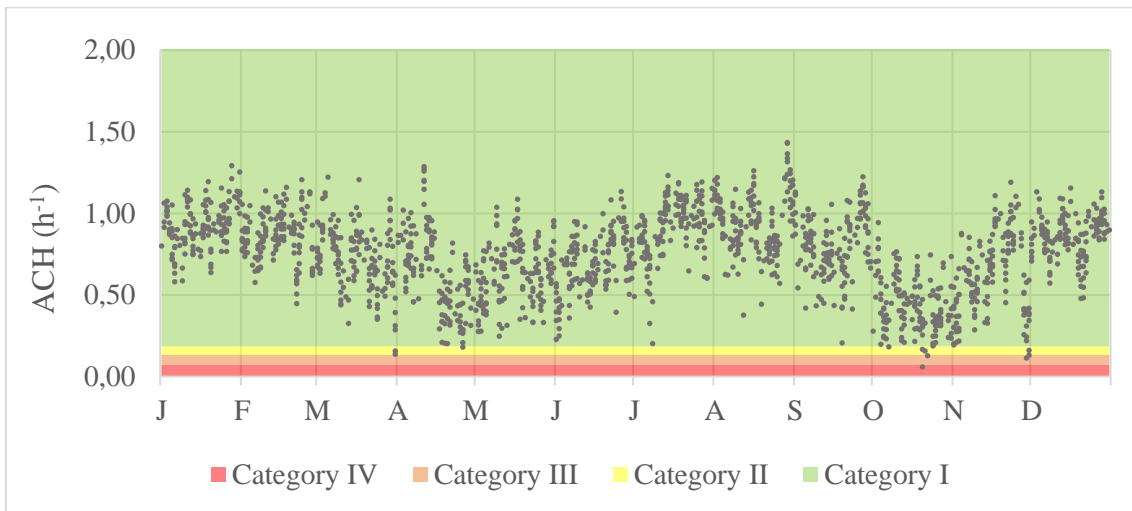


Figure 111- Sim\_3.2: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period

The closed period ventilation rates are the same for all simulations, and as such, no further analysis will be made.

The prescribed ventilation rates for the acceptable IAQ level, category III, are surpassed 90% of the year, endowing an extremely high air quality to the church microclimate, as presented in Table 40.

Table 40- Sim\_3.2: EN 15251 Category based on ACH values

EN 15251 Category based on ACH values	number of hours in category			% of time spent in category per year			% of time spent in category per attendance status		
	visitation period	mass period	closed period	visitation period	mass period	closed period	visitation period	mass period	closed period
Category I	1757	296	4271	20.06%	3.38%	48.76%	99.3%	94.3%	64.0%
Category II	7	15	1557	0.08%	0.17%	17.78%	0.4%	4.8%	23.3%
Category III	3	3	768	0.03%	0.03%	8.77%	0.2%	1.0%	11.5%
Category IV	2	0	80	0.02%	0.00%	0.91%	0.1%	0.0%	1.2%
TOTAL	1769	314	6676	20.2%	3.6%	76.2%	100%	100%	100%

On a yearly average, less than 1% of the time is spent under category IV. This can be perceived in Figure 112.

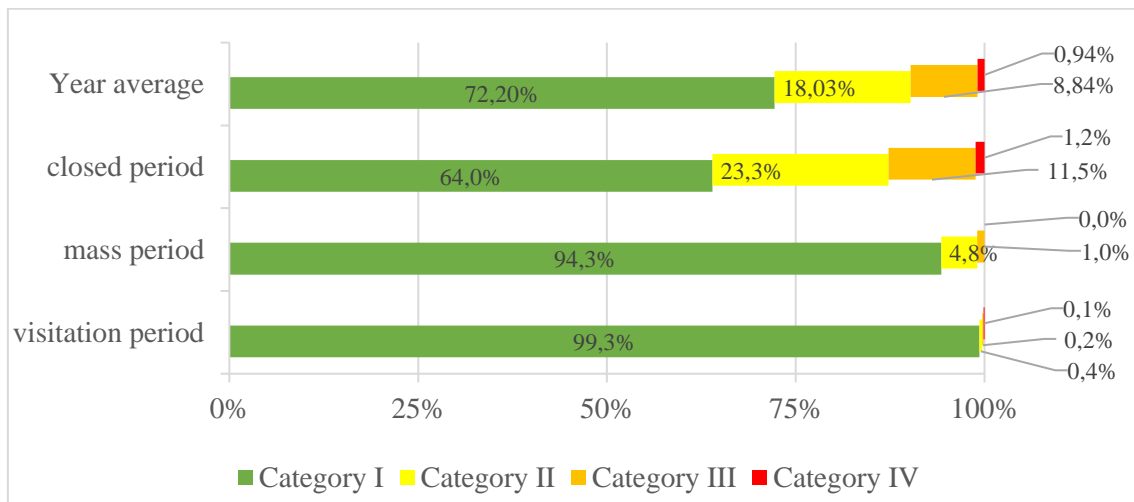


Figure 112- Sim\_3.2: Percentage of time spent in each EN 15251 category per church attendance status

#### 4.2.4.2.3. Sim\_3.2: EN 13779

With the application of EN 13779, it is possible to see in Figure 113 that the CO<sub>2</sub> concentration levels never surpassed the 350ppm threshold to exit category I.

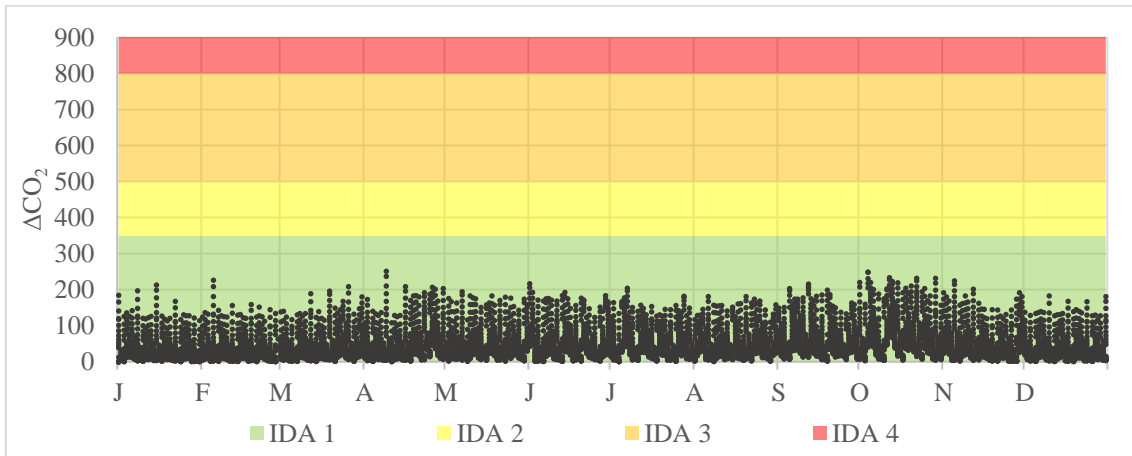


Figure 113- Sim\_3.2: CO<sub>2</sub> levels in São Cristóvão's main nave (units in ppm above outdoor concentration)

An hourly average CO<sub>2</sub> concentration by day type and season reveals the small variations in the peak values throughout the week. Winter is the season that shows the lowest peak values during the weekdays, however, through Sunday, the average concentration for Summer is lower compared to the other seasons.

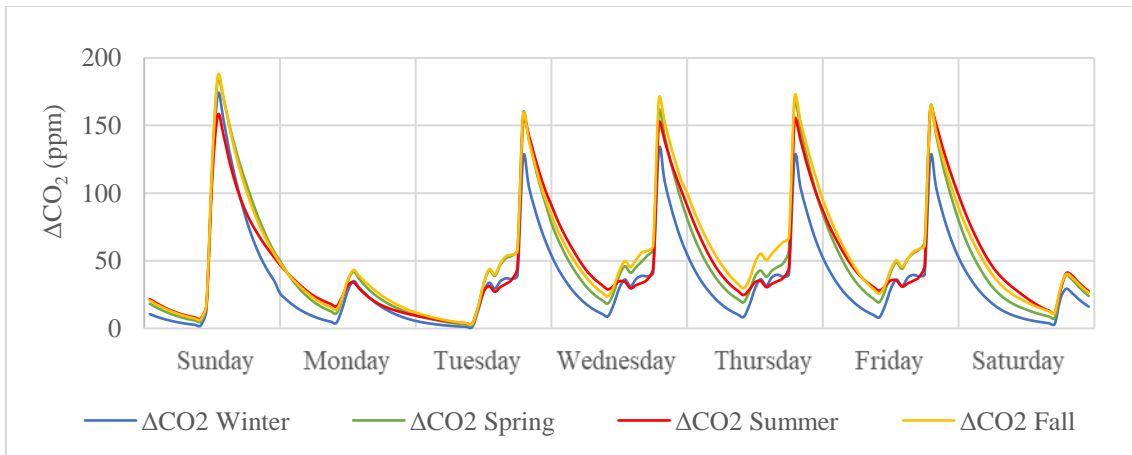


Figure 114- Sim\_3.2: ΔCO<sub>2</sub> levels and ACH average per day of the week and by Season

Visible in Figure 115, are the higher ach values during Winter and Summer and the higher CO<sub>2</sub> concentrations during Spring and Autumn.

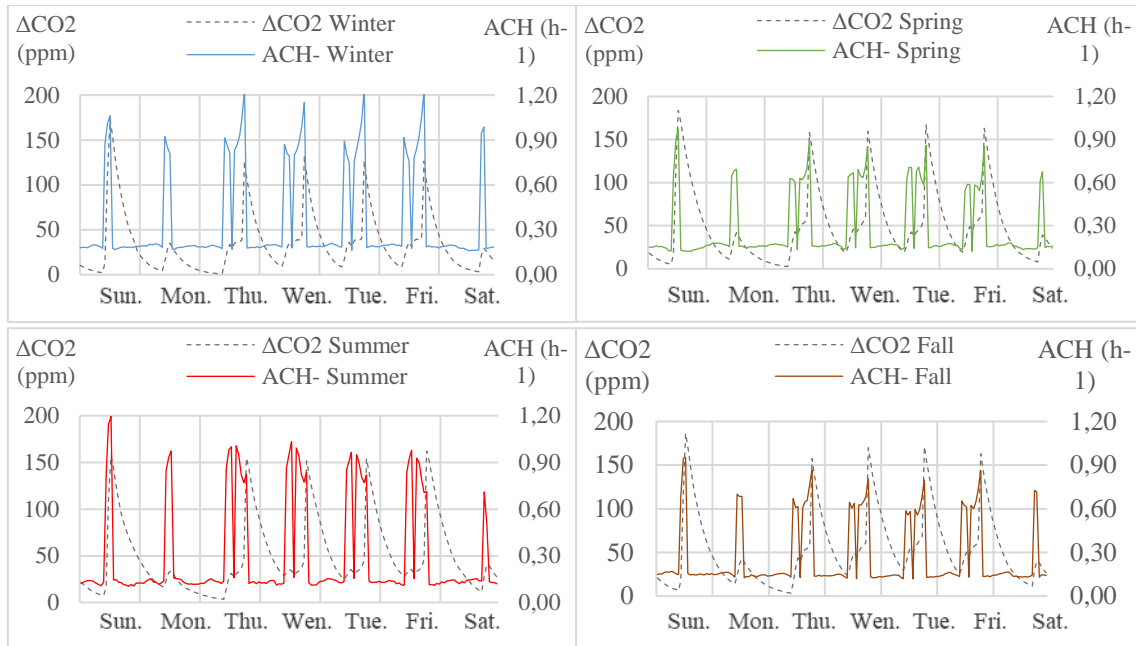


Figure 115- Sim\_3.2:  $\Delta CO_2$  levels and ACH average per day of the week and by Season

Sim\_3.2's  $CO_2$  concentrations, not surpassing the IDA 2 category threshold of 350ppm above outdoors concentration, have 100% of its time spent in IDA 1.

The visitation period registered all but one hour in compliance with the recommended ventilation rates and the mass attendance status was only able to assure the prescribed rates 67% of the time.

Table 41 summarizes the information mentioned above.

Table 41- Sim\_3.2: IDA Category based on  $CO_2$  levels and prescribed airflows verification

IDA Category	CO2 level above outdoor air (ppm-default value)	Airflow per person [m3/(h.person)]	% of time spent in IDA Category		% of time spent in IDA Category and respecting prescribed ACH values	
			visitation period	mass period	visitation period	mass period
IDA 1	350	72	100.0%	100.0%	99.9%	66.9%
IDA 2	500	45	0.0%	0.0%	-	-
IDA 3	800	29	0.0%	0.0%	-	-
IDA 4	1200	18	0.0%	0.0%	-	-

#### 4.2.4.2.4. Sim\_3.2: ASHRAE 62.1

Regarding the visitation period (Figure 116) of Sim\_3.2, ventilation rates are superior to the recommended by ASHRAE except for 2 hours in October.

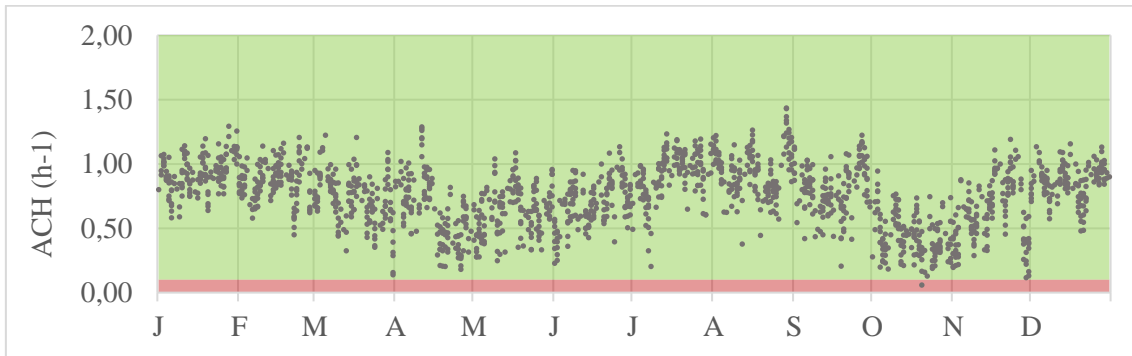


Figure 116- Sim\_3.2: ASHRAE 62.1 prescribed ACH for visitation attendance status

The entirety of the mass attendance status (Figure 117) is spent complying with the prescribed ach.

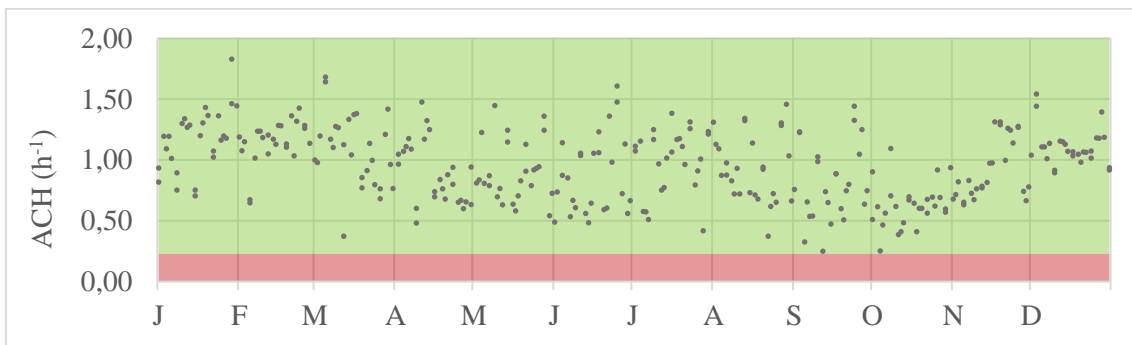


Figure 117- Sim\_3.2: ASHRAE 62.1 prescribed ACH for mass attendance status

During the closed period (Figure 118), 6.5% of the time registers ventilation rates below the threshold of the recommended values.

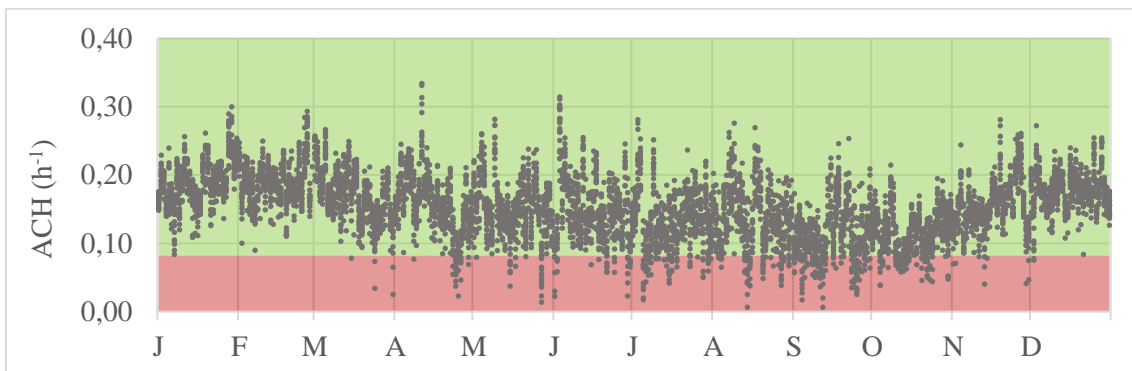


Figure 118- Sim\_3.2: Ashrae 62.1 prescribed ACH for closed attendance status

A year-long evaluation reveals 95% of the time respecting the recommended ventilation rates and the period with the lowest amount of acceptable ach is the closed attendance status.

Figure 119 and

Table 42 synthesizes the information presented above.

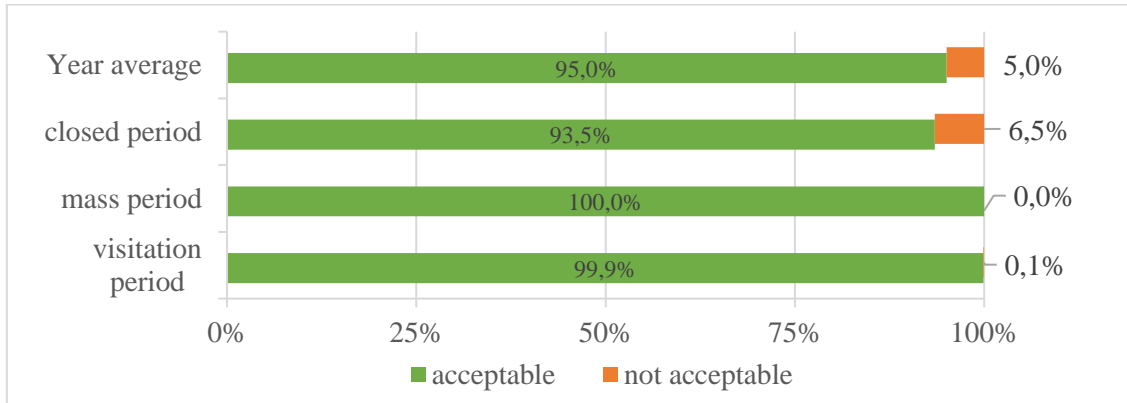


Figure 119- Sim\_3.2: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates

Table 42- Sim\_3.2: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status

attendance status	Number of hours in accordance with airflow prescribed values	% of time respecting prescribed ACH values per year	% of time respecting prescribed ACH values per attendance status
visitation period	1767	20.2%	99.9%
mass period	314	3.6%	100.0%
closed period	6242	71.3%	93.5%

#### 4.2.4.2.5. Sim\_3.2: CIBSE Guide A

The analysis of sim\_3.2 by the lens of CIBSE Guide A revealed the full compliance of prescribed ventilation rates through the visitation period (Figure 120).

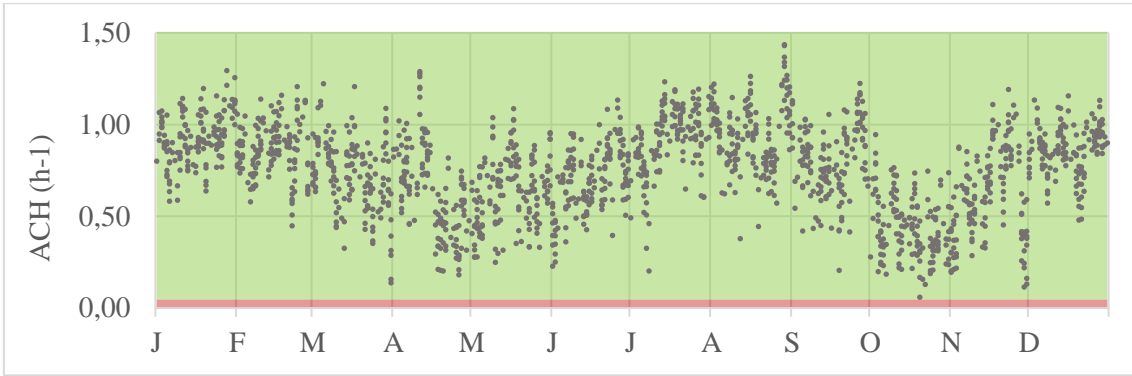


Figure 120- Sim\_3.2: CIBSE guide A prescribed ACH for visitation attendance status

From August until October, 5 data points revealed ventilation rates below the prescribed ones during the mass period (Figure 121).

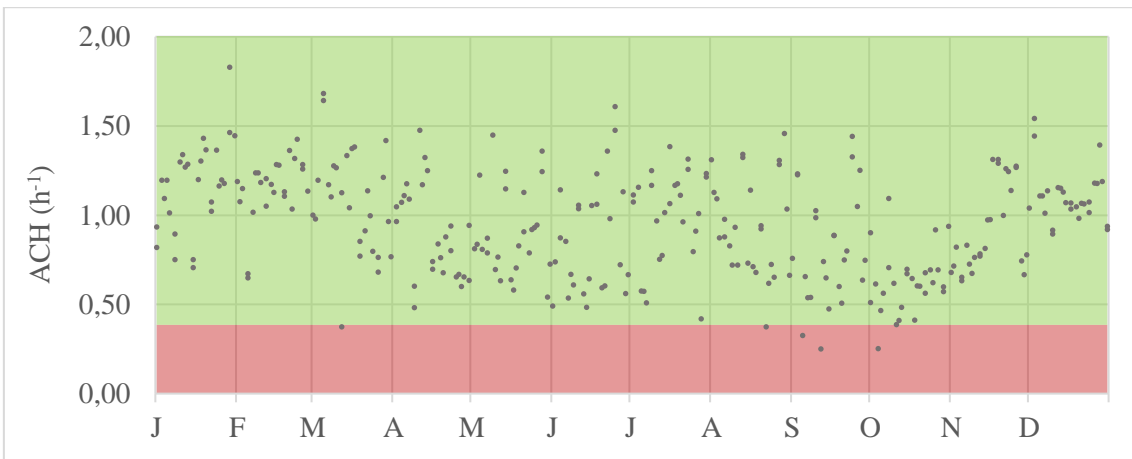


Figure 121- Sim\_3.2: CIBSE guide A prescribed ACH for mass attendance status

All around, and as comprehended with the analysis of Figure 122, the ventilation rates achieved translate into a very high IAQ by this standard.

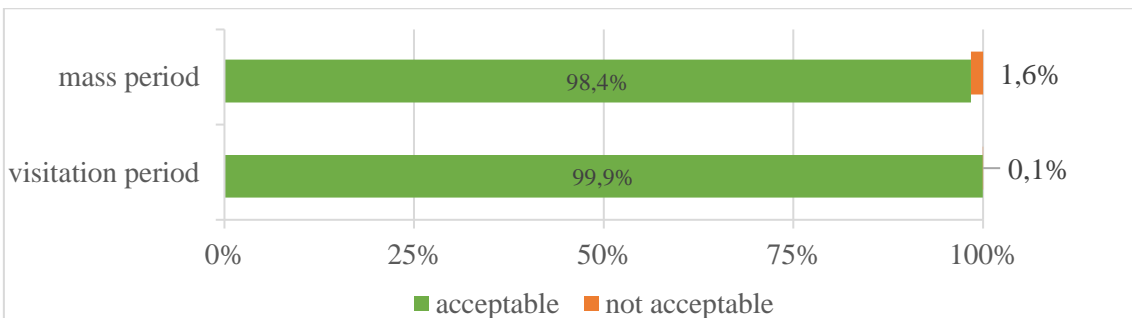


Figure 122- Sim\_3.2: Percentage of time respecting CIBSE guide A acceptable ventilation rates for visitation and mass attendance status

## 4.2.5. Ventilation strategies: Sim\_4

### 4.2.5.1. Sim\_4: General information

Sim\_4 aims to represent the expected increase in tourism in the year 2027. With a predicted annual increase of 6.1% of visits to Lisbon, the same amount was set to occupants of the church. During the visitation period, the equivalent of 9 persons CO<sub>2</sub> discharge was set, and during the mass period, the discharge of 72 occupants.

The open doors and windows were set to the same conditions as for Sim\_02, this is, the main door and the set of doors that give access to the mortuary house are open throughout the visitation and mass attendance status. The side door that connects the sacristy to the nave is open during the mass period as displayed in Figure 123.

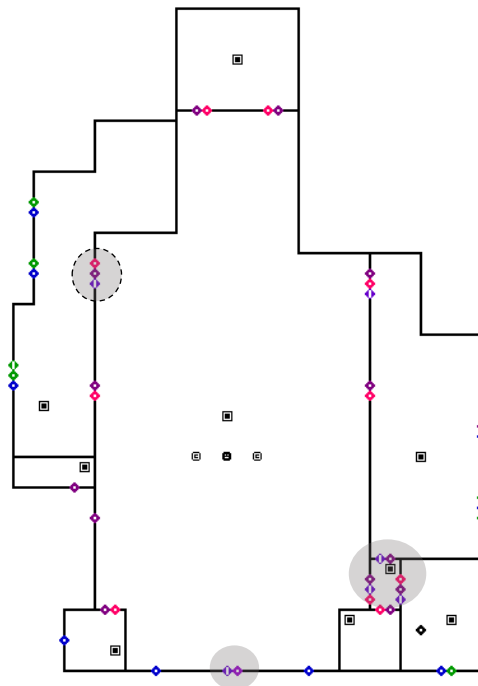


Figure 123- Sim\_4: floor 1 open/closed spans schematic

Because the simulation settings are the same as Sim\_02, except for the number of occupants, ventilation rates and average values are also the same. These results can be consulted in sub-chapter 4.2.1.1 and in the table below.

Table 43- Sim\_4: ACH values for each season and church attendance status throughout the year

Church attendance status	Season			
	Winter	Spring	Summer	Autumn
closed period	0.19	0.16	0.13	0.14
visitation period	0.87	0.63	0.87	0.64
mass period	0.93	0.64	0.68	0.70

#### 4.2.5.2. Sim\_4: EN 15251

The main differences in this simulation are the prescribed ventilation rates due to the increase in the number of occupants during the visitation and mass attendance status.

During the visitation period (Figure 124), the increase in people does not change the results previously achieved as the 4 people augment, from 5 to 9, do not weigh heavily on the ventilation formula. 99.5% of the time is spent under categories I and II, revealing an extremely acceptable IAQ.

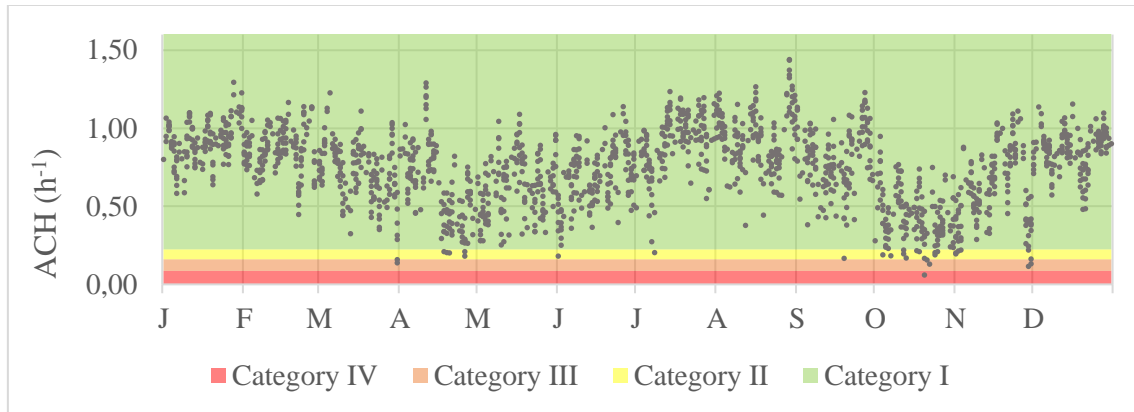


Figure 124- Sim\_4: ventilation rates vs EN 15251 hourly prescribed ventilation rates: visitation period

Throughout the mass period, bigger changes occur compared to the other simulation. A rapid examination of Figure 125 shows the increase of registered hours complying with category III and IV, comparing with other simulations.

The 72 occupants of the church during the mass service are responsible for the 28.7%, 23.9%, and 6.1% of time spent under categories II, III, and IV, respectively, leaving 41.4% of the time in category I. Given that the description of category IV is “Values outside the criteria for the above categories. This category should only be accepted for a limited part of the year” the result shows the acceptable IAQ, even with the increase in population and with no changes to the current ventilation strategy.

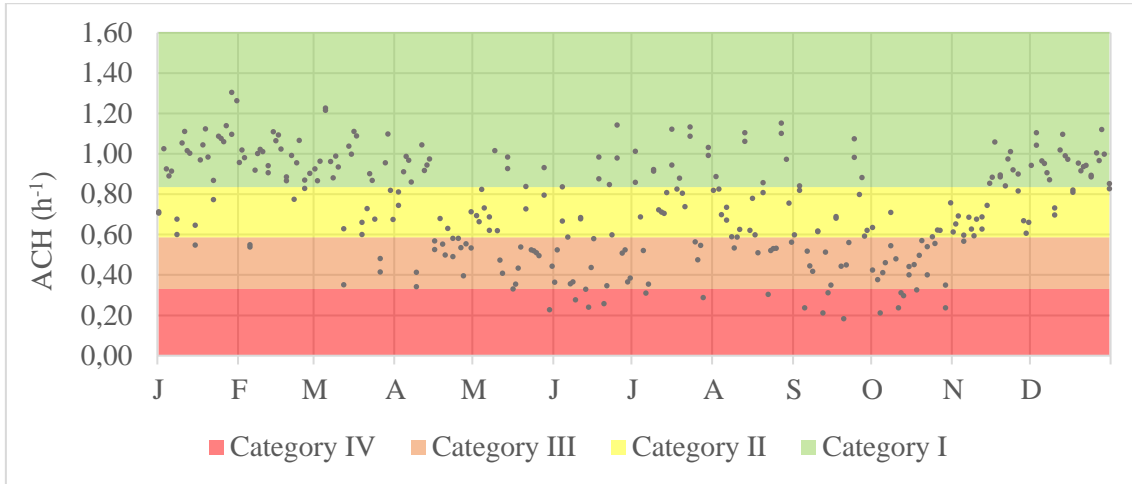


Figure 125- Sim\_4: ventilation rates vs EN 15251 hourly prescribed ventilation rates: mass period

The analysis of the closed period can be consulted in sub-chapter 4.2.1.2.

When an analysis of Table 44 is made, it is possible to conclude that only 0.24% of the time is spent under category IV and during a period with people inside the church.

Table 44- Sim\_4: EN 15251 Category based on ACH values

EN 15251 Category based on ACH values	number of hours in category			% of time spent in category per year			% of time spent in category per attendance status		
	visitation period	mass period	closed period	visitation period	mass period	closed period	visitation period	mass period	closed period
Category I	1736	130	4271	19.82%	1.48%	48.76%	98.1%	41.4%	64.0%
Category II	25	90	1557	0.29%	1.03%	17.78%	1.4%	28.7%	23.3%
Category III	6	75	768	0.07%	0.86%	8.77%	0.3%	23.9%	11.5%
Category IV	2	19	80	0.02%	0.22%	0.91%	0.1%	6.1%	1.2%
<b>Total</b>	1769	314	6676	20.2%	3.6%	76.2%	100%	100%	100%

The most relevant church attendance status for the application of this standard is the mass period where the larger number of occupants is set.

Figure 126 compares the three different church attendance statuses and displays the percentage of time each period complies with the prescribed ventilation rates.

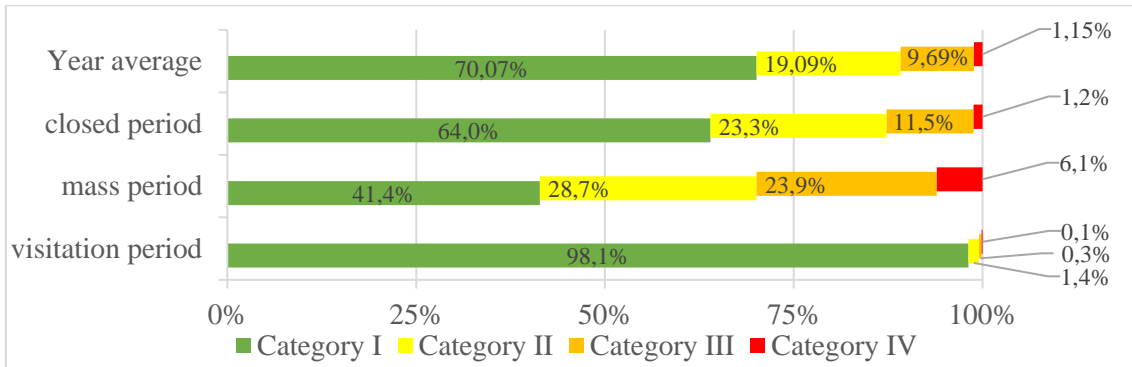


Figure 126- Sim\_4: Percentage of time spent in each EN 15251 category per church attendance status

#### 4.2.5.3. Sim\_4: EN 13779

Considering the uprise in occupants. especially during the mass period, CO<sub>2</sub> concentrations increase significantly when comparing with any other simulation (Figure 127).

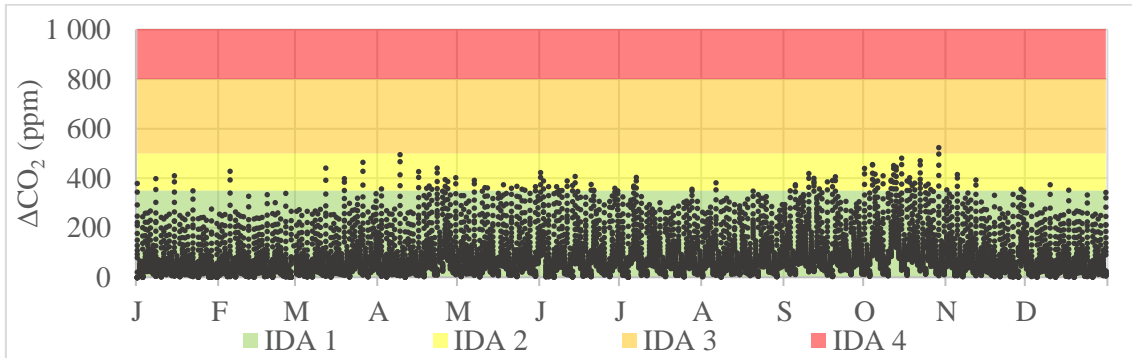


Figure 127- Sim\_4: CO<sub>2</sub> levels in São Cristovão's main nave (units in ppm above outdoor concentration)

Average seasonal peak values, immediately after the Sunday mass, range from 323 to 401 ppm above outside concentrations, for the Summer and Autumn, respectively. Figure 128 displays the effective dissipation of the pollutant due to the higher ach during Winter weekdays, and the inability to restore CO<sub>2</sub> levels to outside values throughout Spring, Summer and Autumn.

During the weekdays when mass occurs, CO<sub>2</sub> average peak concentrations for the Wintertime are circa 22% lower than the remaining seasons.

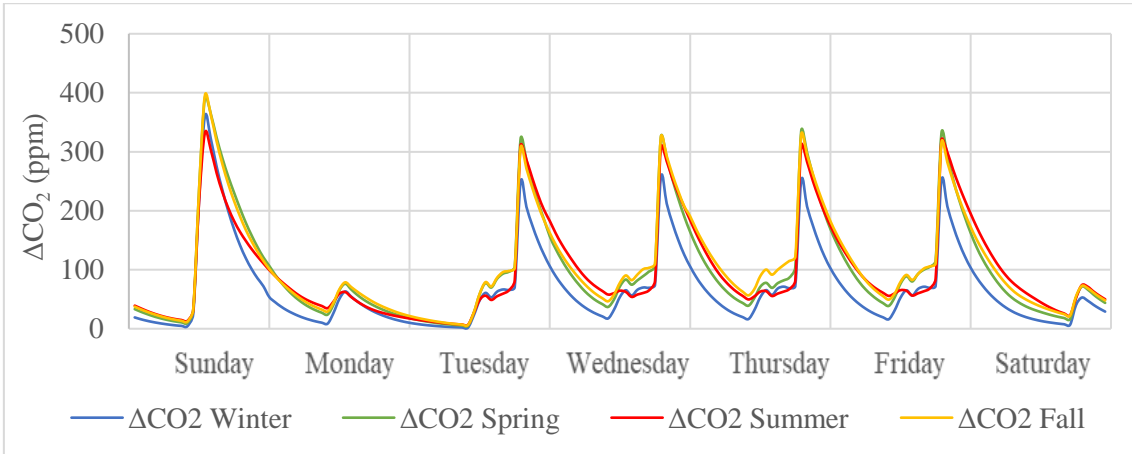


Figure 128- Sim\_4: CO<sub>2</sub> hourly average concentration levels by day of the week and season

Visible in Figure 129 Figure 115 are the higher ach values during Winter and Summer and the higher CO<sub>2</sub> concentrations during Spring and Autumn.

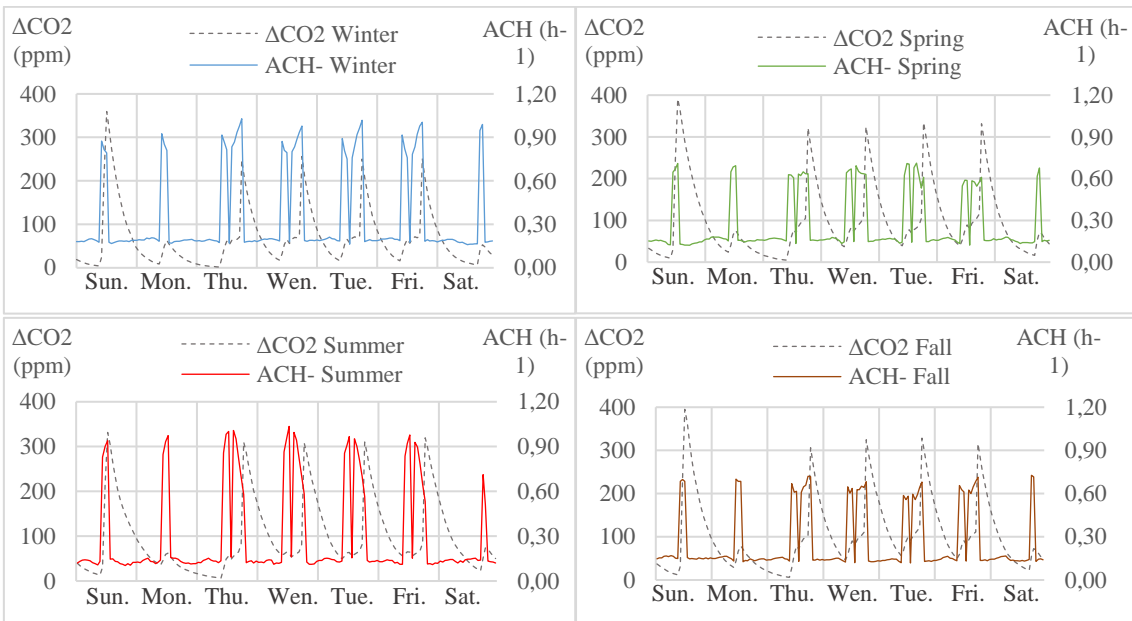


Figure 129- Sim\_4: Average hourly ACH and CO<sub>2</sub> concentrations above out-door levels by day type and season

Table 45 synthesizes the amount of time in compliance with EN 13779 ventilation rates for each IDA category for the year that was simulated in Contam. It is possible to see that for the entirety of the mass period, prescribed ventilation rates are not met for any IDA category.

Table 45 Sim\_4: IDA Category based on CO2 levels and prescribed airflows verification

IDA Category	CO2 level above the level of outdoor air (ppm-default value)	Airflow per person [m3/(h.person)]	% of time spent in IDA Category		% of time spent in IDA Category and respecting prescribed ACH values	
			visitation period	mass period	visitation period	mass period
IDA 1	350	72	100.0%	76.8%	99.3%	0%
IDA 2	500	45	0.0%	22.9%	-	0%
IDA 3	800	29	0.0%	0.3%	-	0%
IDA 4	1200	18	0.0%	0.0%	-	-

#### 4.2.5.4. Sim\_4: Ashrae 62.1

Given the difference in the number of occupants of Sim\_4 compared to the other simulations, ASHRAE 62.1 prescribes a larger amount of fresh air. New ventilation rates are presented in Table 46.

Table 46- ASHRAE 62.1 Prescribed airflow rates

Compartment type	r <sub>p</sub> - Airflow per person [m3/(h.person)]	r <sub>a</sub> - Airflow per floor area [m3/(h.m2)]	church airflow needs (ACH)		
			visitation period (9 per.)	mass period (72 per.)	closed period (0 per.)
museums	13.7	1.08	0.116	0.348	0.083
churches	9	1.08	0.105	0.257	

Most of the time, prescribed airflow rates are respected during the visitation period (Figure 130).

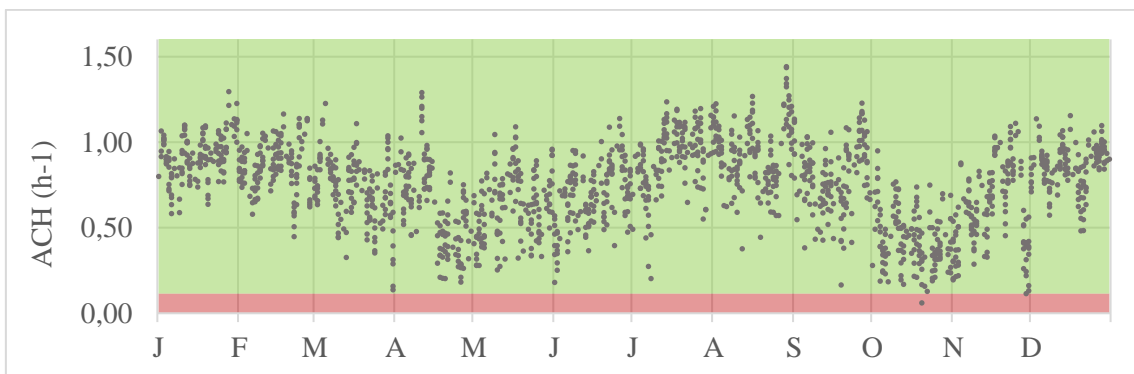


Figure 130- Sim\_4: ASHRAE 62.1 prescribed ACH for visitation attendance status

The occurrence of days where mass period prescribed ventilation rates are not respected befall from March until November (Figure 131). During these months, wind speeds and temperature differential are not enough to achieve the recommended ACH.

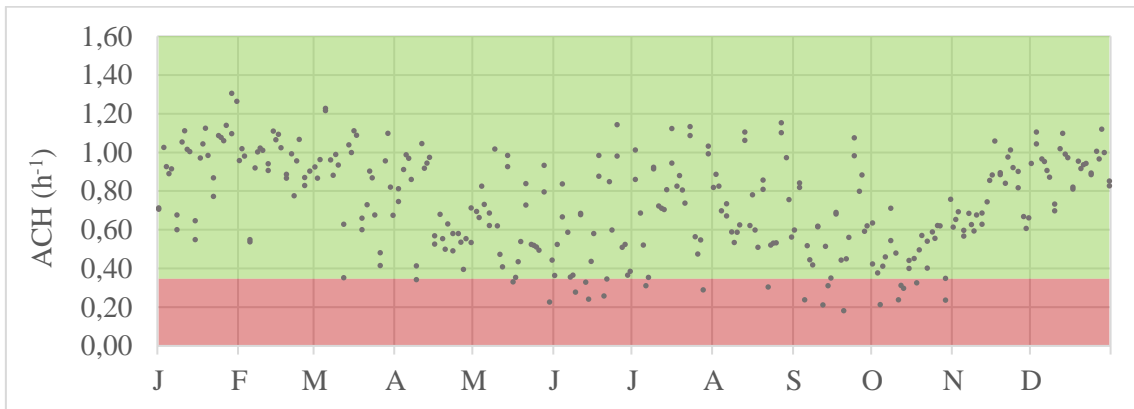


Figure 131- Sim\_4: ASHRAE 62.1 prescribed ACH for mass attendance status

During the closed period (Figure 132), circa 94% of the time is spent under the prescribed ventilation rates.

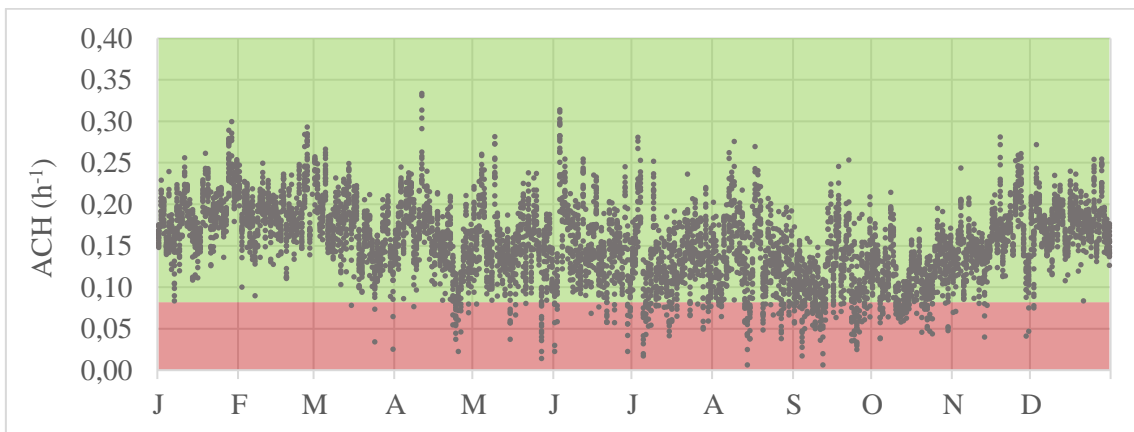


Figure 132- Sim\_4: ASHRAE 62.1 prescribed ACH for closed attendance status

Figure 133 and Table 47 compile the information previously mentioned.

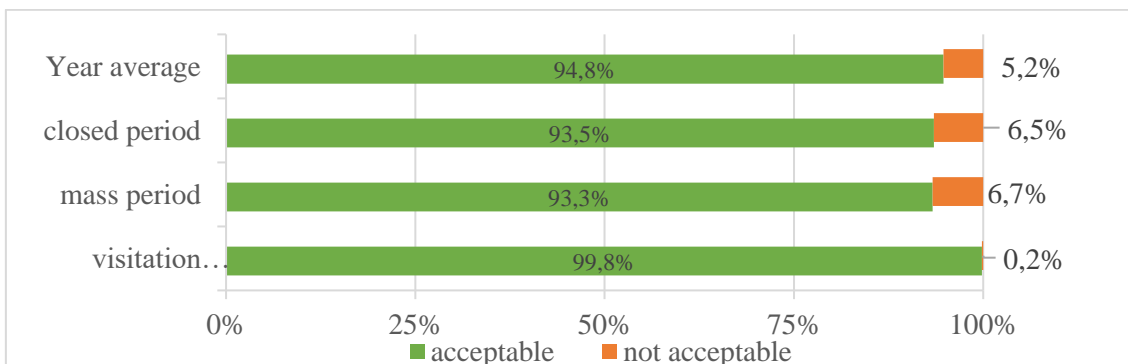


Figure 133- Sim\_4: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates

Table 47- Sim\_4: Percentage of time respecting ASHRAE 62.1 prescribed ventilation rates by church attendance status

attendance status	Number of hours in accordance with airflow prescribed values	% of time respecting prescribed ACH values per year	% of time respecting prescribed ACH values per attendance status
visitation period	1766	20.2%	99.8%
mass period	293	3.3%	93.3%
closed period	6242	71.3%	93.5%

#### 4.2.5.5. Sim\_4: Cibse Guide A

Through the visitation period (Figure 134), only one hour of the year was recorded not complying with the prescribed ventilation rate of 0.087 ach. This point is referent to the 20<sup>th</sup> of October at 16:00.

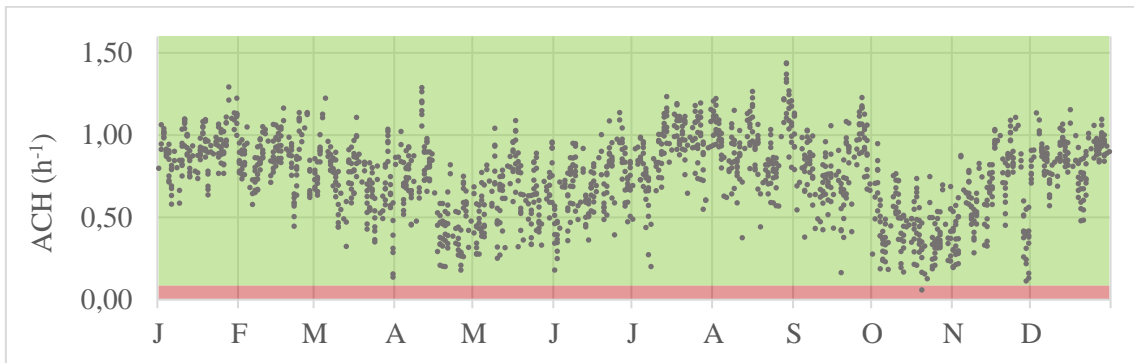


Figure 134- Sim\_4: CIBSE guide A prescribed ACH for visitation attendance status

During the mass attendance status of Sim\_4 (Figure 135), the prescribed ventilation rate is achieved approximately half the time. The occasions that are not possible to respect the ach values start with a higher frequency in April and diminish in November.

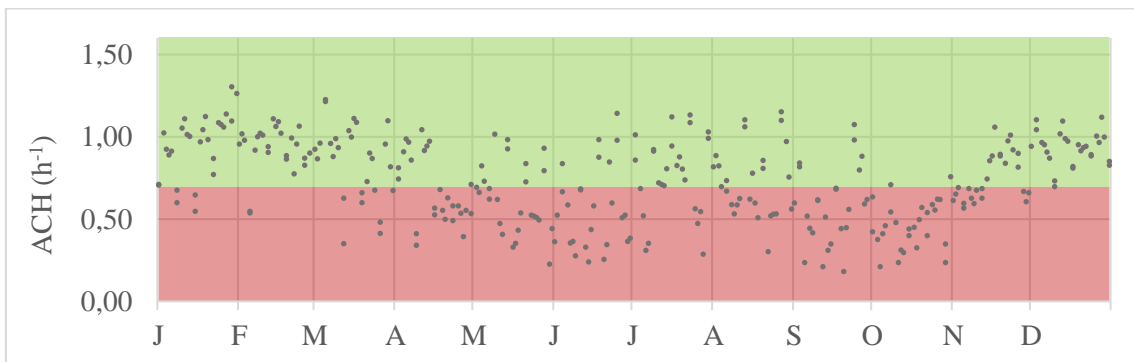
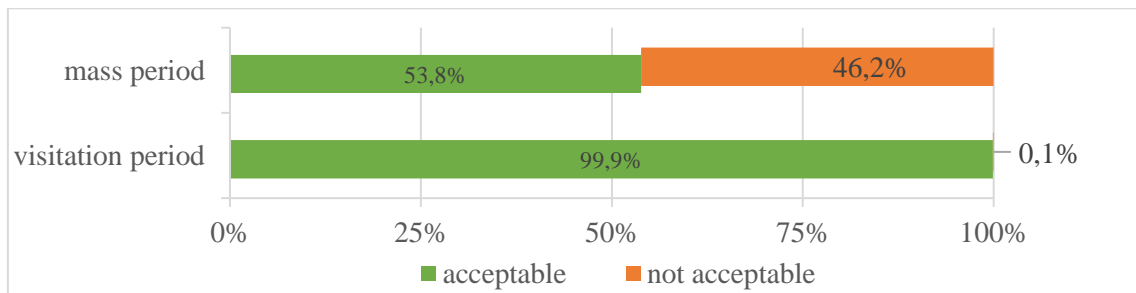


Figure 135- Sim\_4: CIBSE guide A prescribed ACH for mass attendance status

Figure 136 compiles the information displayed above.



*Figure 136 - Sim\_4: Percentage of time respecting CIBSE guide A acceptable ventilation rates for visitation and mass attendance status*

With the increase in the number of occupants, CO<sub>2</sub> levels are not the only factor that should be studied. Such growth is likely to affect the RH of the church as the population release water vapor into the church climate. Whether this increase is significant enough to affect the conservation of the sculptures, painted panels and furniture is not going to be quantified, whoever can be discussed.

During the Spring season, the walls of the church are cold due to the high thermal inertia, as they lost heat during the Winter month. Exterior temperatures, during the day, are warmer and RH levels are high some days. Adding to this, water vapor present in the church due to the mass services should increase the overall indoor RH. If ventilation rates are increased during the latter part of the day or even at night, some damaging effects may occur. This situation creates conditions for the occurrence of superficial condensations. The warmer and nearly saturated air, when in contact with the colder wall surface, condense.

As so, the increase in ventilation rates, especially during the Spring should be carefully analyzed to avoid the risk of biological proliferation.

### 4.3. Comparison of the results

The focus of this sub-chapter will be to compare all the simulations in terms of ventilation rates, CO<sub>2</sub> concentrations and the results of the application of different standards.

The first and last simulations, Sim\_02 and Sim\_4, having the same span opening/closing schedule, ACH values are also the same (Figure 139). What differs is CO<sub>2</sub> concentrations as the number of occupants are different for the two simulations.

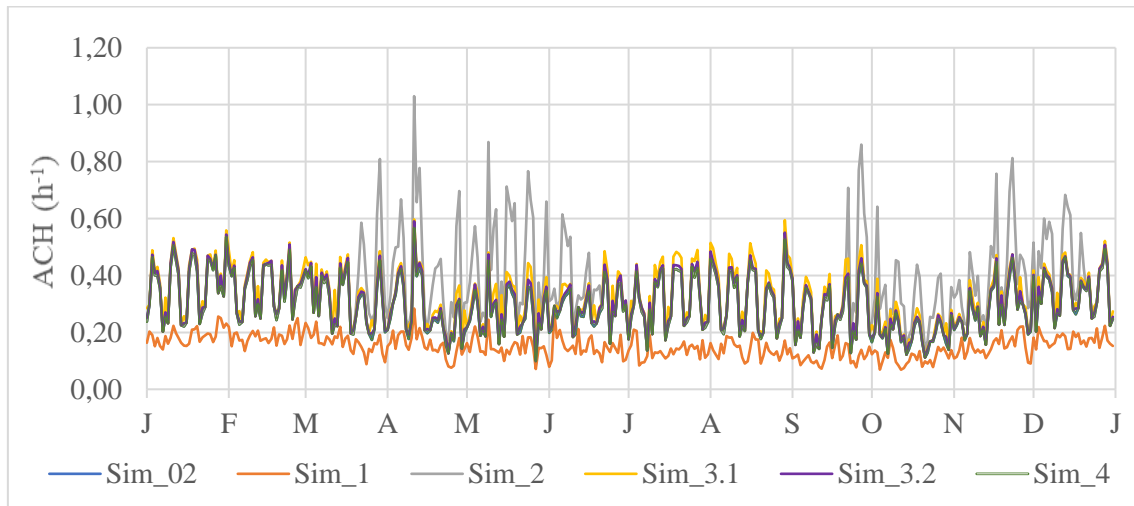


Figure 137- Average daily ach for each simulation

Sim\_1, representing the closed status for the entire year, will not be referenced as much as the other simulation because it is a hypothetical scenario in which some standards do not apply, and given that there is no occupant, CO<sub>2</sub> concentrations are static. This simulation can supply an important base for future works that study the implications of the covid-19 pandemic and its impact on the artwork roosted in the church of São Cristóvão.

Sim\_2, presenting the highest spikes in ventilation rates due to the opening of the bell towers during Spring and Autumn, is the strategy with the highest seasonal average ACH for these two seasons. The average ACH for the Summer and Winter are the same as Sim\_02 that represents the current ventilation behaviour. If a comparison with the current ventilation behaviour is made, for the time when the Sim\_2 strategy is in place, an increase of 28% in m<sup>3</sup> of air per hour is achieved.

Sim\_3.1 and Sim\_3.2, the two cross-ventilation strategies implemented in CONTAM, show good results. Sim\_3.1, having the 2<sup>nd</sup> grater ACH average of all simulations ensures an acceptable IAQ by all standards. On a monthly average, Sim\_3.1 has a 5% increase in ventilation capacity compared to Sim\_3.1.

The seasonal average ACH is displayed in Figure 138.

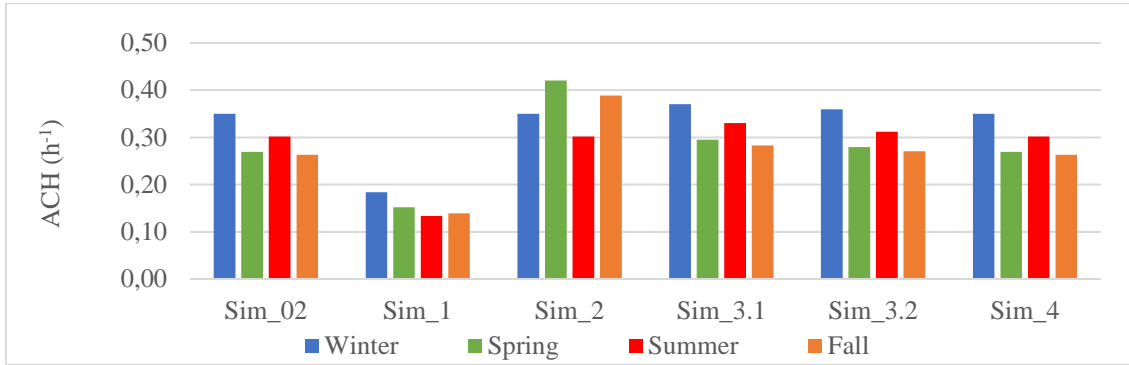


Figure 138- Average seasonal ach for each simulation

During Winter and Summer, sim\_02, Sim\_3.1 and Sim\_4 have the same ventilation characteristics and therefore, ACH values. Sim\_2 has the largest amount of fresh air entering the church during the Spring and Autumn, compared to the other simulations.

Sim\_3.2 shows the ventilation capabilities of the church if the correct pathways are available for the air to move through. If the two small windows are open in a small room, during the mass time, very similar results are achieved compared to the Sim\_3.1, simulation where windows and doors on opposite sides of the church need to remain open for the duration of the mass service.

A monthly analysis of the results, Figure 139, can display the far superior ventilation capability of the Sim\_2 strategy, and the small variations between sim\_02 and the remaining simulations, apart from Sim\_1.

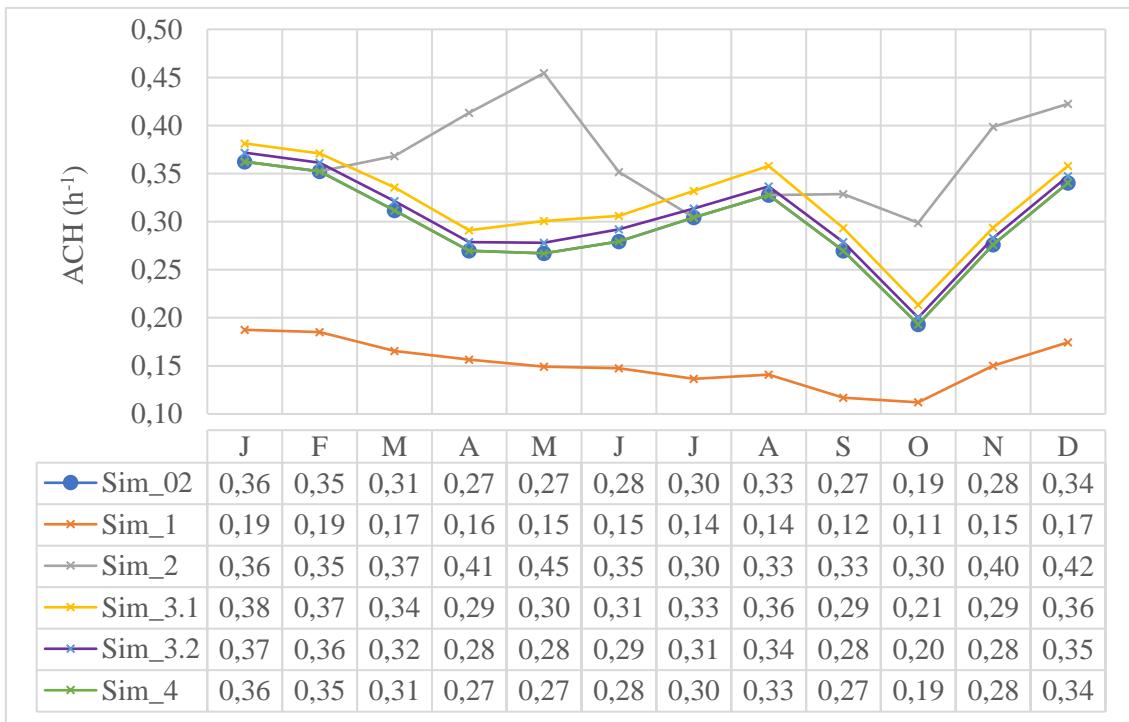


Figure 139- Average monthly ach for each simulation

An interesting and relevant comparison is the one where all simulations are studied against the current ventilation behaviour of the church. For this purpose, Table 48 is presented.

Sim\_1 shows circa -48% of the fresh air circulation in the church. Sim\_2, although only applicable during a limited amount of the year shows a significant increase in ACH values. With this strategy implemented, new studies should be made regarding the air velocity and trajectory near the artworks displayed inside the church in a conservation effort, which is not the aim of this document.

Although both Sim\_3.1 and Sim\_3.2 also increase the ventilation rates throughout the year, the first has a more significant effect as the direction of the wind tends to follow a north-south trajectory and the windows opened are also larger.

Sim\_4, having the same ventilation performance as Sim\_02 will be compared in the CO<sub>2</sub> analysis.

*Table 48- Ventilation rate comparison to the current ventilation performance, by month*

Month	Simulation ACH variation compared to Sim_02				
	Sim_1	Sim_2	Sim_3.1	Sim_3.2	Sim_4
January	-48%	0%	5%	3%	0%
February	-47%	0%	5%	3%	0%
March	-47%	18%	8%	3%	0%
April	-42%	53%	8%	3%	0%
May	-44%	70%	13%	4%	0%
June	-47%	26%	9%	4%	0%
July	-55%	0%	9%	3%	0%
August	-57%	0%	9%	3%	0%
Septembre	-57%	22%	9%	3%	0%
Octobre	-42%	55%	10%	4%	0%
November	-46%	44%	6%	3%	0%
December	-49%	24%	5%	2%	0%
<b>yearly average</b>	<b>-48%</b>	<b>26%</b>	<b>8%</b>	<b>3%</b>	<b>0%</b>

Seasonally, the CO<sub>2</sub> indoor/outdoor differential was examined. During Winter, all simulations showed the highest ach values leading to low CO<sub>2</sub> concentrations, apart from Sim\_2, where the lowest concentration was found in the Spring, as depicted in Figure 140.

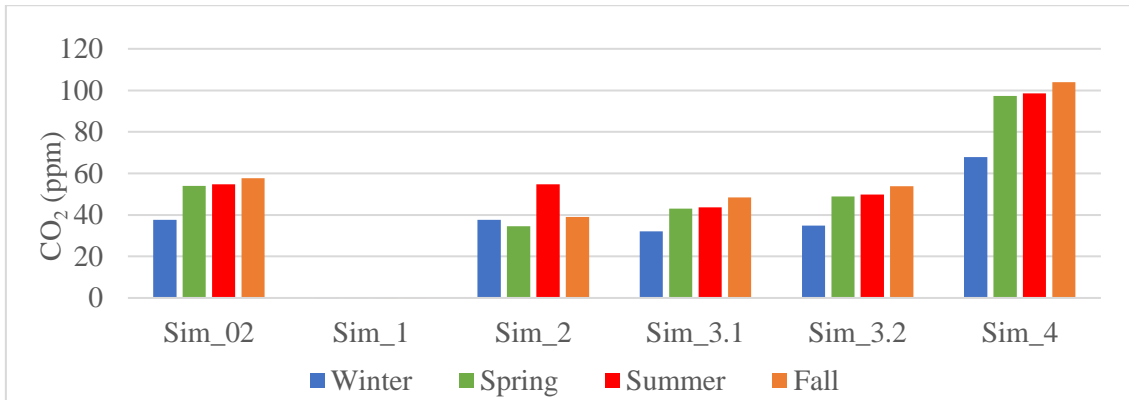


Figure 140- Average seasonal  $\Delta CO_2$ (ppm), by simulation

Figure 141 shows the hourly evolution of all simulations throughout the year.

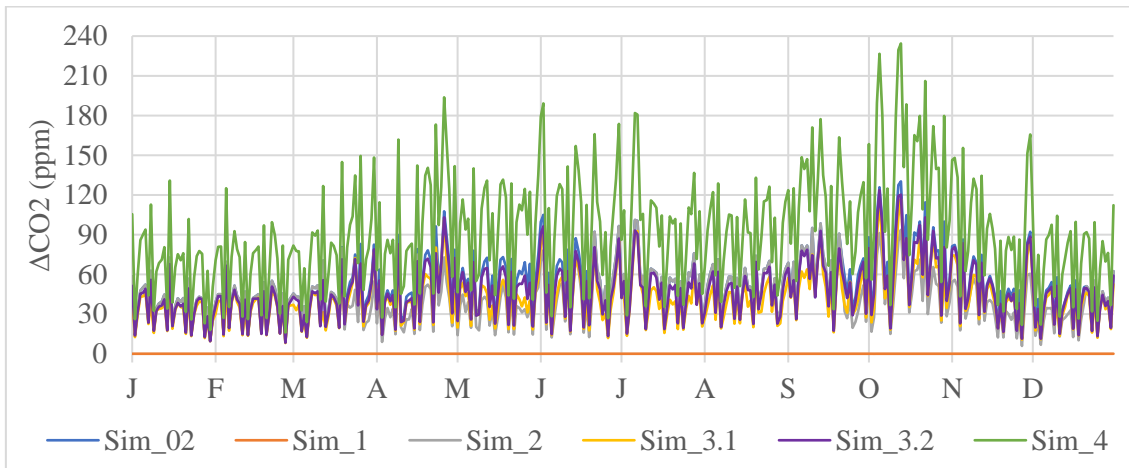


Figure 141- Average daily  $\Delta CO_2$ (ppm), by simulation

An analysis was conducted regarding the average hourly  $CO_2$  concentrations in the church's nave by day of the week. This examination of the pollutant behaviour can, firstly, eliminate extreme events such as the spikes observed in some days of October, and secondly, give a visual aid in the comprehension of  $CO_2$  extraction patterns. The values showed in Figure 142 are the hourly average for the entire year.

The only simulation that shows a relevant difference is Sim\_4, as the number of occupants is significantly larger comparing to the other scenarios. Sunday peak values average 370 ppm above outdoor concentrations, corresponding to IDA 2 category. All other simulations do not show significant variation considering the 350ppm threshold that separates IDA 1 from IDA 2.

Observable in Figure 142 are the highest values are seen in Sim\_4 for the larger number of occupants during the open hours. This increase compared to Sim\_02 is responsible for the passage of IDA category from 1 to 2. It is relevant to mention the good IAQ attributed to IDA classes 1,2 and even 3.

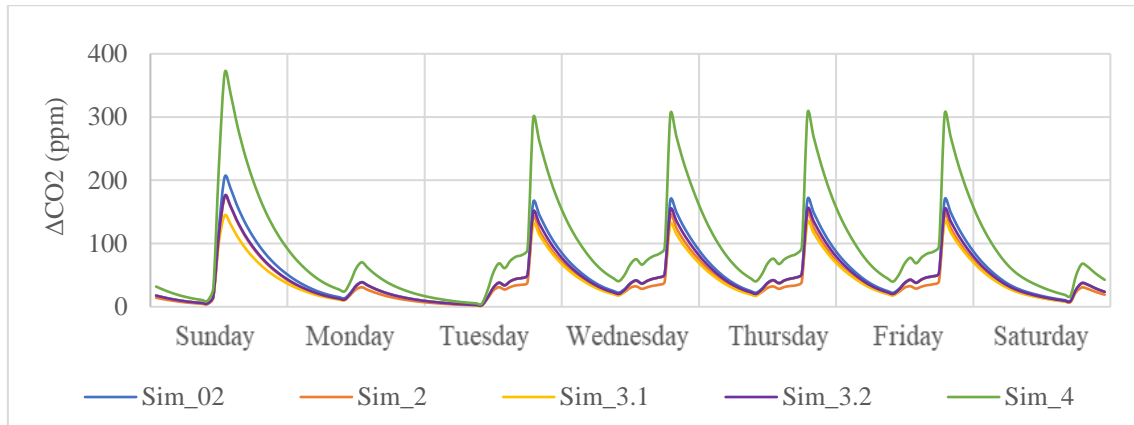


Figure 142- Average  $\Delta CO_2$ (ppm) for each simulation, by day type

Although a more in-depth analysis will be made, the monthly average  $\Delta CO_2$  concentration, displayed in Table 49, shows the larger values of Sim\_4.

Table 49- Monthly average  $\Delta CO_2$  concentration, by month in ppm

Month	Simulation					
	Sim_02	Sim_1	Sim_2	Sim_3.1	Sim_3.2	Sim_4
January	36	0	36	31	34	65
February	37	0	37	32	34	66
March	45	0	38	38	41	81
April	54	0	37	44	49	97
May	53	0	33	39	47	96
June	57	0	47	46	51	103
July	51	0	51	41	47	93
August	49	0	49	38	45	89
September	62	0	56	50	56	112
October	77	0	54	64	72	139
November	52	0	36	45	49	93
December	39	0	31	34	36	70
<b>yearly average</b>	<b>51</b>	<b>0</b>	<b>42</b>	<b>42</b>	<b>47</b>	<b>92</b>

Considering a seasonal analysis of average hourly  $CO_2$  by day type, it is possible to infer the proximity of results during the Wintertime for all simulations, excluding Sim\_1 and Sim\_4. Sim\_1 has 0 occupants and therefore, a constant 0  $\Delta CO_2$  concentrations. Therefore, no comparison or analysis will be made; Sim\_4 has a larger number of both visitors and mass attendees.

All other ventilation strategies show similar results in terms of this pollutant. The reason for this is the fact that mass service is the main responsible for  $CO_2$  emissions, and after this period, once the church is closed, the ventilation of the building is secured totally by infiltration. Since in all simulations, infiltration parameters of spans, walls and roofing

are the same, infiltration rates are the same as well. What this means is that carbon dioxide concentrations can only be controlled by ventilation rates attributed to the open-door period, if considering the simulations that are presented in this document.

Sim\_3.1 presents the lowest concentrations in the Winter and Summer seasons, with maximum average values of 139 for both seasons (Figure 143). These values occur during Sunday mass.

During the Spring and Autumn seasons, Sim\_2 poses the lowest results as the seasonal opening of the bell towers creates an increase in ventilation rates during the open doors period.

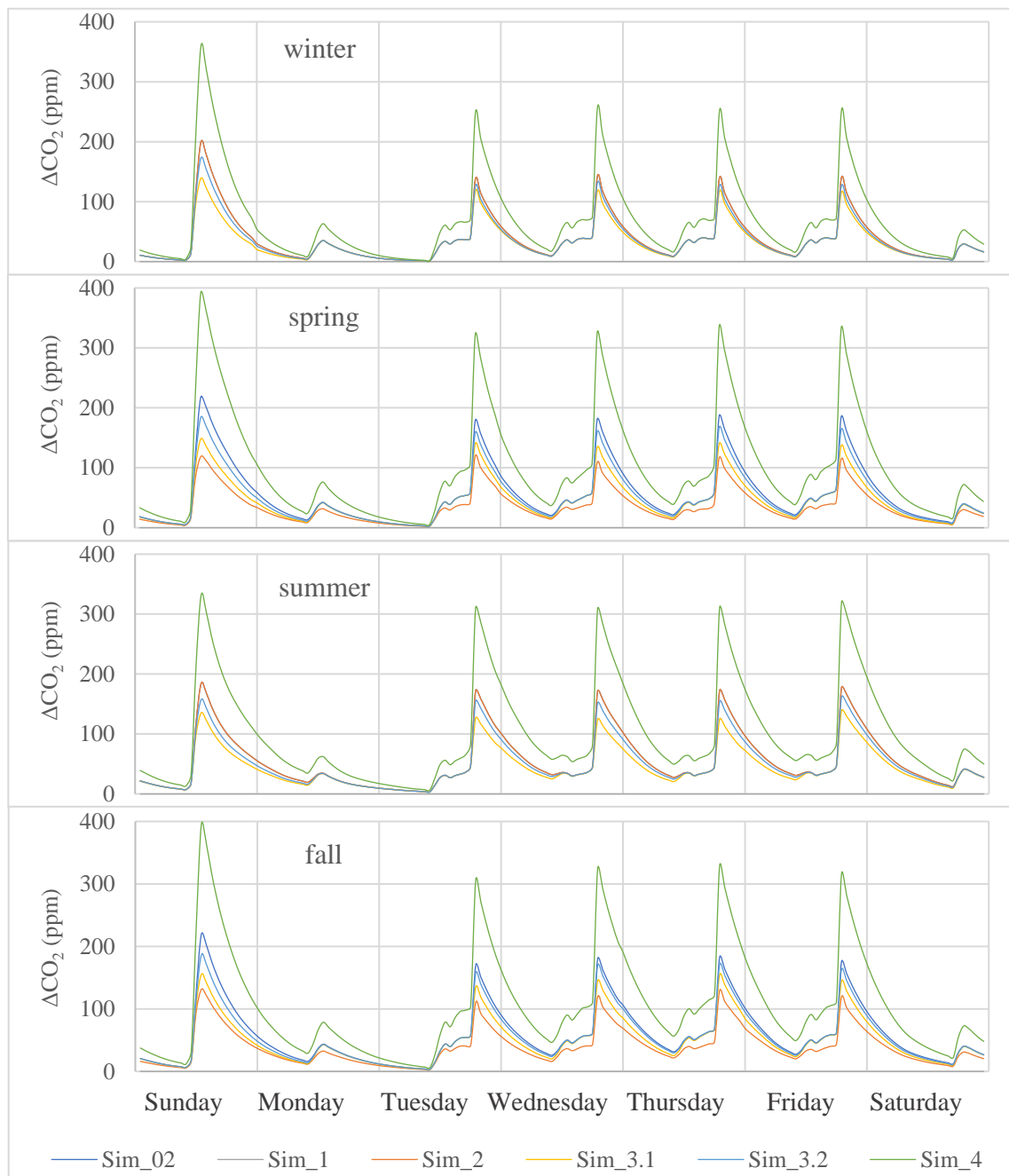


Figure 143- Average  $\Delta\text{CO}_2$ (ppm) for each simulation by day type for all seasons.

A comparison between Sim\_02 and the remaining simulations was made in order to better understand the effects of increasing the church's ach in CO<sub>2</sub> concentrations.

Sim\_2 has a reduction of 28% and 23% of CO<sub>2</sub> concentration for the Spring and Autumn seasons, respectively, and an 18% decrease considering the entire year. For the Winter and Summer seasons, since the ventilation strategies are the same for sim\_02 and Sim\_2, no variations are detected in Figure 143.

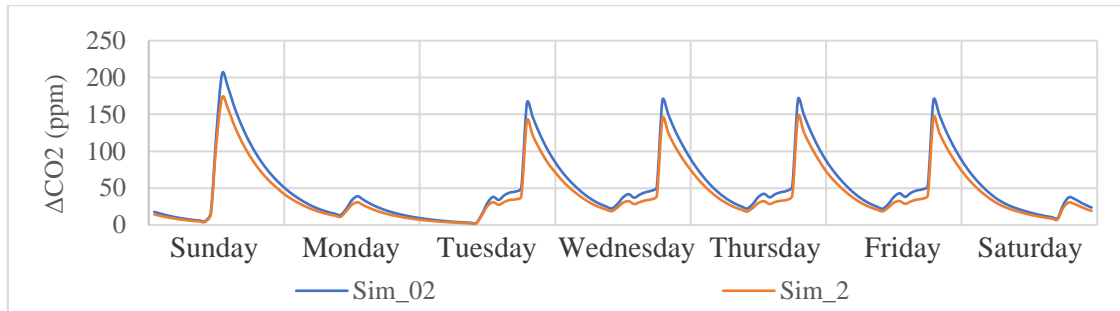


Figure 144 Average hourly CO<sub>2</sub> concentration by day of the week comparison between Sim\_02 and Sim\_2

Sim\_3.1 presented an annual average decrease in CO<sub>2</sub> concentration of 18%. Sunday's average peak value of 144ppm, immediately after the mass service, is relatively lower compared to the 205ppm for the same period of Sim\_02. During the weekdays where mass occurs, CO<sub>2</sub> concentration difference between the two simulations is circa 33ppm and a 2 to 5ppm difference was found at the moment the doors of the church open at each day.

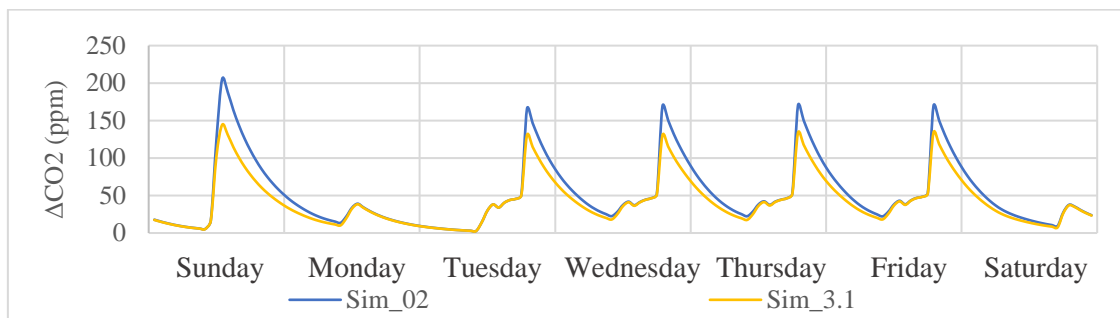


Figure 145- Average hourly CO<sub>2</sub> concentration by day of the week comparison between Sim\_02 and Sim\_3.1

Sim\_3.2 presented an annual average decrease in CO<sub>2</sub> concentration of 8%. Sunday's average peak value of 160ppm, immediately after the mass service, is relatively lower compared to the 205ppm for the same period of Sim\_02. During the weekdays where mass occurs, CO<sub>2</sub> concentration difference between the two simulations is circa 33ppm and no difference was found when opening the church doors each day.

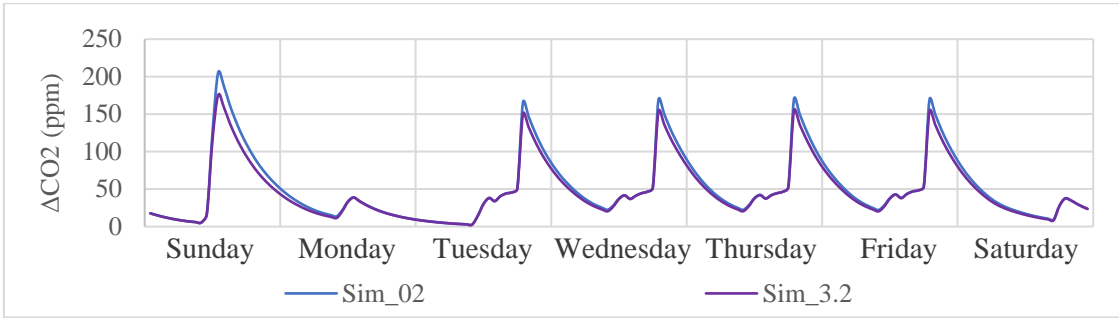


Figure 146- Average hourly CO<sub>2</sub> concentration by day of the week comparison between Sim\_02 and Sim\_3.2

Sim\_4 presented an annual average increase in CO<sub>2</sub> concentration of 80% (Figure 149). Sunday average peak value of 338ppm, immediately after the mass service. During the weekdays where mass occurs, CO<sub>2</sub> concentration difference between the two simulations is circa 135ppm, and, unlike the previously examined simulations, a difference was found at the moment the doors of the church open at each day, this is, the ventilation by infiltration during the closed hours is no longer able to remove as much used air. Circa 25ppm difference was detected right before the doors of the church are open on Wednesday, Thursday, and Friday. The remaining days of the week, Sunday, Monday and Saturday have an extended period of time before the doors are open where no occupants are releasing CO<sub>2</sub>.

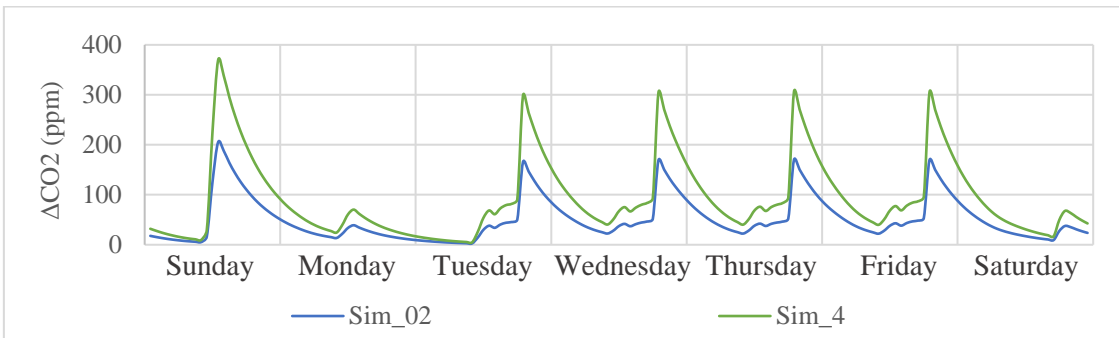


Figure 147- Average hourly CO<sub>2</sub> concentration by day of the week comparison between Sim\_02 and Sim\_4

Table 50 shows the percentage difference of the monthly CO<sub>2</sub> concentration average compared to the current ventilation behaviour of São Cristóvão church, sim\_02.

An important conclusion is the one that acknowledges the lack of necessity regarding changes in ventilation strategy. Sim\_02, the current ventilation strategy, showed to be highly capable of maintaining low levels of the analyzed pollutant. The increase in ventilation rates comes with an increase in air velocity both around the occupants, reducing the thermal sensation of people inside and around the artwork displayed, possibly augmenting deposition rates of other pollutants and fomenting abrasion.

Table 50- Monthly average  $\Delta\text{CO}_2$  concentration comparison to the current ventilation performance, by month

Month	Simulation $\Delta\text{CO}_2$ variation compared to Sim_02				
	Sim_1	Sim_2	Sim_3.1	Sim_3.2	Sim_4
January	-	0%	-15%	-7%	80%
February	-	0%	-14%	-7%	80%
March	-	-15%	-16%	-8%	80%
April	-	-31%	-17%	-8%	80%
May	-	-38%	-26%	-11%	80%
June	-	-18%	-20%	-11%	80%
July	-	0%	-20%	-9%	80%
August	-	0%	-22%	-8%	80%
September	-	-10%	-20%	-9%	80%
October	-	-31%	-18%	-7%	80%
November	-	-30%	-13%	-5%	80%
December	-	-20%	-13%	-6%	80%
<b>yearly average</b>	-	-17%	-18%	-8%	80%

Observing the different simulations through the lens of EN 15251, some conclusions can be reached.

All simulations showed very satisfying results, with at least 86% of the year pent in IDA category 1 and 2. The simulation with the lowest IAQ was Sim\_1 that was the simulation where the closed period is extended throughout the entire year, and for that reason, a true comparison cannot be made due to the lack of occupants to experience the space. However, since some standards divide de ventilation rates in the number of people and area of the compartment, this ventilation strategy was inserted in the comparison, as seen in Figure 148.

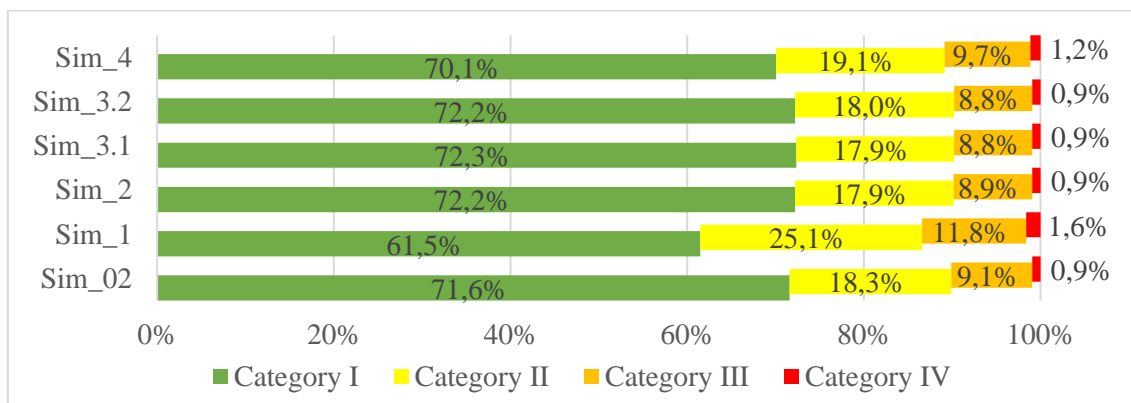


Figure 148- Comparison of the percentage of time respecting EN 15251 recommended ventilation rates for the entire year.

The similarities in the results presented in Figure 149 can be explained by the fact that the church is closed 77% of the week, corresponding to 129 hours. The remaining 29 hours are divided, very unsymmetrical, in the visitation and mass period. This last period occurs 6 hours per week, leading to a higher height factor for the attendance status with the lowest amount of relevance in terms of IAQ. For this reason, an attendance status study was conducted.

Considering the visitation period, all simulations presented very high IAQ levels. Due to the higher number of visitors of Sim\_4, 8 hours of the year were identified outside the categories I and II.

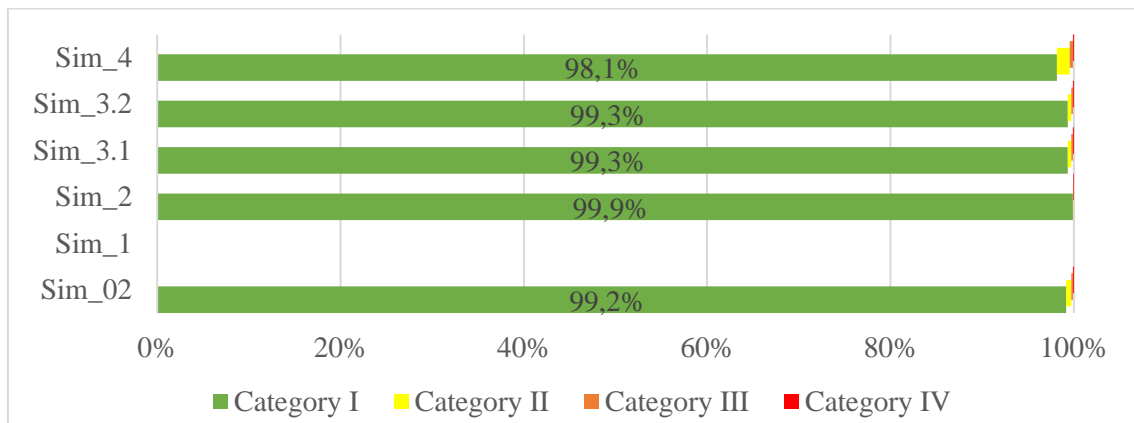


Figure 149- Comparison of the percentage of time respecting EN 15251 recommended ventilation rates for the visitation attendance status.

The major differences in CO<sub>2</sub> concentrations (Figure 150) were found in the mass attendance status, as expected, due to the significantly larger number of occupants.

Sim\_02 exhibited 29 days of the year where the mass service was conducted under category III and only 1 day under category IV.

Sim\_2, the first simulation with a ventilation strategy in mind, shows the 14 hours where category I and II ventilation rates were not achieved.

Between Sim\_3.1 and 3.2, only a 1-hour difference exists in category III. The first cross-ventilation strategy shows 2 hours spent in category II and Sim\_3.2, 3 hours, which is a negligible difference.

Sim\_4, trying to estimate the increase in future occupants with the same ventilation strategy that is in place at the moment, presented 19 mass services where IAQ levels were inserted in category IV and 75 services in category III.

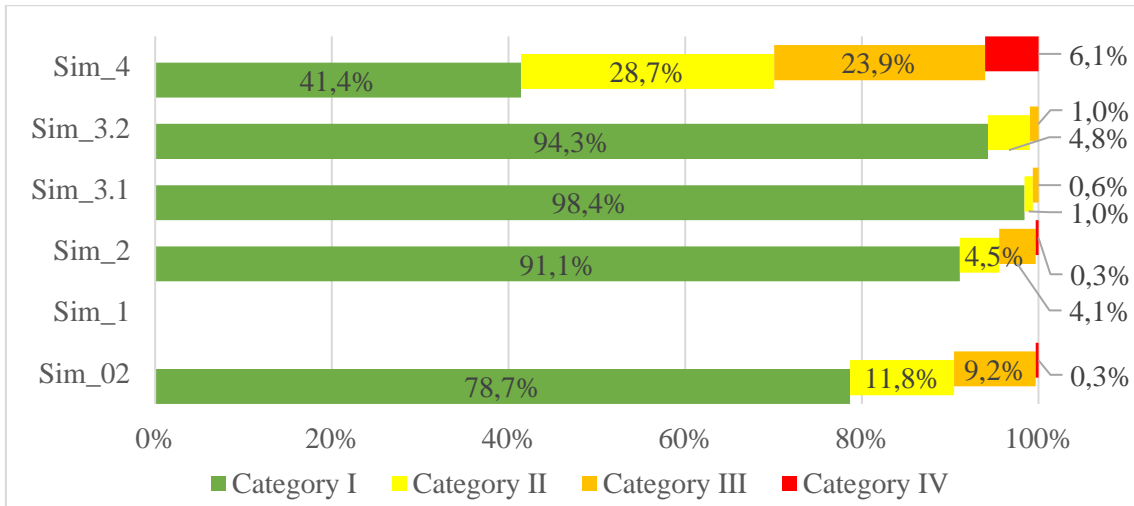


Figure 150- Comparison of the percentage of time respecting EN 15251 recommended ventilation rates for the mass attendance status.

Regarding the closed period (Figure 153), Sim\_1 displays a difference from the other simulations due to the schedule change, this is, the church is closed the entire year.

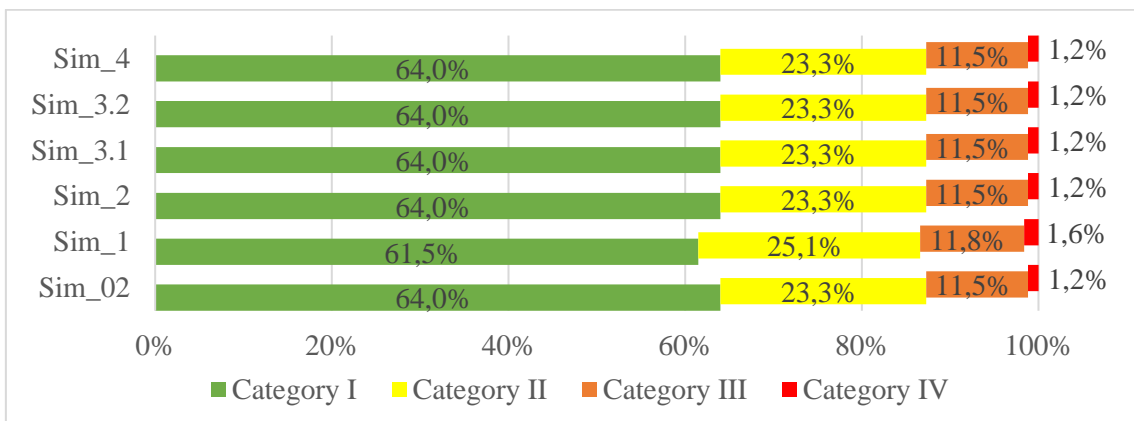


Figure 151- Comparison of the percentage of time respecting EN 15251 recommended ventilation rates for the closed attendance status.

Regarding EN 13779 standard, two analyses are necessary. Firstly, understand the amount of time that CO<sub>2</sub> reference values are surpassed for each IDA category and secondly if the prescribed ventilation rates are being practiced for each category.

As mentioned previously, the visitation period did not present any carbon dioxide excessive presence due to the low number of occupants, as the reference value for IDA 1 of 350ppm above outdoor concentrations is very rarely surpassed. Therefore, the most critical period to examine is the mass attendance status. Figure 152 presents the two-step analysis mentioned in the previous paragraph.

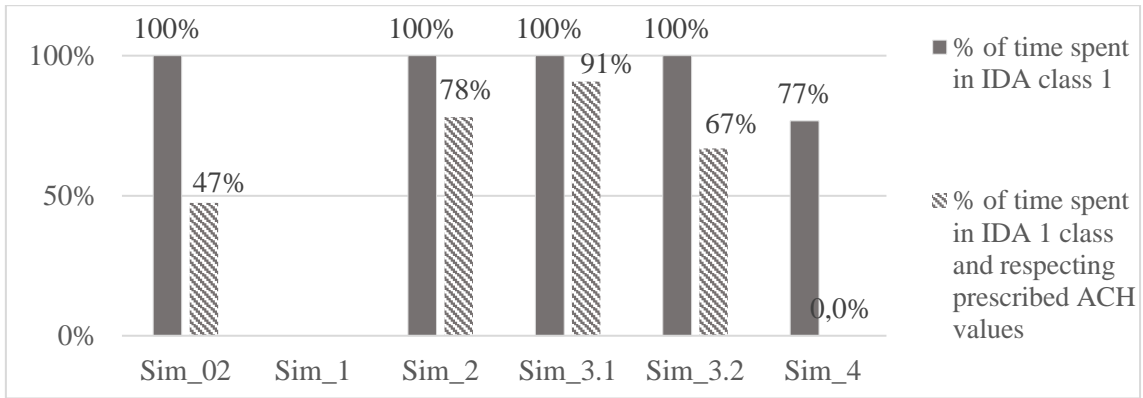


Figure 152- Comparison of all simulations for the percentage of time spent on IDA 1 and respecting EN 13779 recommended ventilation rates for the mass attendance status.

Sim\_02, during the mass period, spent all the time in IDA 1, with CO<sub>2</sub> concentrations below the 350ppm threshold, however, the prescribed ventilation rate was in place only 47% of the time.

Sim\_2, Sim\_3.1 and Sim 3.2 ventilation strategies presented then self has a viable solution for the improvement of IAQ during the mass period even if the current ventilation of Sim\_02 was showed extremely acceptable results.

Finally, Sim\_4 was able to maintain CO<sub>2</sub> concentration below 350ppm 76.8% of the time. Since this simulation is the only one that presented values outside IDA 1, further analysis is exhibited.

Figure 153 shows the amount of time spent in each IDA category. This ventilation strategy is the same as sim\_02 and therefore represents the predictable increase in occupants, according to the Portuguese government for 2027, with no changes to the ventilation behaviour of the São Cristóvão church. In this scenario, EN 13779 ventilation rates are not meet any percentage of the time, in any IDA class, for the mass attendance status.

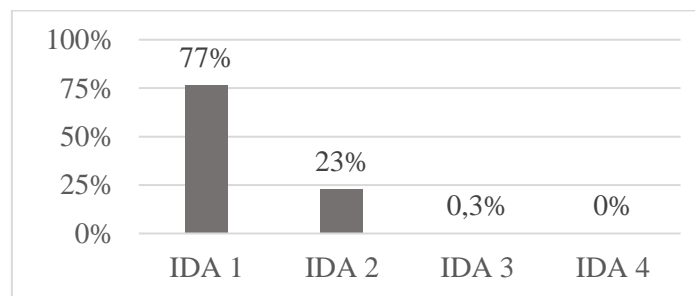


Figure 153- Sim\_4: Percentage of time spent in each IDA category for mass period

Given the binary system based on acceptable/not-acceptable IAQ of ASHRAE 62.1, some results of the simulations made are more similar. Even more, the not acceptable threshold value is lower than the one prescribed for an IAQ category IV of a low polluting building in EN 15251.

For the visitation period (Figure 154), all ventilation strategies showed good results with values above 99% of the time respecting the prescribed rates. Sim\_1 will not be mentioned in some analyses as no occupants are accounted for.

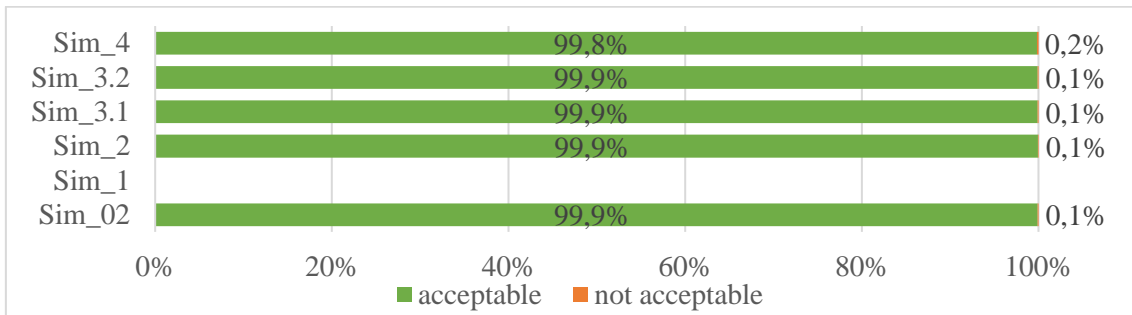


Figure 154- Comparison of the percentage of time respecting ASHRAE 62.1's recommended ventilation rates for the visitation attendance status.

With the implementation of simulations 3.1 and 3.2, ASHRAE's prescribed ventilation rates were met all year for the mass attendance status (Figure 155). Regarding the Sim\_4, 6.7% of the time, the church's natural ventilation was not able to assure the recommended ACH value.

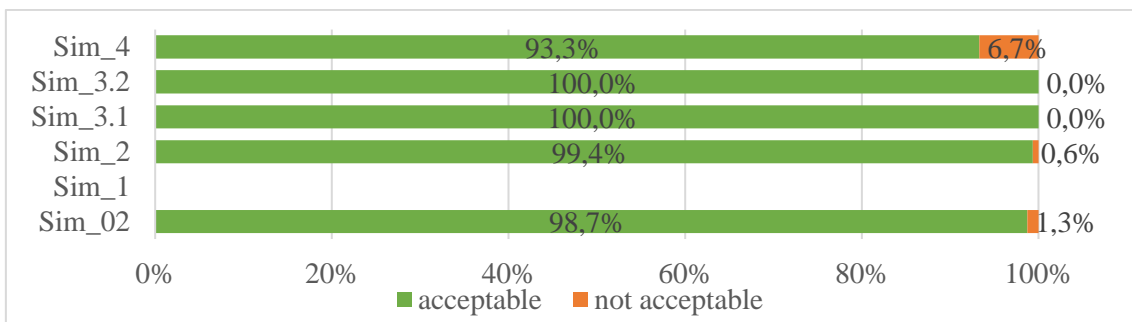


Figure 155- Comparison of the percentage of time respecting ASHRAE 62.1's recommended ventilation rates for the mass attendance status.

Because Sim\_1 is closed the entirety of the year and for all other simulations, the closed period is the same with identical conditions, Figure 156 shows similar results.

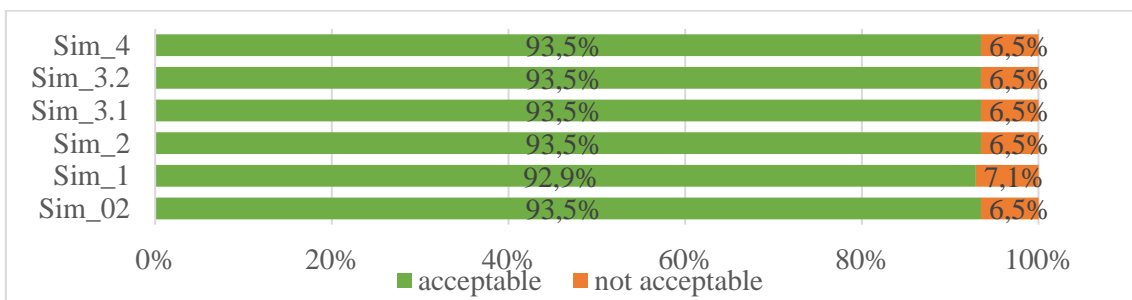


Figure 156- Comparison of the percentage of time respecting ASHRAE 62.1's recommended ventilation rates for the closed attendance status.

CIBSE Guide A recommended ventilation rates are solely dependent on the number of occupants, therefore the closed period will not be examined.

The visitation attendance status, like previously displayed, reported an extremely high percentage of time complying with prescribed ventilation rates, as depicted in Figure 157. The lower number of persons inside the church through this period is low (5 to 9) and the building can renew its used air.

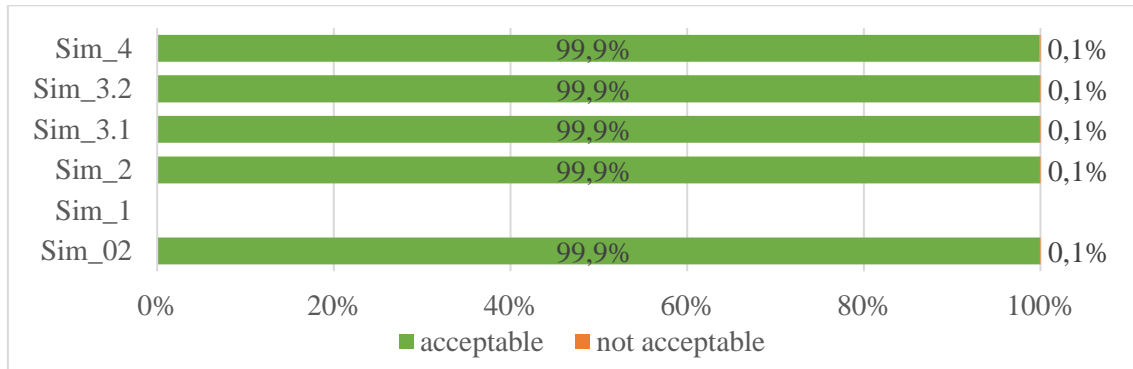


Figure 157- Comparison of the percentage of time respecting CIBSE Guide A recommended ventilation rates for the visitation attendance status.

During the mass period (Figure 158), the ventilation strategies implemented that are different from the current one presented an improvement. From 10% of time not complying with the recommended ventilation rates in Sim\_02, Sim\_2, Sim\_3.1, and Sim\_3.2 showed a decrease of 5.4%, 9.2% and 8.6%, respectively.

Regarding Sim\_4, with the almost double increase in occupants, only 54% of time is spent complying with the recommended ventilation rates of circa 2600 m<sup>3</sup>/h (0,70 ACH).

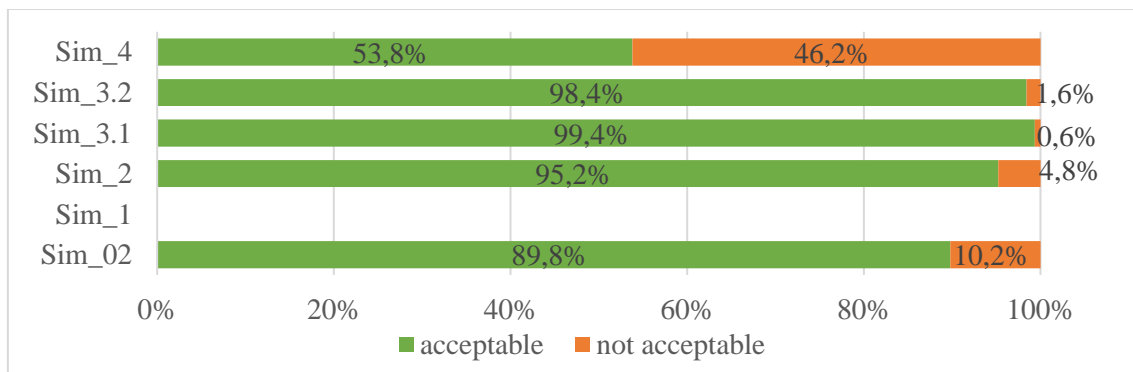


Figure 158- Comparison of the percentage of time respecting CIBSE Guide A recommended ventilation rates for the mass attendance status.

## 5. Conclusion and future works

### 5.1. Summary

The natural ventilation analysis of any building is a very uncertain study to conduct. Variables such as wind speed and direction are easily averaged with past data, but the accuracy and representation of the future pattern are hard to predict. Even more, cultural heritage buildings, such as the São Cristóvão church endows the analysis with additional variables, such as the parameter and coefficients to apply in degraded or broken pathways without *in situ* testing.

This document aimed to establish the current ventilation behaviour of the church, achieved in sub-chapter 4.1 and presented five additional strategies to mitigate CO<sub>2</sub> concentrations, discussed in sub-chapter 4.2.

For Sim\_02, the current ventilation strategy, an average ACH of 0.75 during the open doors period can be projected, and for the duration of the closed period, a ACH of 0.15 was established. On a yearlong analysis, an average ACH of 0.30 was obtained. Table 51 summarizes the average ACH for each of the simulations.

Table 51- Average ACH value by church status, for each simulation

Church open/closed period	Sim_02	Sim_1	Sim_2	Sim_3.1	Sim_3.2	Sim_4
open doors	0.75		1.04	0.85	0.79	0.75
Closed doors	0.15	0.15	0.15	0.15	0.15	0.15
all year	0.30	0.15	0.37	0.32	0.31	0.30

When a global analysis is made, a conclusion is reached concerning the IAQ of the church. No matter which strategy is chosen, all ventilation rates and CO<sub>2</sub> levels are within the acceptable range by all standards, raising the question regarding the need of implementing new ventilation tactics. Even so, Spring and Autumn seasons exhibited the lowest ACH values for all simulations, except sim\_2, and consequently, the highest CO<sub>2</sub> concentrations occur during these seasons.

The notion that the number of church attendees grows at the same rate as the number of tourists in Lisbon is not realistic, however, this simulation clarified the church's ventilation behaviour in a crowded condition. Nevertheless, Sim\_4 was the simulation with the biggest CO<sub>2</sub> concentration due to the near doubling in attendees, recording average peak values, during Sunday mass, of 370ppm, and therefor, entering IDA 2 category.

The peak values that were attained at the end of Sunday mass for every simulation were sufficiently low, under 350ppm, so the ventilation through infiltration during the closed period an ACH of 0.15 was able to significantly reduce such pollutants. In the cases where ventilation rates during visitation and mass were lower, like Sim\_02 and Sim\_4, the fact that on Monday no mass is celebrated aids in the reduction of CO<sub>2</sub> concentrations in subsequent days.



## 5.2. Future work

Because this document focused solely on CO<sub>2</sub> concentrations and ventilation performance, some important analyses were left out, such as the implications of airspeed increase near the artwork displayed all over the church.

Another element that needs to be studied is the distribution of CO<sub>2</sub> concentrations in the main nave of the church. In this document, and using the capabilities of the *software* CONTAM, the assumption of a well-mixed volume of air was in place. This may bring future implications on the result achieved throughout the text, mainly concerning CO<sub>2</sub> concentrations surrounding the mass attendees.

The implications of the ACH fluctuations throughout the different simulation will definitely affect the indoor climate. Temperature and RH changes, and its implications in the conservation of materials should be studied. Even more, the comfort of visitors can be impacted by an increase in the velocity of the air masses.

Finally, the study on the influence of outside pollutants in the IAQ is also relevant.



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## Appendix

### A.1. Ventilation by temperature difference

To validate some parameters used in the *CONTAM* simulation conducted in this document, a simple model was built, run and the results compared to does analytically achieved.

A square with 6m\*6m\*6m in size was created and submitted to different kinds of natural ventilation, being them ventilation by buoyancy and ventilation by wind

#### A.1.1. Model

The general parameters were:

- Ambient Temperature: 0 °C
- Indoor Temperature: 20 °C
- HR: null
- Wind direction and speed: null

To test this type of ventilation it was considered 2 flow paths at different heights (0.5m and 4.5m) the location of these paths is irrelevant at this point due to the lack of wind and the pressure it applies. In this simulation, one-way paths were used, measuring 0.4m of width by 1m of height. The discharge coefficient of the openings was set to 0.61 and the flow exponent set at 0.5.

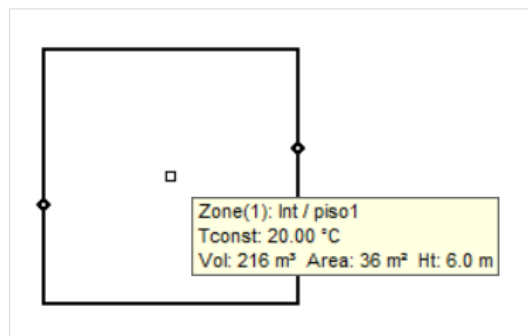


Figure 159- Geometric setup for the test simulation

The result text file indicated an airflow of approximately 0.725 kg/s or 0.581 m³/s, corresponding to 9.7 air changes per hour.

Table 52- Results from project:test\_Buoyancy

zone	P (Pa)	Path	from	dP (Pa)	Flow (kg/m³)
Interior	-3.23	O_out	Ambt	-0.92	-0.7246
		O_in	Ambt	2.40	0.7246

### A.1.2. Analytical calculus

To calculate the airflow by temperature difference. the BS 5925:1991 was followed.

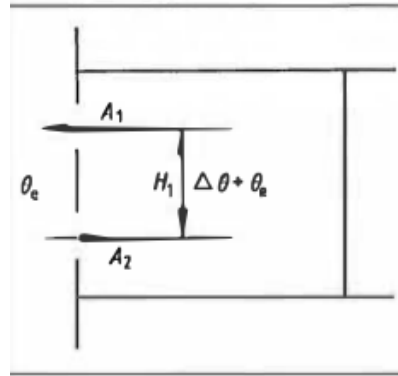


Figure 160- Airflow due to temperature difference with two openings model [62]

Using the equations proposed by BS 5925:1991 in table 11.b). the ventilation rate was be achieved by:

$$Q = C_d \cdot A_b \cdot \sqrt{\frac{2 \cdot \Delta T \cdot g \cdot H}{T_{med}}} \quad (16)$$

Where.

- $C_d$  Discharge coefficient;
- $\Delta T$  Temperature differential [ $^{\circ}C$ ];
- $T_{med}$  Average temperature [K];
- $g$  Gravity acceleration [m/s<sup>2</sup>];
- $H$  height difference between the central point of the openings [m];
- $A_b$  Equivalent opening area [cm<sup>2</sup>]. calculated by the equation:  
 $1/A_b^2 = 1/(A_1)^2 + 1/(A_2)^2$ .

The results showed an airflow of 0.583 m<sup>3</sup>/s. The difference between the automated and analytically obtained results can be justified by the approximations made by the author as minor changes in the density of the air lead to different airflows.

## B. Wind intensity and direction from different sources

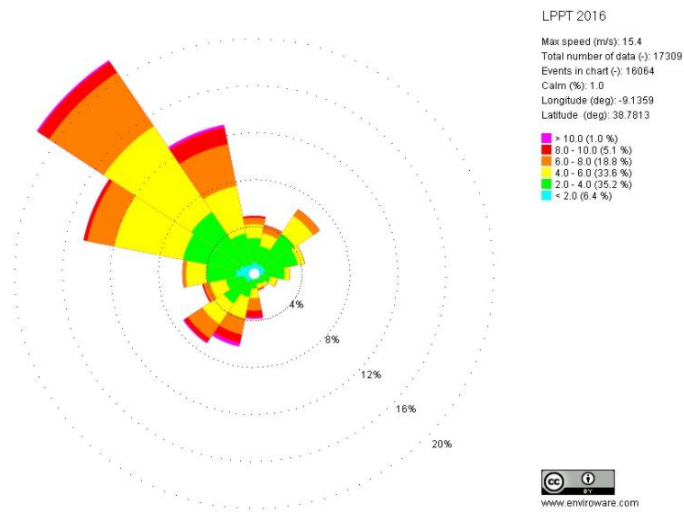


Figure 161- Wind direction and intensity throughout the year of 2016 [93]

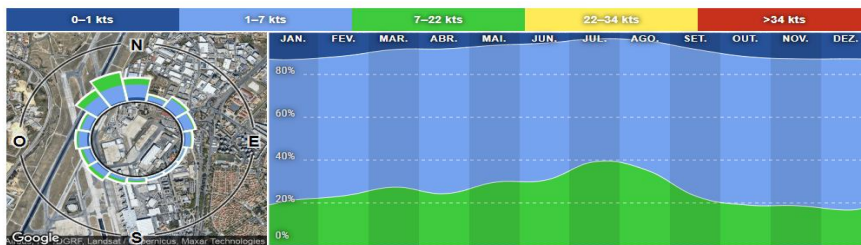


Figure 162- Wind direction and intensity throughout the year; 1kts = 0.5144m/s [94]

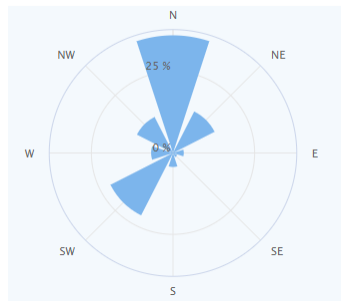


Figure 163- Wind direction and intensity throughout the year (2) [95]

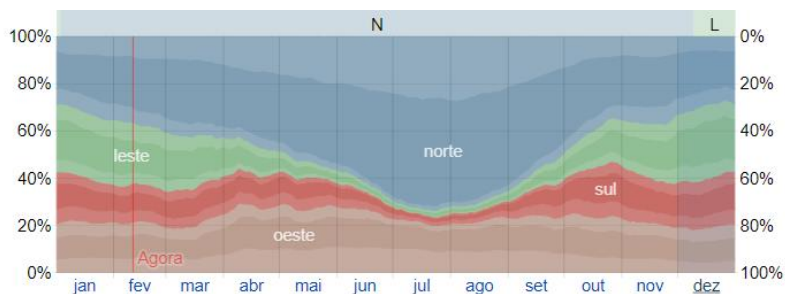


Figure 164- Wind direction throughout the year [96]

## C. CONTAM flow paths layout

The layout of the *CONTAM* simulation is presented in the following pictures. No scale was used.

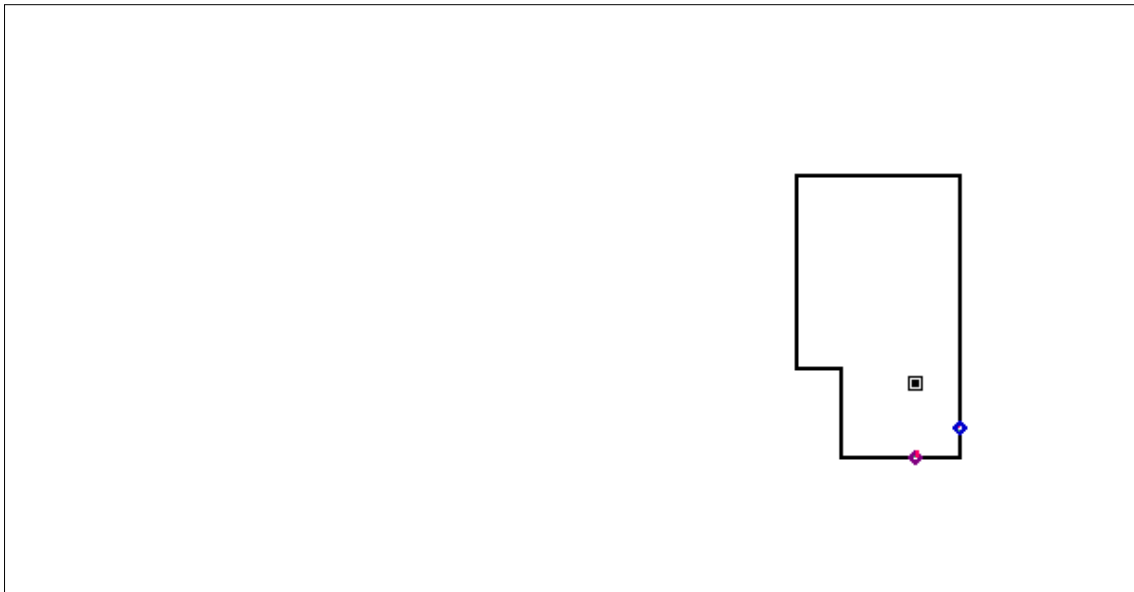


Figure 165- *CONTAM* layout: Ground Floor

Symbol	Color	Type of flow path
◆	Green	Double casement window frame leakage
◆	Green	Double casement window open
◆	Drack Blue	Fixed window frame leakage
◆	Orange	Single hung window frame leakage
◆	Orange	Single hung window frame open
◆	Purple	Close door leakage
◆	Purple	Open door
◆	Rose pink	Interior door under-gap
◆	Spring green	Small orifice in broken window
◆	Black	Wooden floor/ceiling leakage
◆	Light Blue	Stairwell
◆	Dark green	Bell tower orifice

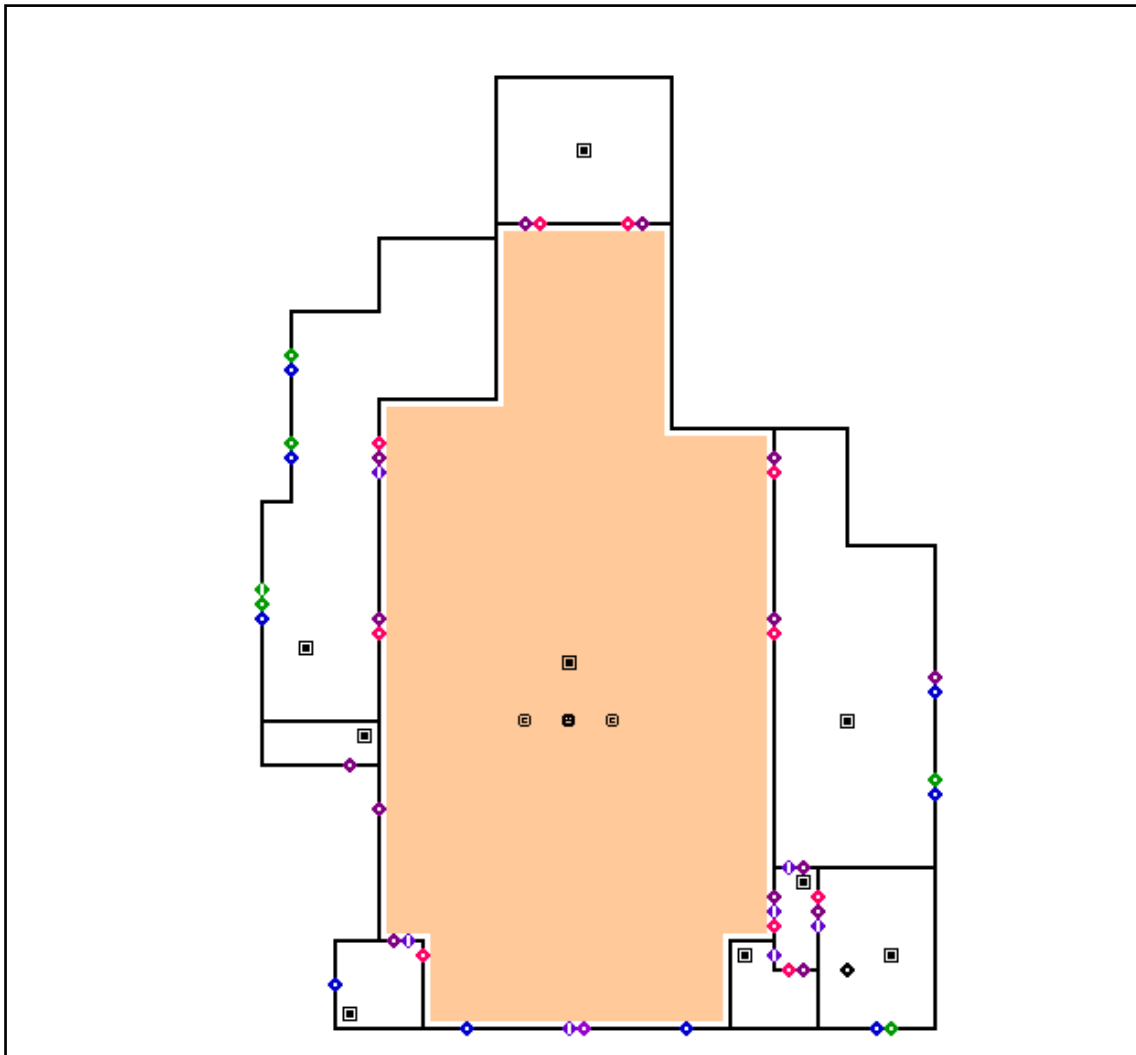


Figure 166- CONTAM layout: 1st Floor

Symbol	Color	Type of flow path
◆	Green	Double casement window frame leakage
◆	Green	Double casement window open
◆	Drack Blue	Fixed window frame leakage
◆	Orange	Single hung window frame leakage
◆	Orange	Single hung window frame open
◆	Purple	Close door leakage
◆	Purple	Open door
◆	Rose pink	Interior door under-gap
◆	Spring green	Small orifice in broken window
◆	Black	Wooden floor/ceiling leakage
◆	Light Blue	Stairwell
◆	Dark green	Bell tower orifice

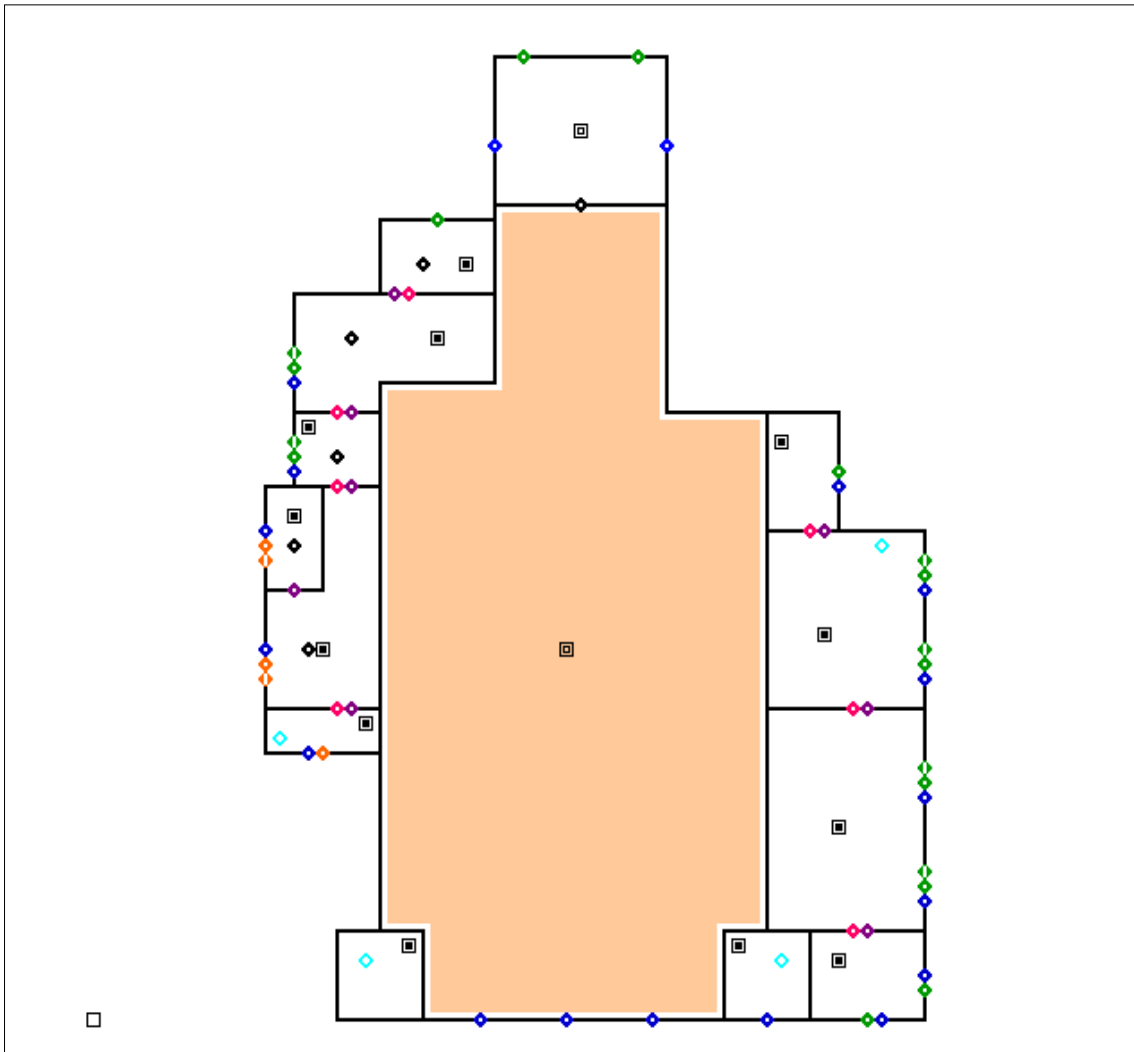


Figure 167- CONTAM layout: 2nd Floor

Symbol	Color	Type of flow path
	Green	Double casement window frame leakage
	Green	Double casement window open
	Dark Blue	Fixed window frame leakage
	Orange	Single hung window frame leakage
	Orange	Single hung window frame open
	Purple	Close door leakage
	Purple	Open door
	Rose pink	Interior door under-gap
	Spring green	Small orifice in broken window
	Black	Wooden floor/ceiling leakage
	Light Blue	Stairwell
	Dark green	Bell tower orifice

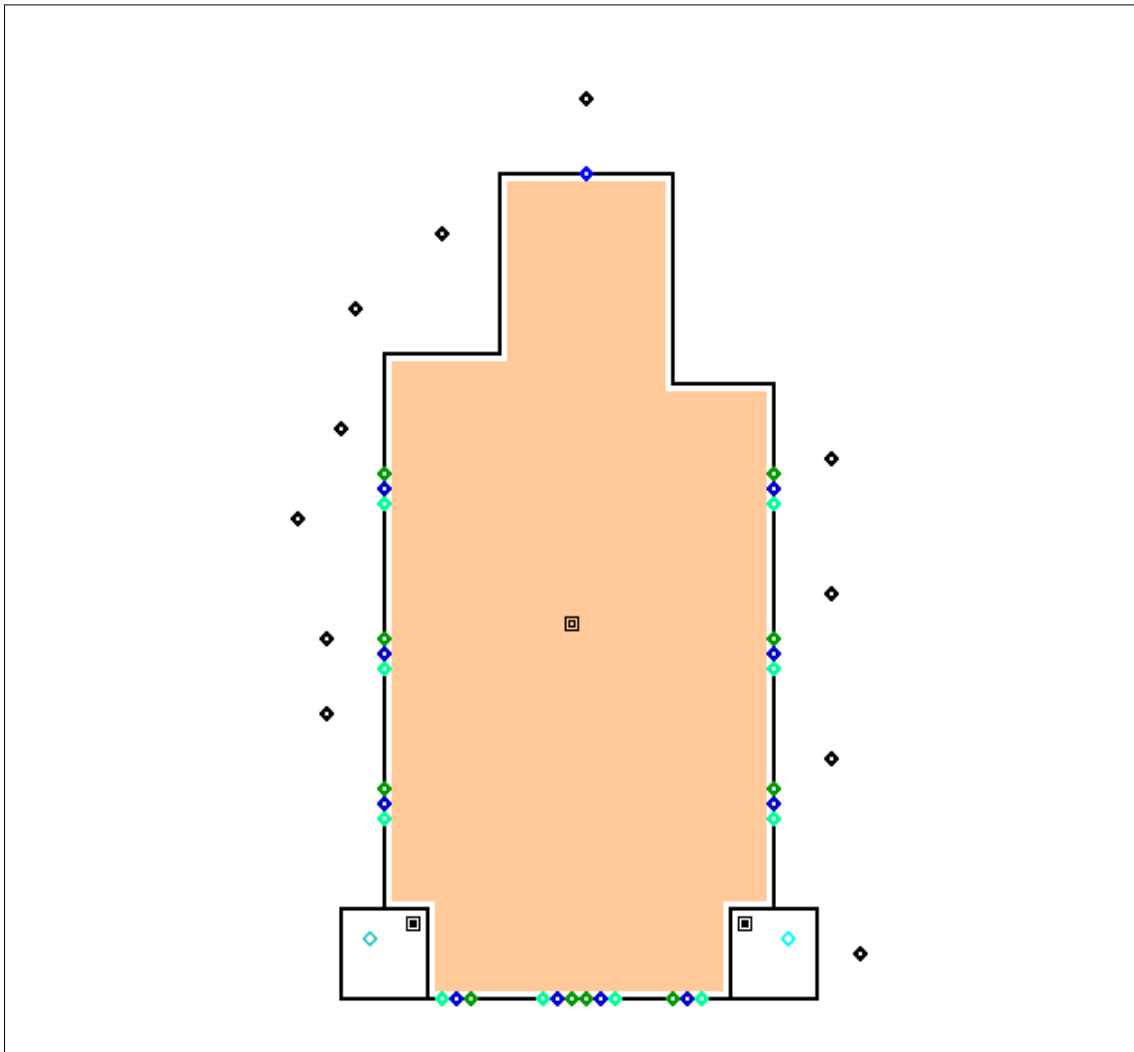


Figure 168- CONTAM layout: 3rd Floor

Symbol	Color	Type of flow path
	Green	Double casement window frame leakage
	Green	Double casement window open
	Drack Blue	Fixed window frame leakage
	Orange	Single hung window frame leakage
	Orange	Single hung window frame open
	Purple	Close door leakage
	Purple	Open door
	Rose pink	Interior door under-gap
	Spring green	Small orifice in broken window
	Black	Wooden floor/ceiling leakage
	Light Blue	Stairwell
	Dark green	Bell tower orifice

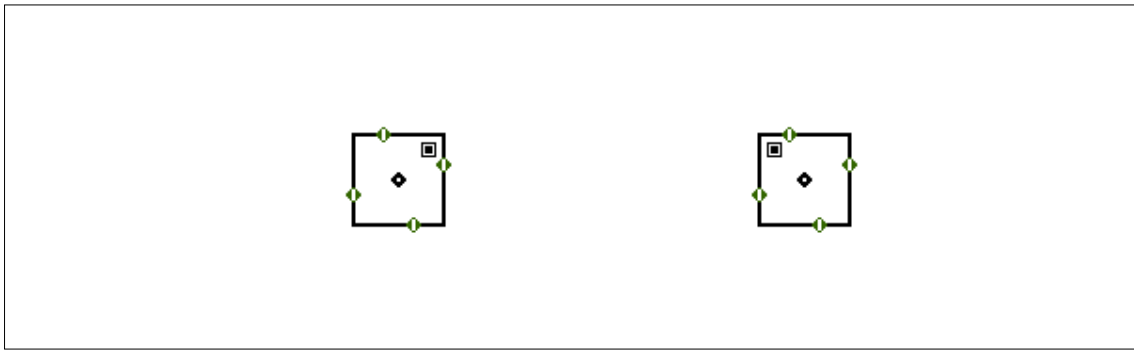


Figure 169- CONTAM layout: 4th Floor

Symbol	Color	Type of flow path
	Green	Double casement window frame leakage
	Green	Double casement window open
	Drack Blue	Fixed window frame leakage
	Orange	Single hung window frame leakage
	Orange	Single hung window frame open
	Purple	Close door leakage
	Purple	Open door
	Rose pink	Interior door under-gap
	Spring green	Small orifice in broken window
	Black	Wooden floor/ceiling leakage
	Light Blue	Stairwell
	Dark green	Bell tower orifice

Table 53- Location and dimensions of spans and air paths implemented in the Contam simulations

Floor	Path type	North		South		Est		West	
		Dim. (m)	Type	Dim. (m)	Type	Dim. (m)	Type	Dim. (m)	Type
1st	Ext. Doors					0.9*2.1	Side-hung		
	Windows			0.4*0.2	Fixed				
2nd	Ext. Doors	1.5*3	D-Side Hung	0.9*2.2	Side Hung	2*3.5	D-Side Hung		
						0.6*2.2	Side Hung		
	Windows	0.4*1	D.CAS	0.4*0.9	D.CAS	0.5*0.5	Fixed		
		0.4*1	D.CAS			0.5*0.5	Fixed		
		0.6*1	D.CAS			1.1*1.35	D.CAS		
	0.2*0.5	Fixed							
3rd	Windows	1.1*1.35	D-CAS	0.4*0.6	CAS	1.1*1.35	Single Hung	0.4*0.4	CAS
		1.1*1.35	D-CAS	0.7*1.3	D-CAS	0.5*0.5	Fixed	0.4*0.4	CAS
		1.1*1.35	Single Hung	0.9*2.5	D-CAS	0.5*0.5	Fixed	0.4*0.4	CAS
		1.1*1.35	Single Hung	0.9*2.5	D-CAS	0.5*0.5	Fixed		
				0.9*2.5	D-CAS	0.5*0.5	Fixed		
				0.7*1.3	D-CAS	0.9*2.5	D-CAS		
			1.5*1.5	Fixed-galssed	1.5*1.5	Fixed-galssed			
4th	Windows							0.9*1	Fixed-glassed
		0.9*1.3	D-CAS+band(0.3)	0.9*1.6	D-CAS+band(0.3)	0.6*1.8	D-CAS+band(0.0.4)		
		0.9*1.3	D-CAS+band(0.3)	0.9*1.3	D-CAS+band(0.3)	1*1.8	D-CAS+band(0.0.4)		
		0.9*1.6	D-CAS+band(0.3)	0.9*1.3	D-CAS+band(0.3)	0.6*1.8	D-CAS+band(0.0.4)		
		<b>No orientation</b>							
	Int. Doors	0.9*2.1	Side hung						
	Roof	Var							
	Bell hatch	4 m2	Horizontal						

Table 54- Description of the types of spans and air paths encountered in São Cristóvão's Church

abbreviations	Description
Side Hung	span with 1panels (door) hung from the side
D-Side Hung	span with 2 panels (doors) hung from both sides
Single Hung	Operable window with single vertical slider
fixed	Non-operable window
fixed-glassed	Non-operable window with extra layer of glass from the outside
CAS	Operatable window with vertical side pivot
D-CAS	Operatable window with 2 panels and 2 vertical side pivot
D-CAS+band(0.3)	Operatable window with 2 panels and 2 vertical side pivot and a fixed window on top

### **C. Simulations ACH data**

In annex C, all the simulations ach values are displayed graphicly instead of written data due to a large amount of space required. For additional information and data set please contact the author.

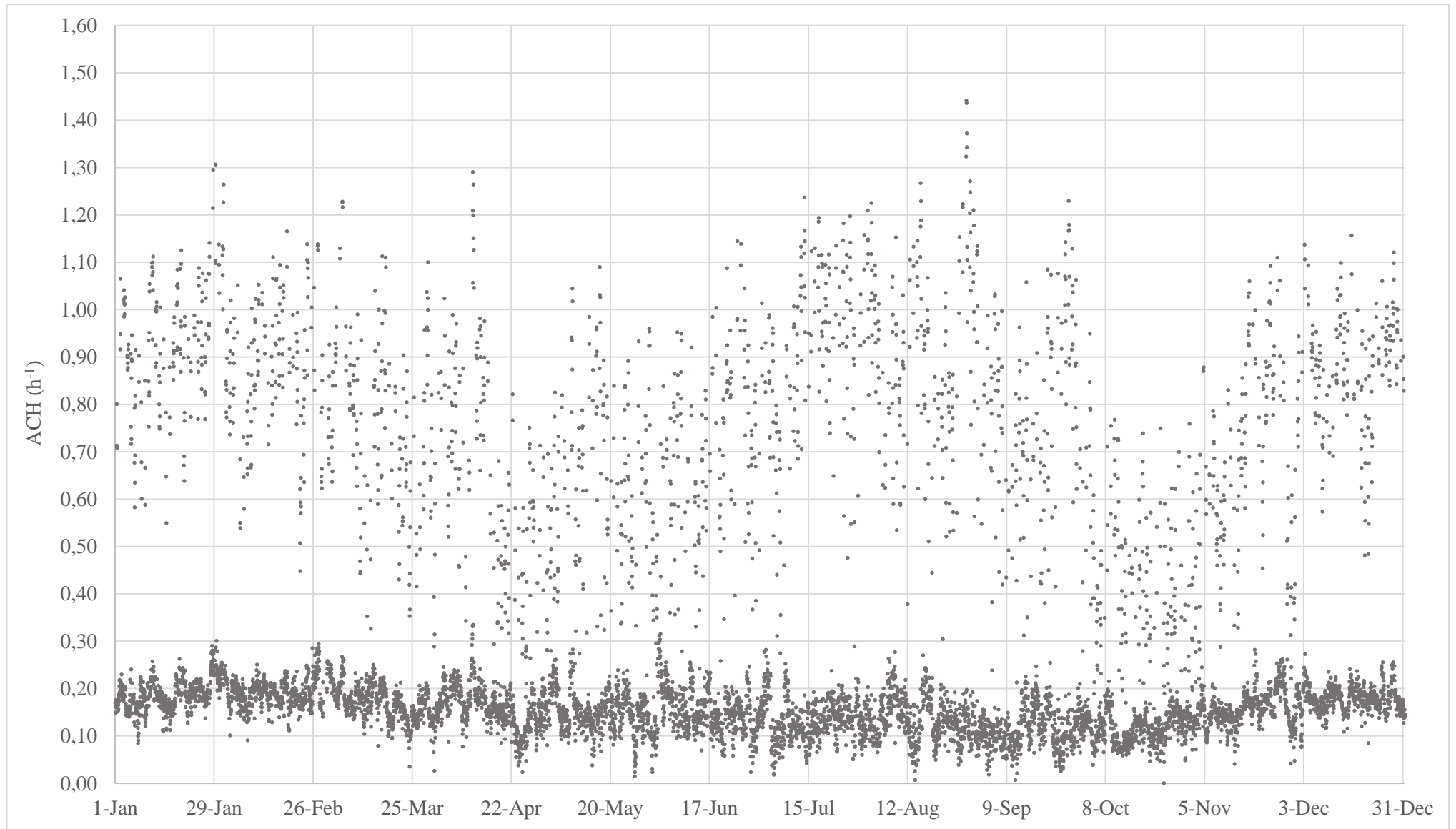
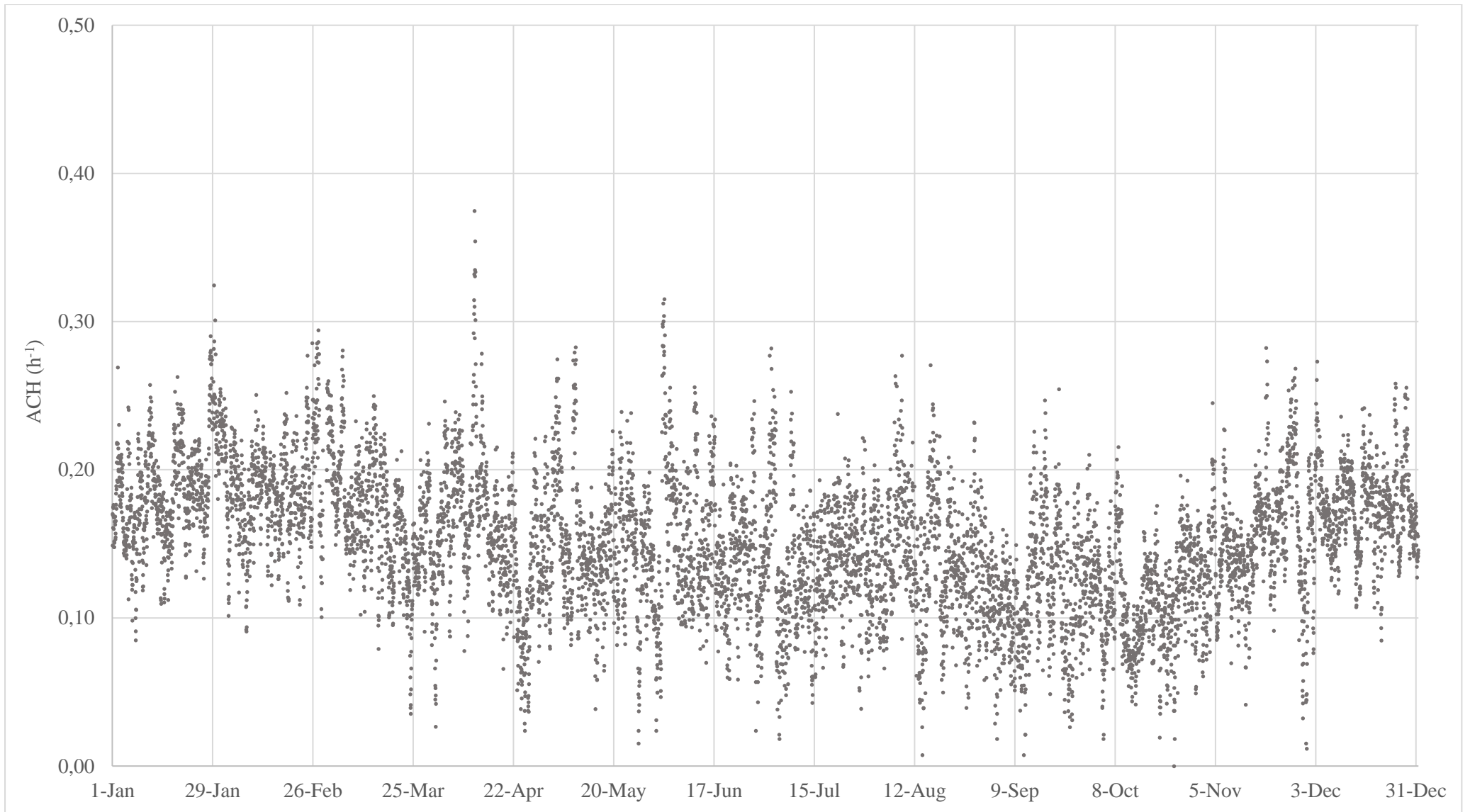


Figure 170- Sim\_02: ACH data



*Figure 171- Sim\_1: ACH data*

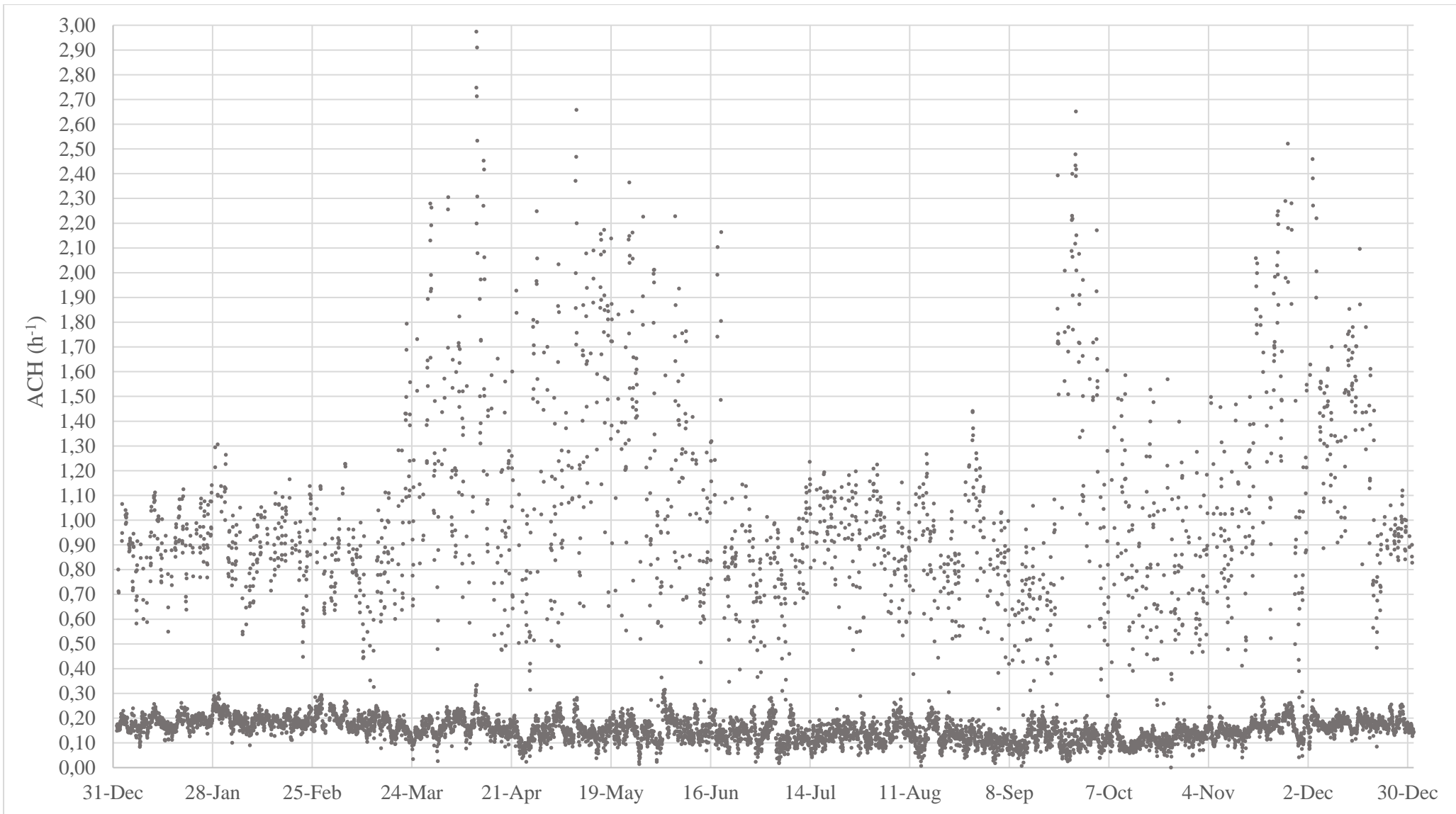


Figure 172- Sim\_2: ACH data

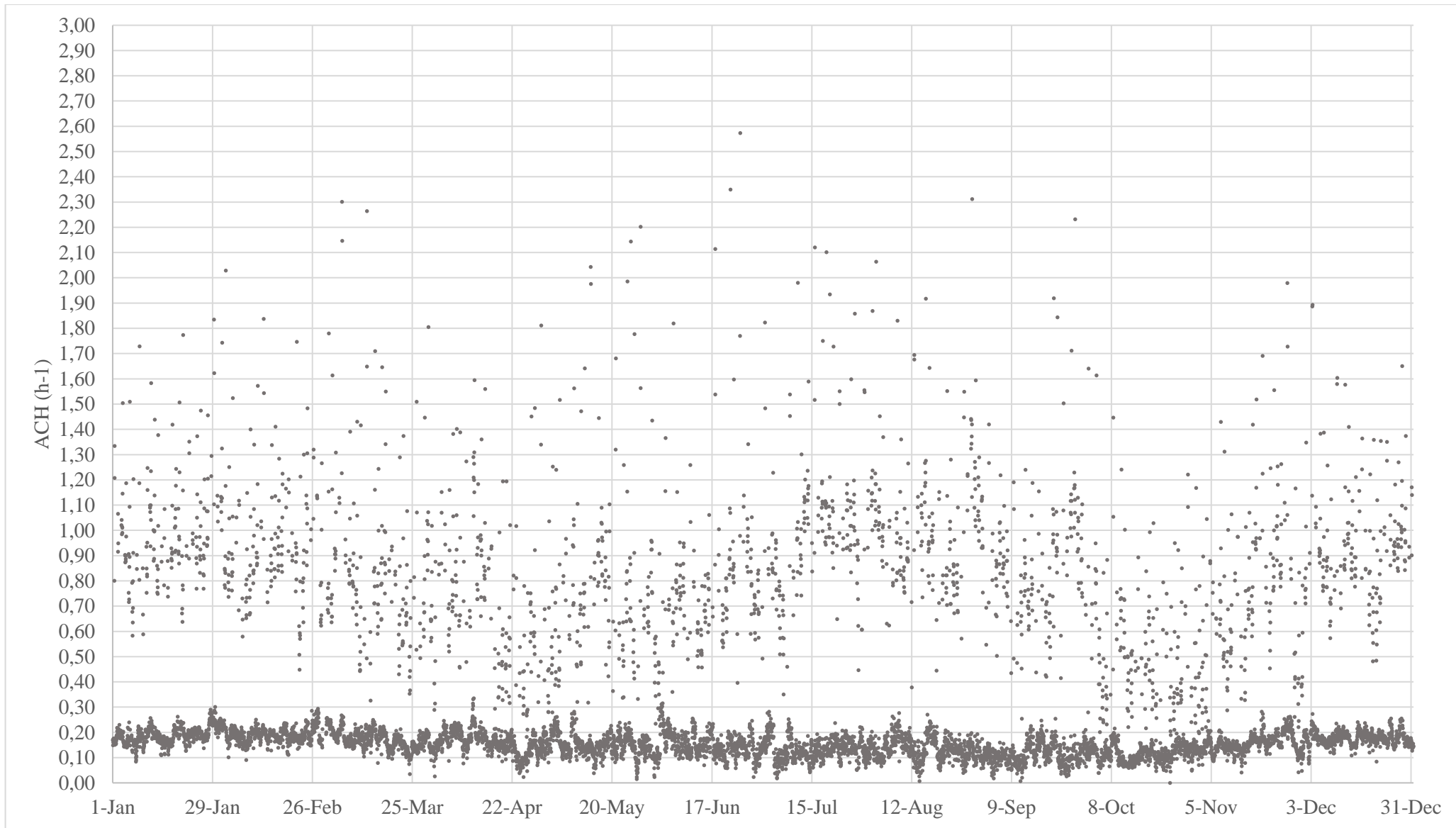


Figure 173- Sim\_3.1: ACH data

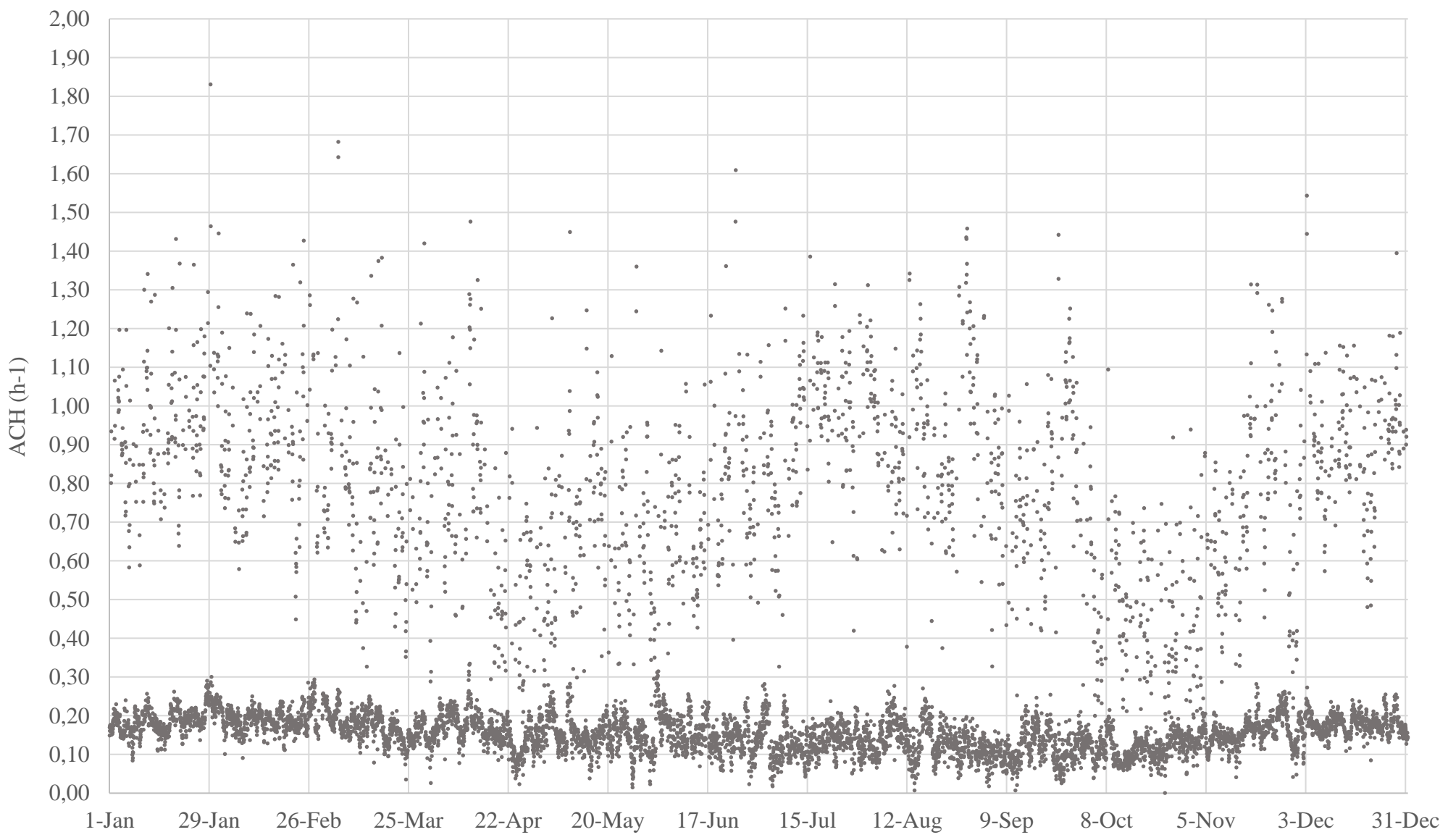


Figure 174- Sim\_3.2: ACH data

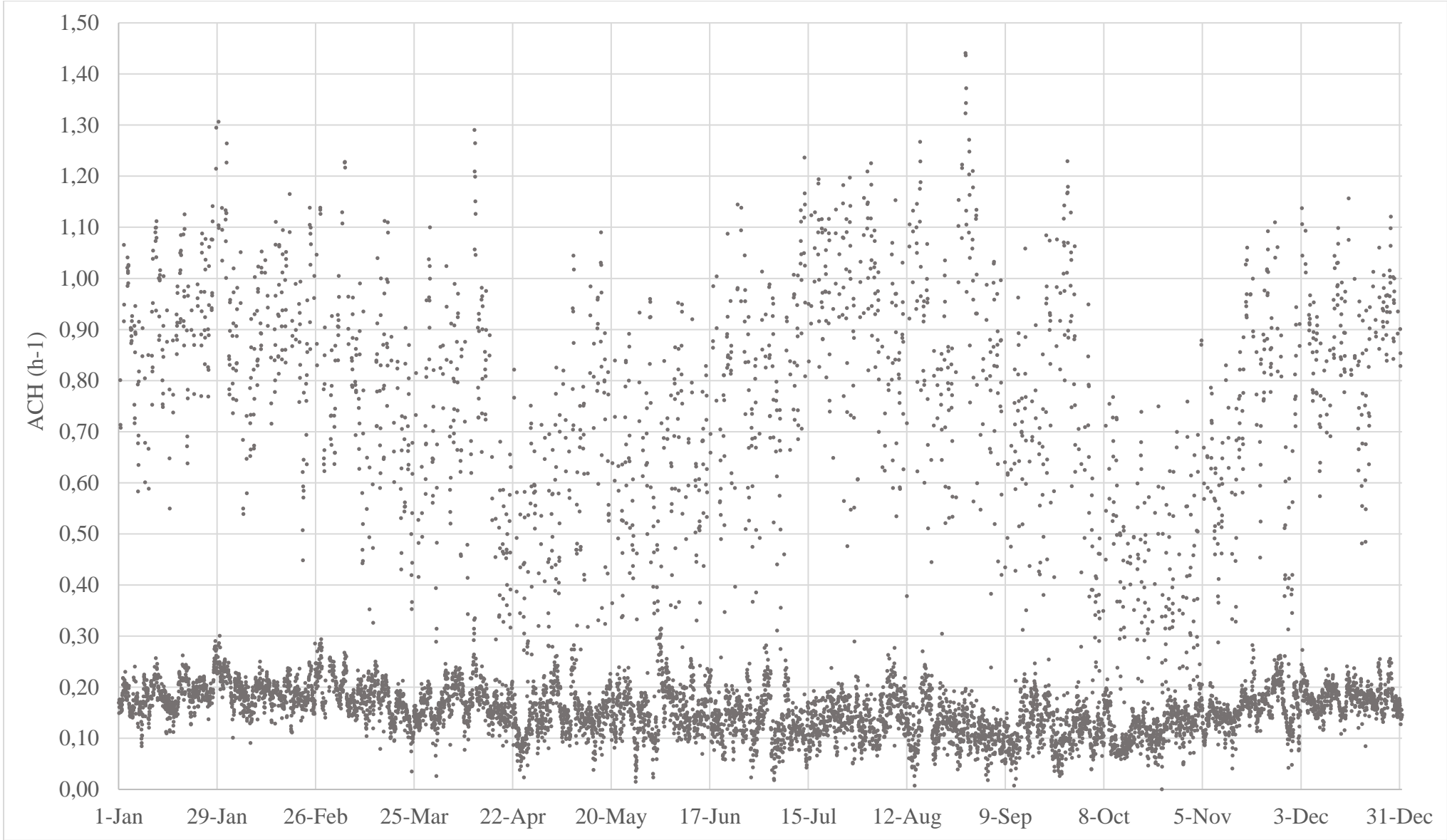


Figure 175- Sim\_4: ACH data

