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Optimal combination of natural and mechanical ventilation in ZEB Laboratory

Based on simulations performed with CONTAM

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Energy planning and environmental analysis, Master's Thesis
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Maren Elise Leinum
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Abstract

The building sector is an energy-intensive sector, consuming over 40% of the total energy use in Norway. Energy efficiency improvement of the building sector is crucial to fulfilling the Norwegian obligations to the UN. *Zero Emission Building*, ZEB, are constructed to achieve an on-site production of renewable energy compensating any greenhouse gas emissions occurring throughout the lifespan of the building.

ZEB Laboratory is a 2000 square meters office and education building currently under construction located in Trondheim, Norway. ZEB Laboratory strives to act as an example for future office and educational buildings aiming to achieve a level of ZEB. The object of this Master's Thesis is to find the optimal use of mechanical and natural ventilation in ZEB Laboratory regarding energy demand, without compromising the indoor environment of the building.

An extensive literature review was performed. The definitions, recommendations, and requirements of a good indoor environment in offices and educational building were reviewed. Further, the different methods and strategies of ventilation were evaluated, in addition to a state of the art review of energy efficient ventilation strategies. There is a lack of literature regarding how well-functioning office and educational buildings only supplied with only natural ventilation are in colder climates, so studies performed in southern regions were reviewed.

Provided information regarding ZEB Laboratory, including building structure, zonal division, external openings, and planned available mechanical ventilation, has been reviewed. This information formed a basis for the composition of a simulation model of ZEB Laboratory. A basic building model of the ZEB Laboratory was created, including different controllers of the natural and mechanical ventilation systems. The basic building model was simulated in three different ventilation modes: A) Clean natural mode, B) Clean mechanical mode, and C) Hybrid mode, during three different cases: Case 1) Winter, Case 2) Transition, and Case 3) Summer. Some corrections of the modes were performed to minimize the energy demand while not compromising the indoor environment.

The results from the simulations show that the largest amount of demanded energy is due to the heating requirement of cold ambient air entering the building. Hence, the most energy efficient ventilation mode during the winter is a clean mechanical mode. During the transition season, a hybrid ventilation mode is the most energy efficient solution due to lower requirements of fan power. The building should be implemented with passive cooling outside the occupied hours during the summer season. This will lead to a satisfactory indoor environment when the building is supplemented with clean natural ventilation. Further, the simulations show that a clean natural ventilation mode is substantial to ensure a good indoor environment during the entire year.

However, it's important to note that the simulations doesn't simulate internal heat gains, heat transfer, or the resulting temperature change. The simulation results may therefore deviate from the real resulting energy demand and indoor environment.

Sammendrag

Bygningssektoren er en energiintensiv sektor, med et forbruk på over 40% av det totale energiforbruket i Norge. Energien forbrukes blant annet til oppvarming og nedkjøling av bygninger. Et stort energiforbruk skyldes derfor ventilasjon. Energieffektivisering av bygningssektoren er avgjørende for å oppfylle de norske forpliktelsene til FN. *Nullutslippsbygninger*, ZEB, blir konstruert med et mål om å kunne produsere nok fornybar energi på stedet til å kompensere for eventuelle klimagassutslipp som dannes under byggets levetid.

ZEB Laboratory er et 2000 kvadratmeters kontor- og utdannelsesbygg i Trondheim, Norge, som per dags dato er under konstruksjon. Målet med ZEB Laboratory er å fungere som rollemodell for fremtidige kontor- og utdannelsesbygg som ønsker å oppnå et nivå av ZEB. Formålet med denne masteroppgaven er å finne den optimale bruken av mekanisk og naturlig ventilasjon i ZEB Laboratory i henhold til energibehov, uten å gå på kompromiss med innemiljøet i bygningen.

Et omfattende litteraturstudie har blitt utført. Definisjoner, anbefalinger og krav til et godt innemiljø har blitt gjennomgått. Videre ble ulike metoder og strategier for ventilasjon vurdert, i tillegg til en gjennomgang av toppmoderne og energieffektive ventilasjonsstrategier. Det er mangel på litteratur som omhandler hvor velfungerende kontorer og utdanningsbygninger som kun suppleres med naturlig ventilasjon er i kalde klima. Derfor ble studier gjennomført i sydligere regioner analysert.

Informasjon om ZEB Laboratory har blitt gjennomgått. Dette inkluderer blant annet bygningsstrukturen, soneinndelingen, utvendige åpninger og planlagt mekanisk ventilasjon. Denne informasjonen ga grunnlag for sammensettingen av en simuleringsmodell av ZEB Laboratory. En grunnleggende modell av ZEB Laboratory med ulike regulatorer av det naturlige og mekaniske ventilasjonssystemet har blitt konstruert. Modellen ble simulert i tre ulike ventilasjonsmoduser: A) Ren naturlig modus, B) Ren mekanisk modus og C) Hybrid modus, og for tre ulike årstider: 1) Vinter, 2) Overgang og 3) Sommer. Noen korrigeringer av de ulike modusene ble gjort for å minimere energibehovet uten å forringe innemiljøet.

Simuleringsresultatene viser at det største energibehovet skyldes oppvarmingen av kald, omgivende luft som suppleres til bygningen. Derfor er den mest energieffektive ventilasjonsmodusen om vinteren en ren mekanisk modus. I overgangssesongen vil en hybrid ventilasjonsmodus være energi effektiv på grunn av det lave energibruket til vifter. Bygningen bør implementeres med passiv nedkjøling om sommeren. Dette vil føre til et tilfredsstillende innemiljø når bygningen suppleres med naturlig ventilasjon. Videre viser simuleringene at en ren naturlig ventilasjonsmodus kan sikre et godt innemiljø gjennom hele året.

Det er i midlertidig viktig å merke seg at simuleringene ikke tar hensyn til interne varmetilskudd, varmeoverføring eller den resulterende temperaturendringen. Dermed vil simuleringsresultatene avvike fra det reelle energibehovet og innemiljøet.

Contents

Acknowledgement **i**

Abstract **iii**

Sammendrag **iv**

List of Figures **x**

List of Tables **xviii**

Abbreviations **xx**

Nomenclature **xxi**

1 Introduction **1**

1.1 Background and motivation 1

1.2 Problem description 2

1.3 Approach 2

1.4 The structure of this Master's Thesis 3

1.5 Priorities and limitations 4

2 Indoor environment in office and education buildings **5**

2.1 Thermal environment 5

2.1.1 Activity level 5

2.1.2 Clothing 6

2.1.3 Thermal neutrality 7

2.1.4 Temperature 7

2.1.5 Air velocity 8

2.1.6 Relative humidity . . . 8
2.2 Atmospheric environment . . . 9
2.2.1 CO_2 levels . . . 9
2.2.2 Outdoor pollution . . . 9
2.3 Possible consequences of poor indoor environment . . . 11

3 Building ventilation 13
3.1 Strategies of ventilation . . . 13
3.1.1 Natural Ventilation . . . 13
3.1.2 Mechanical Ventilation . . . 14
3.1.3 Hybrid Ventilation . . . 15
3.2 Mathematical models of ventilation . . . 17
3.2.1 The Network Model . . . 17
3.3 Distribution of ventilated air . . . 23
3.3.1 Displacement ventilation . . . 23
3.3.2 Mixing ventilation . . . 25
3.4 Controllers of ventilation . . . 26
3.4.1 CAV . . . 26
3.4.2 VAV . . . 26
3.4.3 DCV . . . 27
3.5 Classification of ventilation . . . 28
3.5.1 Age of air . . . 28
3.6 Energy demand for ventilation systems . . . 30
3.7 A state of the art review of energy efficient ventilation . . . 30
3.7.1 Ventilative cooling . . . 31
3.7.2 Building automation and ventilation control . . . 32
3.7.3 Nydalen Vy . . . 33

4 Presentation of ZEB Laboratory 35
4.1 Zero Emission Buildings . . . 35
4.2 ZEB Laboratory . . . 36
4.2.1 Ambition level . . . 36

4.2.2 Building structure . . . 36
4.2.3 Windows, doors and hatches . . . 37
4.2.4 Usage . . . 38
4.3 Ventilation in ZEB Laboratory . . . 39
4.3.1 Mechanical ventilation . . . 39
4.3.2 Natural ventilation . . . 39
4.3.3 Ventilation modes . . . 40
4.3.4 Ventilation control . . . 40

5 The structure of the models and cases in CONTAM 41

5.1 The simulation tool . . . 41
5.1.1 Validation of CONTAM . . . 42
5.2 The structure of the model of ZEB Flexibel Lab . . . 42
5.2.1 Building structure . . . 42
5.2.2 External openings . . . 43
5.2.3 Zonal division . . . 45
5.2.4 Internal openings . . . 46
5.2.5 Internal temperature levels . . . 47
5.2.6 Occupants . . . 47
5.2.7 Levels and generation of pollution . . . 48
5.2.8 Mechanical ventilation . . . 49
5.2.9 Automation systems . . . 51
5.3 The properties of the ambient conditions . . . 54
5.3.1 Location . . . 54
5.3.2 Air temperature . . . 54
5.3.3 Humidity ratio . . . 55
5.3.4 Wind . . . 55
5.4 The structure of the basic and corrected models . . . 57
5.4.1 Model A: Only natural ventilation . . . 57
5.4.2 Model B: Only mechanical ventilation . . . 57
5.4.3 Model C: Hybrid ventilation . . . 58
5.4.4 Summary of simulated building models . . . 58

6 Presentation and discussion of the results **59**
6.1 Case 1: Winter week . . . 59
6.1.1 Energy heating demand . . . 60
6.1.2 Required fan power . . . 62
6.1.3 Air change rates . . . 63
6.1.4 Age of air vs. CO_2 levels . . . 64
6.2 Case 2: Transition week . . . 65
6.2.1 Energy heating demand . . . 65
6.2.2 Required fan power . . . 68
6.2.3 Air change rates . . . 69
6.2.4 Age of air vs. CO_2 level . . . 70
6.3 Case 3: Summer week . . . 71
6.3.1 Pressure profiles and corresponding air flows . . . 71
6.3.2 Atmospherically environment . . . 74
6.3.3 Air change rate . . . 76

7 Discussion **77**

8 Conclusion **80**

9 Further Work **82**

Bibliography **83**

A Floor plans **88**

B Building facade **92**

C Calculation of air change rate **96**

D Schedule for opening of windows and doors **97**

E P-controller with range from 600 to 1000 ppm **98**

F P-controller with range from 800 to 1100 ppm **100**

G Winter week results **102**

G.1 Resulting air change rate from simulations 102

G.2 Resulting CO_2 levels from the simulations 103

H Transition week results **136**

H.1 Resulting air change rate from simulations 136

H.2 Resulting CO_2 levels from the simulations 137

I Summer week results **170**

I.1 Resulting pressure profiles from simulations of Model A.1 170

I.2 Resulting air flows from simulations of Model A.1 171

I.3 Resulting age of air vs. $CO2$ level from simulations of Model A.1 and A.3 172

I.4 Resulting CO_2 levels from the simulations 173

J Risk assessment **186**

List of Figures

3.1 Concurrent mixed-mode ventilation (reproduced from CBE (2013)). 16
3.2 Change-over mixed-mode ventilation (reproduced from CBE (2013)). 16
3.3 Zoned mixed-mode ventilation (reproduced from CBE (2013)). 17
3.4 A graphical presentation of the Network Model applied to a simple building. 18
3.5 General pressure profile resulting from internal internal temperature larger than external temperature (inspired by Li et al. (2000)). 20
3.6 Pressure profiles resulting from temperature differences over different building facades (inspired by Jo et al. (2007)). 20
3.7 Resulting pressure profile form wind (inspired by (Walker 2006)). 21
3.8 Resulting pressure profile form the effects of stack and wind (inspired by Walker (2006)). 22
3.9 A thermal plume with associated temperature and velocity profile (reproduced from Kofoed (1991)). 24
3.10 Displacement ventilation (inspired by Etheridge & Sandberg (1996)). 24
3.11 Mixing ventilation (inspired by Etheridge & Sandberg (1996)). 25
3.12 A simple DCV system (reproduced from Kolokotroni & Heiselberg (1997)). 27
3.13 A graphical presentation of a P-controller (reproduced from Novakovic et al. (1996)). . . 28
3.14 Definition of age of air (reproduced from Etheridge & Sandberg (1996)). 29

4.1 Architectural drawing of the floors of ZEB Laboratory (permission for display given by Cecilie Schei, Civil Architect, Link Arkitektur). 37
4.2 The facades of ZEB Laboratory with openable windows marked as blue, red and yellow (permission for display given by Cecilie Schei, Civil Architect, Link Arkitektur). 38

5.1 The facades of the building model of ZEB Laboratory with openabale windows and doors implemented in the building model. 43

5.2 The floor plans of the building model of ZEB Laboratory implemented in the building model. . . . 46
5.3 Simple presentation of the main return duct work within the building model of ZEB Laboratory. . . . 51
5.4 Graphical presentation of a general P-controller with a range from a lower to an upper limit. 52
5.5 Block diagram of a general P-controller with the range from a lower to an upper limit, with the proportional coefficient equal the slope, with associated modifier and control loop. 53
5.6 Ambient air temperatures implemented in the simulations (based on measurements performed by Yr (2018)). . . . 55
5.7 Ambient humidity ratio implemented in the simulations (based on measurements performed by Yr (2018)). . . . 55
5.8 Wind roses describing the properties of wind implemented in CONTAM (based on measurements performed by Yr (2018)). . . . 56
5.9 Wind pressure coefficients implemented in the simulations (based on measurements performed by Tokyo Polytechnich University (2007)). . . . 57

6.1 Maximum heating power required to heat ambient air during the winter week. . . . 60
6.2 The resulting required heating power of ambient air entering four given zones during the winter week. . . . 61
6.3 Power required to run the fans during the winter week. . . . 62
6.4 The resulting air change rate for model B.1 and B.2 in during the winter week. . . . 63
6.5 The resulting age of air vs. CO_2 levels from simulations of Model B.1 and B.2 during the winter week. . . . 64
6.6 Maximum heating power required to heat ambient air during the transition week. . . . 66
6.7 The resulting required heating power of ambient air entering four given zones during the transition week. . . . 67
6.8 Power required to run the fans during the transition week. . . . 68
6.9 The resulting air change rate for model A.2 and B.2 during the transition week. . . . 69
6.10 The resulting age of air vs. CO_2 levels from simulations with Model A.2 and B.2 during the transition week. . . . 70

6.11 Resulting pressure differences over openings at the east facade of Model A.1 during Monday and Wednesday in the summer week. The horizontal axis describes the pressure difference, while the elevation of the openings are shown on the vertical axis. The color of the graph indicates the time. 72
6.12 Resulting air flows through openings at the east facade of Model A.1 during Monday and Wednesday in the summer week. The horizontal axis describes the air flow rate, while the elevation of the openings are shown on the vertical axis. The color of the graph indicates the time. 73
6.13 The time period a zone maintains a CO_2 level above 900 ppm during the summer week. . 74
6.14 The resulting age of air vs. CO_2 levels from simulations of Model A.1 and A.3 at Monday during the summer week. 75
6.15 The resulting air change rate of Model A.1 and Model A.3 during the summer week. . . 76

A.1 Floor plan of the first floor of ZEB Laboratory. 88
A.2 Floor plan of the second floor of ZEB Laboratory. 89
A.3 Floor plan of the third floor of ZEB Laboratory. 90
A.4 Floor plan of the fourth floor of ZEB Laboratory. 91

B.1 East facade of ZEB Laboratory. 92
B.2 West facade of ZEB Laboratory. 93
B.3 North facade of ZEB Laboratory. 94
B.4 South facade of ZEB Laboratory. 95

D.1 Scheduled opening of manually controlled doors, windows and motorized windows for morning aeration. 97

E.1 Graphical presentation of P-controller with range from 600 to 1000 ppm. 98
E.2 Modified graphical presentation of P-controller with range from 600 to 1000 ppm. 98
E.3 Block diagram describing a P-controller with range from 600 to 1000 ppm. 99

F.1 Graphical presentation of P-controller with range from 800 to 1100 ppm. 100
F.2 Modified graphical presentation of P-controller with range from 800 to 1100 ppm. 100
F.3 Block diagram describing a P-controller with range from 800 to 1100 ppm. 101

G.1 The resulting air changes rates of different corrected building models simulated during the winter season. 102
G.2 Labels describing the resulting CO_2 levels from the simulations. 103
G.3 Resulting CO_2 in the first floor when simulating building model A.1 during the winter. . 104
G.4 Resulting CO_2 in the second floor when simulating building model A.1 during the winter. 105
G.5 Resulting CO_2 in the third floor when simulating building model A.1 during the winter. . 106
G.6 Resulting CO_2 in the fourth floor when simulating building model A.1 during the winter. 107
G.7 Resulting CO_2 in the first floor when simulating building model A.2 during the winter. . 108
G.8 Resulting CO_2 in the second floor when simulating building model A.2 during the winter. 109
G.9 Resulting CO_2 in the third floor when simulating building model A.2 during the winter. . 110
G.10 Resulting CO_2 in the fourth floor when simulating building model A.2 during the winter. 111
G.11 Resulting CO_2 in the first floor when simulating building model B1 during the winter. . 112
G.12 Resulting CO_2 in the second floor when simulating building model B.1 during the winter. 113
G.13 Resulting CO_2 in the third floor when simulating building model B.1 during the winter. . 114
G.14 Resulting CO_2 in the fourth floor when simulating building model B.1 during the winter. 115
G.15 Resulting CO_2 in the first floor when simulating building model B.2 during the winter. . 116
G.16 Resulting CO_2 in the second floor when simulating building model B.2 during the winter. 117
G.17 Resulting CO_2 in the third floor when simulating building model B.2 during the winter. . 118
G.18 Resulting CO_2 in the fourth floor when simulating building model B.2 during the winter. 119
G.19 Resulting CO_2 in the first floor when simulating building model A.1+B.1 during the winter. 120
G.20 Resulting CO_2 in the second floor when simulating building model A.1+B.1 during the winter. 121
G.21 Resulting CO_2 in the third floor when simulating building model A.1+B.1 during the winter. 122
G.22 Resulting CO_2 in the fourth floor when simulating building model A.1+B.1 during the winter. 123
G.23 Resulting CO_2 in the first floor when simulating building model A.1+B.2 during the winter. 124
G.24 Resulting CO_2 in the second floor when simulating building model A.1+B.2 during the winter. 125
G.25 Resulting CO_2 in the third floor when simulating building model A.1+B.2 during the winter. 126

G.26 Resulting CO_2 in the fourth floor when simulating building model A.1+B.2 during the winter. 127
G.27 Resulting CO_2 in the first floor when simulating building model A.2+B.1 during the winter. 128
G.28 Resulting CO_2 in the second floor when simulating building model A.2+B.1 during the winter. 129
G.29 Resulting CO_2 in the third floor when simulating building model A.2+B.1 during the winter. 130
G.30 Resulting CO_2 in the fourth floor when simulating building model A.2+B.1 during the winter. 131
G.31 Resulting CO_2 in the first floor when simulating building model A.2+B.2 during the winter. 132
G.32 Resulting CO_2 in the second floor when simulating building model A.2+B.2 during the winter. 133
G.33 Resulting CO_2 in the third floor when simulating building model A.2+B.2 during the winter. 134
G.34 Resulting CO_2 in the fourth floor when simulating building model A.2+B.2 during the winter. 135

H.1 The resulting air changes rates of different corrected building models simulated during the transition season season. 136
H.2 Labels describing the resulting CO_2 levels from the simulations. 137
H.3 Resulting CO_2 in the first floor when simulating building model A.1 during the transition. 138
H.4 Resulting CO_2 in the second floor when simulating building model A.1 during the transition. 139
H.5 Resulting CO_2 in the third floor when simulating building model A.1 during the transition. 140
H.6 Resulting CO_2 in the fourth floor when simulating building model A.1 during the transition 141
H.7 Resulting CO_2 in the first floor when simulating building model A.2 during the transition. 142
H.8 Resulting CO_2 in the second floor when simulating building model A.2 during the transition. 143
H.9 Resulting CO_2 in the third floor when simulating building model A.2 during the transition. 144
H.10 Resulting CO_2 in the fourth floor when simulating building model A.2 during the transition 145
H.11 Resulting CO_2 in the first floor when simulating building model B.1 during the transition. 146
H.12 Resulting CO_2 in the second floor when simulating building model B.1 during the transition. 147
H.13 Resulting CO_2 in the third floor when simulating building model B.1 during the transition. 148
H.14 Resulting CO_2 in the fourth floor when simulating building model B.1 during the transition 149

H.15 Resulting CO_2 in the first floor when simulating building model B.2 during the transition. 150
H.16 Resulting CO_2 in the second floor when simulating building model B.2 during the transition. 151
H.17 Resulting CO_2 in the third floor when simulating building model B.2 during the transition. 152
H.18 Resulting CO_2 in the fourth floor when simulating building model B.2 during the transition 153
H.19 Resulting CO_2 in the first floor when simulating building model A.1+B.1 during the transition. 154
H.20 Resulting CO_2 in the second floor when simulating building model A.1+B.1 during the transition. 155
H.21 Resulting CO_2 in the third floor when simulating building model A.1+B.1 during the transition. 156
H.22 Resulting CO_2 in the fourth floor when simulating building model A.1+B.1 during the transition 157
H.23 Resulting CO_2 in the first floor when simulating building model A.1+B.2 during the transition. 158
H.24 Resulting CO_2 in the second floor when simulating building model A.1+B.2 during the transition. 159
H.25 Resulting CO_2 in the third floor when simulating building model A.1+B.2 during the transition. 160
H.26 Resulting CO_2 in the fourth floor when simulating building model A.1+B.2 during the transition 161
H.27 Resulting CO_2 in the first floor when simulating building model A.2+B.1 during the transition. 162
H.28 Resulting CO_2 in the second floor when simulating building model A.2+B.1 during the transition. 163
H.29 Resulting CO_2 in the third floor when simulating building model A.2+B.1 during the transition. 164
H.30 Resulting CO_2 in the fourth floor when simulating building model A.2+B.1 during the transition 165
H.31 Resulting CO_2 in the first floor when simulating building model A.2+B.2 during the transition. 166

H.32 Resulting CO_2 in the second floor when simulating building model A.2+B.2 during the transition. 167
H.33 Resulting CO_2 in the third floor when simulating building model A.2+B.2 during the transition. 168
H.34 Resulting CO_2 in the fourth floor when simulating building model A.2+B.1 during the transition 169

I.1 Resulting pressure differences over openings at the east facade of Model A.1 during Tuesday, Thursday and Friday. The horizontal axis describes the pressure difference, while the elevation of the openings are according to the vertical axis. The color of the graph indicates the time. 170
I.2 Resulting air flows through openings at the east facade of Model A.1 during Tuesday, Thursday and Friday. The horizontal axis describes the air flow rate, while the elevation of the openings are according to the vertical axis. The color of the graph indicates the time. 171
I.3 The resulting age of air vs. CO_2 levels from simulations of Model A.1 and A.3 at Wednesday during the summer week. 172
I.4 Labels describing the resulting CO_2 levels from the simulations. 173
I.5 Resulting CO_2 in the first floor when simulating building model A.1 during the summer. 174
I.6 Resulting CO_2 in the second floor when simulating building model A.1 during the summer. 175
I.7 Resulting CO_2 in the third floor when simulating building model A.1 during the summer. 176
I.8 Resulting CO_2 in the fourth floor when simulating building model A.1 during the summer. 177
I.9 Resulting CO_2 in the first floor when simulating building model A.1 with night-open internal doors during the summer. 178
I.10 Resulting CO_2 in the second floor when simulating building model A.1 with night-open internal doors during the summer. 179
I.11 Resulting CO_2 in the third floor when simulating building model A.1 with night-open internal doors during the summer. 180
I.12 Resulting CO_2 in the fourth floor when simulating building model A.1 with night-open internal doors during the summer. 181
I.13 Resulting CO_2 in the first floor when simulating building model A.1 with night-open internal doors and morning aeration during the summer. 182

I.14 Resulting CO_2 in the second floor when simulating building model A.1 with night-open internal doors and morning aeration during the summer. 183
I.15 Resulting CO_2 in the third floor when simulating building model A.1 with night-open internal doors and morning aeration during the summer. 184
I.16 Resulting CO_2 in the fourth floor when simulating building model A.1 with night-open internal doors and morning aeration during the summer. 185

J.1 Risk assessment 186

List of Tables

2.1 Activity level and corresponding metabolism (Novakovic et al. 1996). 6

2.2 Clothing and corresponding insulation (Novakovic et al. 1996). 6

2.3 Description of building categories (Standard Norge 2007). 7

2.4 Recommended air temperature levels for buildings in category II (Standard Norge 2007). 8

2.5 Recommended temperature levels (TEK17 2017). 8

2.6 Criteria for air quality zone division (Miljøverndepartementet 2012). 10

2.7 Recommended values for category II buildings (Standard Norge 2007). 11

2.8 Criteria for air quality (Standard Norge 2007) in rooms common in offices and education buildings. 11

5.1 Dimension and properties of windows inserted in the building model of ZEB Laboratory. 44

5.2 Total and relative elevation of height of openings inserted in the building model of ZEB Laboratory. 45

5.3 Internal zonal temperatures in the building model of ZEB Laboratory. 47

5.4 Average number of occupants in a given zone during a given time present in the building model of ZEB Laboratory implemented in the building model. 48

5.5 The properties of CO_2 within the building model of ZEB Laboratory implemented in the building model (Dols & Polidoro 2015). 49

5.6 Inserted CO_2 generation of the occupants in the building model of ZEB Laboratory. . . . 49

5.7 Recommended and implemented values of exhaust air flow rates in the building model of ZEB Laboratory (Standard Norge 2007). 49

5.8 Recommended and implemented values of air flow rates in the building model of ZEB Laboratory (Standard Norge 2007). 50

5.9 A tabular summary of the corrected building models of ZEB Laboratory. 58

6.1 The total heat energy demand of air during the winter week in four chosen zones. 61

6.2 The total heat energy demand of air during the transition week in four chosen zones. . . . 68

C.1 Required air flows according to NS15251:2007. 96
C.2 Required air change rate when unoccupied. 96
C.3 Required air change rate when maximum occupied. 96

Abbreviations

Symbol	Description
NTNU	Norwegian University of Science and Technology
FME	The Research Centers for Environmental Friendly Energy
NIST	National Institute of Standards and Technology
ZEB	Zero Emission Building
nZEB	Nearly Zero Emission Building
CAV	Constant Air Volume
VAV	Variable Air Volume
DCV	Demand Controlled Ventilation
SBS	Sick Buildings Syndrome
WHO	World Health Organization
PMV	Predicted Mean Vote
PPD	Predicted Percentage of Dissatisfied
RH	Relative humidity
CFD	Computational Fluid Dynamics
PV	Photovoltaics
HVAC	Heating, Ventilation and Air Conditioning

Nomenclature

Symbol	**Description**	**Unit**
Q	Air flow rate	$[\frac{m^3}{s}]$
$\dot{m}$	Mass flow rate	$[\frac{kg}{s}]$
K	Flow coefficient	[-]
n	Flow exponent	[-]
ρ	Density	$[\frac{kg}{m^3}]$
P	Pressure	[Pa]
U	Velocity	$[\frac{m}{s}]$
z	Height	[m]
C_d	Discharge coefficient	[-]
A	Area	$[m^2]$
T	Temperature	[°C]
g	Gravitational acceleration	$[\frac{m}{s^2}]$
C_p	Pressure coefficient	[-]
τ	Age of air	[h]
V	Volume	$[m^3]$
SFP	Specific fan power	$[\frac{kW}{m^3/s}]$
η	Efficiency	[-]
ε	Effectiveness	[-]
c_p	Specific heat	$[\frac{kJ}{kg \cdot K}]$

Subscripts

Symbol	Description
I	Internal
E	External
s	Stack
w	Wind
0	Reference
NL	Neutral Level
O	Operative
D	Dry bulb
R	Radiation
sat	Saturation
p	Point
n	Nominal
e	Exhaust
r	Room
c	Contaminant
dyn	Dynamic

Chapter 1

Introduction

The energy demand of the Norwegian building sector varies and depends on the ambient conditions, the state of the buildings, and the energy cost (Brattebø et al. 2014). However, 40% of the total energy use in Norway is consumed by the building sector and is utilized, among others, in heating, cooling and ventilation (Holstad & Bøeng 2013). The energy efficiency of the building sector will be crucial to decrease the energy demand and to fulfill the Norwegian obligations to the UN (Dokka 2009).

A transition towards energy efficient buildings is one of the most profitable measures with the aim to decrease the emissions of greenhouse gasses (Jacobsen & Andresen 2018). *Zero Emission Buildings*, ZEB, has the overall goal of producing renewable energy on-site to compensate for emissions of greenhouse gasses during the lifetime of the building (Fufa et al. 2016). A development towards energy efficient buildings, such as ZEB, can include an energy efficiency potential of 10.0 TWh, which reduces the emissions of greenhouse gas equivalents by six million tonnes (Dokka 2009).

1.1 Background and motivation

SINTEF is one of Europe's leading research institutes in the field of technology, science, and social studies (Gjørv Bech et al. 2018). SINTEF Byggforsk is the research institute of sustainable development of buildings, infrastructure, and mobility (Gjørv Bech et al. 2018). SINTEF has a close collaboration with NTNU resulting in, among others, *The Research Centre on Zero Emission Buildings* and *ZEB Laboratory* (Jacobsen & Andresen 2018).

ZEB Laboratory is an office and education building under construction located at Gløshaugen Campus, Trondheim (SINTEF 2017*b*). The building will achieve the level of ZEB-COM, act as a *living laboratory* and will hopefully result in a national resource for further research (Jacobsen & Andresen 2018).

ZEB Laboratory has the aim of achieving a level of ZEB-COM (SINTEF 2017*a*). Hence, on-site production of renewable energy must compensate for greenhouse gas emissions from the construction and transportation of the materials, the construction of the building, the operational energy demand, and the deconstructing and disposal of the building (Fufa et al. 2016). By acting as a flexible living laboratory ZEB Laboratory will be well suited for development of international industry, in addition to acting as a national resource developing technology suitable for Zero Emission Buildings (SINTEF 2017*a*). ZEB Laboratory will be occupied by office workers and students, while different actions concerning efficient energy use and the indoor climate are performed.

ZEB Laboratory will be a central part of new research of *Zero Emission Neighborhoods*, ZEN, and will hopefully produce innovative solutions in terms of energy efficiency that can be transferred to other buildings (SINTEF 2017*a*). ZEB Laboratory will be co-funded by SINTEF, NTNU and Norsk Forskingsråd. SINTEF and NTNU will fund the building to achieve the level of ZEB, while Norsk Forskningsråd will fund the building to act as a living laboratory (Jacobsen & Andresen 2018).

The Project Thesis, *Optimal use of natural ventilation in ZEB Flexible Lab*, was completed during the fall of 2018. Note that ZEB Flexible Lab is the former name of ZEB Laboratory. This thesis contains some information on ventilation strategies and mathematical models of natural ventilation. Further, the thesis concerns the cause and the performance of natural ventilation in a very simplified, one zone, ZEB Laboratory in non-transient ambient surroundings. This completed Project Thesis forms an important basis for further study, and hence some background for this Master's Thesis.

1.2 Problem description

The objective of this Master's Thesis is to study how to combine natural and mechanical ventilation in ZEB Laboratory in an optimal way concerning energy use and indoor climate. Methods of natural, mechanical, and hybrid building ventilation are to be explained, in addition to an emphasis on energy-efficient solutions for ventilation and cooling of office and educational buildings. Simulations will be performed to compare different ventilation systems and evaluating the resulting indoor climate of the building. The different ventilation systems combine natural, mechanical, and hybrid ventilation managed by various control strategies. The resulting energy use of the ventilation systems will be calculated and compared.

1.3 Approach

Knowledge must be obtained to reach the objective of this thesis through a carefully conducted literature review. This includes a review of the definitions of a good indoor environment, the requirements of a good indoor environment in offices and education buildings, in addition to the possible consequences of a poor indoor climate. The literature mainly concerns different ventilation strategies. Natural, mechanical and hybrid ventilation will be reviewed carefully. This includes different methods of air supply, air distribution, ventilation control, with a focus on mathematical models of natural ventilation. Such literature will mainly be based on Norwegian standards, such as NS15251:2007, NS7730:2005 and TEK17, in addition to books, reports, theses, and articles available from search engines as Oria and Google Scholar.

The literature review will include a presentation of state of the art solutions regarding energy efficient building ventilation, emphasizing cooling and controllers of Zero Emission Buildings. The articles are mainly from 2015 to date. Newer Annexes from the *Energy Conservation in Buildings and Community Systems*, EBC Annexes, will be reviewed. In addition, a smaller case study of an office building under construction located in Oslo, Norway, implemented with completely natural ventilation will be performed.

The literature presented in Chapter 2, and 3.1 to 3.4 are to some degree based on literature and knowledge obtained during the work with the previous completed Project Thesis, *Optimal use of natural ventilation in ZEB Flexible Lab*. It's important to obtain a large amount of information regarding the building, so future simulations and the following results are realistic and close to life like. The reviewed information regarding ZEB Laboratory will be based on information presented by SINTEF, NTNU and LINK Arkitektur from 2016 to 2019, and are project descriptions, visions, and architectural drawings.

A building model based on ZEB Laboratory will be created in the simulation tool CONTAM. Different systems of ventilation will be implemented in the building model, leading to three main models - *Model A* a building with only natural ventilation, *Model B* a building with only mechanical ventilation, and *Model C* a building with hybrid ventilation. Although the ventilation systems are different in each of the three main models, the other variables of the building will remain constant. This includes building structure, zonal division, occupants, CO_2 generation, and possible ventilation controllers. The ambient conditions of ZEB Laboratory are assumed to be transient, varying with the season. Three different seasons will be implemented in CONTAM and will be referred to as the different cases of simulation. *Case 1* concerns the winter season, *Case 2* concerns the transition season between winter and summer, and *Case 3* concerns the summer season.

The simulation tool CONTAM provides the possibility to simulate transient air flows through a building model. Each of the presented models will be simulated according to each of the three seasons. The resulting air flows will be analyzed, according to air change rate, age of air, and neutral levels. The indoor environment will be evaluated based on the resulting CO_2 levels of the building. Further, a simple energy calculation with regards to the demanded heating energy and required fan power will be performed.

1.4 The structure of this Master's Thesis

This Master's Thesis will firstly present important finds from the literature review. This includes the requirements and importance of a satisfactory indoor climate, different ventilation strategies and systems with associated mathematical models, and a state of the art review. This literature will act as the foundation for the future evaluation of the results. Further, information regarding ZEB Laboratory relevant to the ventilation possibilities will be presented. This includes the building structure, zonal division, occupant load, and predetermined ventilation strategies.

Secondly, the simulations performed and the structure of the simulated models will be described in detail. This includes information regarding the chosen simulation tool, the structure of the models, and the ambient weather files. The building models are based on the presented information regarding ZEB

Laboratory.

Thirdly, important results from the simulations will be presented and discussed. This includes presentation and comparisons of the simulation results. The results will be evaluated based on the requirements and demands of a good indoor environment. The simulated building models and cases will be further discussed regards to the chosen simulation tool and the constructed structure of the models.

Furthermore, a conclusion regarding the most suitable ventilation system for the winter season, transition season, and summer season will be presented. Some possibilities of further work will be presented at the end of this thesis.

1.5 Priorities and limitations

This Master's Thesis will present and compare different ventilation strategies with associated control systems implemented in ZEB Laboratory. The ventilation system will only include two different proportional controllers and a scheduled control.

Simplified ventilation systems are to be simulated in CONTAM. The building structure, zonal division, external openings, occupancy and pollution load of ZEB Laboratory are to be simplified. Only a given number of different control systems will be simulated. The resulting air flows, CO_2 levels, and energy demand from the completed simulations will be compared with the objective of achieving an optimal combination of natural and mechanical ventilation in ZEB Laboratory.

Chapter 2

Indoor environment in office and education buildings

According to WHO *indoor environment* is defined as the thermal, atmospheric, acoustic, actinic, mechanical, aesthetic and psycho-social environment (Novakovic et al. 1996). Hence, the indoor environment affects all occupants during the entire time while present in a building.

In the following subsections the thermal and atmospheric environment will be discussed including different regulations and requirements regarding the indoor environment. The effects of a poor indoor climate on occupants will also be presented.

2.1 Thermal environment

Novakovic et al. defines thermal comfort as a *a state of mind where we express full satisfaction with the thermal environment* (Novakovic et al. 1996). Hence, the preferred thermal environment is subjective and occupants present in a building will experience a different level of thermal comfort.

The level of thermal comfort depends on activity level, clothing and residence time, as well as the dry bulb temperature of the air, thermal radiation, air humidity, and air velocity (Novakovic et al. 1996).

2.1.1 Activity level

The heat production of an occupant highly depends on their activity level. An occupant will produce a lower level of heat and have a lower metabolism when sedentary than while running. While sedentary the occupant will produce a lower level of excess heat that the body must remove through the skin and the respiratory system. The heat production of an occupant can be evaluated by the unit *met*. 1 met is equal to 58 $\frac{W}{m^2}$, which equals the heat generation of a sedentary person. (Novakovic et al. 1996)

The different activity levels with corresponding values of metabolism are presented in Table 2.1.

Table: 2.1 Activity level and corresponding metabolism (Novakovic et al. 1996).

Activity level	**Metabolism [met]**
Sleeping	0.80
Sedentary, relaxed	1.00
Standing, relaxed	1.20
Sedentary (office, school, lab)	1.10-1.50
Moderate activity	2.00-2.80
Medium activity	2.80-3.50
Walk (2 $\frac{km}{h}$)	1.90
Walk (5 $\frac{km}{h}$)	3.40
Run (9 $\frac{km}{h}$)	7.50
Run (15 $\frac{km}{h}$)	9.50
Maximum performance	13.40
Top-class sport	15.0

As presented in Table 2.1 the metabolism of an occupant present in an office and educational building will most likely be in the range of 1.10 to 1.50 met.

2.1.2 Clothing

The level of thermal comfort experienced by an occupant is affected by clothing. Some garments have a larger thermal resistance and insulation than other garments. The level of insulation can be described by the unit *clo*. 1 clo equals 0.115 $\frac{m^2K}{W}$ (Novakovic et al. 1996). Table 2.2 presents different clothing with the associated levels of insulation.

Table: 2.2 Clothing and corresponding insulation (Novakovic et al. 1996).

Clothing	**Insulation [clo]**
Shorts, underwear, t-shirts, light socks, sandals	0.30
Light dress with sleeves, underwear	0.45
Light pants, short sleeve shirt, underwear, shoes	0.50
Skirt, short sleeve shirt, underwear, sandals	0.60
Skirt, sweater, shirt, underwear, stockings	0.90
Jacket, pants, shirt, underwear, shoes	1.00
Coat, jacket, west, pants, shirt, underwear, shoes	1.50

From Table 2.2 it's reasonable to assume that occupants of an office and educational building will wear clothes with an insulation level in the range from 0.50 to 1.0 during the entire year.

2.1.3 Thermal neutrality

Thermal neutrality implies that an occupant doesn't have any desire for a higher or lower surrounding temperature level, and can serve as a measure of the thermal comfort (Novakovic et al. 1996).

The psycho-physical index of *Predicted Mean Vote*, or PMV, is a seven-point scale used to determine how occupants range their thermal comfort. The scale ranges from +3 to -3, where the index +3 represents hot surroundings, and -3 represents cold surroundings. The index of 0 represents thermal neutrality. Novakovic et al. (1996)

The PMV index can further be used to predict the percentage of dissatisfied occupants present. This is referred to as the PPD index and depends on the PMV index according to Eq. (2.1) (Novakovic et al. 1996).

$$PPD = 100 - 95 \cdot (-0.03353 \cdot PMV^4 - 0.2179 \cdot PMV^2) \tag{2.1}$$

The acceptable levels of the PMV and PPD depend on which *building category* the building belongs to. The different building categories are described in Table 2.3 (Standard Norge 2007).

Table: 2.3 Description of building categories (Standard Norge 2007).

Category	**Explanation**
I	High expectation level. Recommended i rooms where the occupants are very sensitive and vulnerable.
II	Normal expectation level. Should be used in new and rehabilitated buildings.
III	Acceptable, moderate expectation level. Can be used in exciting buildings.

Based on the description in Table 2.3, ZEB Laboratory is categorized as a building in category II. For a building in category II, the level of PPD should be below 10% with an average PMV index in the range of -0.5 to 0.5 (Standard Norge 2007).

2.1.4 Temperature

The surrounding air temperature affects the thermal comfort of an occupant. When there are no significant sources of heat radiation, the air temperature is equal the operative temperature T_O. The operative temperature is dependent of the dry bulb temperature, T_D, and the mean radiation temperature, T_R. Assuming that the average radiation temperature is below 50.0 °C and that the internal air velocity is less than 0.40 $\frac{m}{s}$ the operative temperature can be estimated using Eq. (2.2) (Novakovic et al. 1996).

$$T_O = \frac{1}{2}(T_D + T_R) \tag{2.2}$$

Recommended levels of air temperature in classrooms, office spaces and other rooms that often are present in office and educational buildings are stated in *NS 15251:2007*, and presented in Table 2.4.

Table: 2.4 Recommended air temperature levels for buildings in category II (Standard Norge 2007).

	Cubicle	**Open office**	**Auditorium**	**Cafe**	**Classroom**
Min. temperature while heating [°C]	20.0	20.0	20.0	20.0	20.0
Max. temperature while cooling [°C]	26.0	26.0	26.0	26.0	26.0

Further, *Byggteknisk forskrift* proposes recommended values of the operative temperature based on the activity level, as presented in Table 2.5 (TEK17 2017).

Table: 2.5 Recommended temperature levels (TEK17 2017).

Activity level	**Light work**	**Medium work**	**Hard work**
Operative temperature [°C]	19.0-26.0	16.0-26.0	10.0-26.0

Based on the accepted indoor air temperature according to NS 15251:2007 and TEK17, an indoor temperature of 23.0°C is recommended for office and educational buildings.

2.1.5 Air velocity

The velocity of air inside an occupied zone can affect the level of thermal comfort. The air in motion can cause the sensation of *draught*. Draught is defined as unwanted local convective cooling by Novakovic et al. (Novakovic et al. 1996).

The air velocity inside a category II building should not exceed 0.190 $\frac{m}{s}$ during the winter and 0.160 $\frac{m}{s}$ during the summer (Standard Norge 2005). Higher levels of air velocities can lead to an increased risk of experienced draught and therefore a larger level of PPD.

Occupants may still experience some draught even if the air velocity is within the given criteria. This because the recommended values are based on laminar air flows. In a ventilated room the air flows will often be turbulent. Thus, draught can be experienced at lower velocities (Novakovic et al. 1996).

2.1.6 Relative humidity

The level of thermal comfort can be affected by the humidity of the air (Becher et al. 2016). The relative humidity can be expressed as the ratio of the partial pressure and the saturation pressure of the water vapor. The ratio of the actual amount of water and saturated water in the air also expresses the relative humidity. These relations are presented in Eq. (2.3) (Novakovic et al. 1996).

$$RH = \frac{P}{P_{sat}} = \frac{x}{x_{sat}} \tag{2.3}$$

Based on studies regarding thermal comfort, given a satisfying indoor temperature, it's found that variations of the relative humidity in the range from 20 to 70% will not affect the perceived indoor air quality (Asphaug et al. 2015). However, a very low or very high level of relative humidity should be avoided. A level of RH lower than 20% can lead to dry mucous membranes. A too high level of relative humidity can, among others, cause a bad odor and growth of mold (Becher et al. 2016).

2.2 Atmospheric environment

The atmospheric indoor environment is an indicator of the indoor air quality. The level of comfort and the risk of respiratory diseases are affected by the atmospheric environment (Jerkø et al. 2006).

2.2.1 CO$_2$ levels

The level of CO_2 in a room is a suitable indicator of the indoor air quality. The level can indicate how many occupants that are present in a room, how long they have been present, as well as the air change rate of the room (Jerkø et al. 2006).

The level of CO_2 in a building should not exceed the outdoor CO_2 level by more than 500 ppm Standard Norge (2007). The level of CO_2 in Norway is often found to be in the range of 400 ppm to 450 ppm (Holøs & Mysen 2016). The level of CO_2 in an office and educational building should therefore not exceed 900 ppm.

2.2.2 Outdoor pollution

Outdoor pollution can affect indoor air quality through ventilation. Hence, the level of indoor air quality highly depends on the level of outdoor air quality and ambient pollution levels (TEK17 2017).

Table 2.6 defines the health risk of exposure to different amounts of PM_10 and NO_2 for a given time period (Miljøverndepartementet 2012).

Table: 2.6 Criteria for air quality zone division (Miljøverndepartementet 2012).

	Green Zone	**Yellow Zone**	**Red Zone**
PM_{10}	$< 35.0\frac{\mu g}{m^3}$ 7 days per year	35.0-50.0$\frac{\mu g}{m^3}$ 7 days per year	$> 50.0\frac{\mu g}{m^3}$ 7 days per year
NO_2	$< 40.0\frac{\mu g}{m^3}$ winter mean	40.0 $\frac{\mu g}{m^3}$ winter mean	$> 40.0\frac{\mu g}{m^3}$ annual mean
Health risk		People with severe respiratory and cardiovascular disease do have an increased risk of worsening of the disease. Healthy people will probably not have any health effects.	Persons with respiratory and cardiovascular disease have an increased risk of health effects. Among these, children with respiratory and elderly patients with respiratory and cardiac disorders are most vulnerable.

Any air intake for ventilation should be placed at an external zone characterized as a *green zone*. This is to prevent any transfer of ambient contaminants into a building. No air intakes should therefore be placed close to parking lots or close to smoking areas.

At Elgseter gate in Trondheim, in 2017, the average levels of PM_{10} and NO_2 were $12.0\frac{\mu g}{m^3}$ and $29.0\frac{\mu g}{m^3}$, respectively. These levels both rate in the *green zone* (Luftkvalitet.info 2017). Air intakes can be freely placed in Trondheim. However, high pollution areas like parking lots and smoking areas must be taken into consideration.

Air flow rate

According to the Norwegian standard, *Indoor climate for dimension and evaluation of energy use for a building including indoor air quality, thermal environment, lighting, and acoustics*, there are several factors that affect how ventilation can provide a satisfactory indoor environment (Standard Norge 2007).

For a category II building, the recommended values of ventilation, presented in Table 2.7, must be compiled at least 95% of the occupied time (Standard Norge 2007). The criteria of category II buildings are given in Table 2.8. Both of these tables present values that must be obtained in ZEB Laboratory.

Table: 2.7 Recommended values for category II buildings (Standard Norge 2007).

Variables	Recommended values
Air flow persons	$7.00 \frac{L}{s \cdot persons}$
Air flow materials	$0.350 \frac{L}{s \cdot m^2}$
CO2 level above outdoor level	500 ppm
Air exchange amount	$0.420 \frac{L}{s \cdot m^2}$
Exhaust air kitchen	$20.0 \frac{L}{s}$
Exhaust air bathroom	$15.0 \frac{L}{s}$
Exhaust air toilette	$10.0 \frac{L}{s}$

Table: 2.8 Criteria for air quality (Standard Norge 2007) in rooms common in offices and education buildings.

	Cubicle	Open office	Auditorium	Cafe	Classroom
Area per person [$\frac{m^2}{person}$]	20.0	15.0	0.750	1.50	2.00
Supply air occupants [$\frac{L}{s \cdot m^2}$]	0.700	0.500	10.5	4.90	3.50
Supply air material [$\frac{L}{s \cdot m^2}$]	0.300	0.300	0.300	0.300	0.300
Supply air total [$\frac{L}{s \cdot m^2}$]	1.00	0.800	10.8	5.20	3.80

2.3 Possible consequences of poor indoor environment

A poor indoor environment can entail poor consequences for the occupants, both regarding health and productivity. Studies show that there is a relation between reduced productivity, the health of students, and the lack of indoor air quality in educational buildings (Zhang et al. 2011).

Thermal comfort is an important factor affecting the productivity of occupants. Studies show that a 1.00°C increase of the temperature, when the temperature is in the range from 25.0 to 30.0°C, decreases the productivity of the occupants by 2% (Al Horr et al. 2016).

The relative humidity of the indoor air can affect the indoor environment poorly. Dry and cool air will be perceived as higher quality than moist and hot air (Asphaug et al. 2015). Several studies have shown that there is a correlation between respiratory diseases and moisture damage in buildings. It's estimated that humidity related risk factors in a home can increase the risk of respiratory distress for the occupants by 30 to 50% (Becher et al. 2016).

Occupants exposed to a high level of CO_2 can perceive a poor indoor environment caused by, among others, bad odor (Becher et al. 2016). A high level of CO_2 has been shown to reduce productivity, irritate the mucous membranes and lead to headaches.

Sick building syndrome

Sick building syndrome, SBS, is a collective term of several symptoms including mucous membrane irritation, headache, fatigue, cough, dry skin, and visual disturbances, that occur more often in some buildings than others (Redlich et al. 1997). These symptoms both affect the health and the productivity of the occupants. Hence, SBS is a building-related illness associated with lower indoor air quality (Al Horr et al. 2016).

SBS can be caused by a high level of air contaminants, such as CO_2. Sources of such contaminants are building materials for floors, carpets, cleaning products, and office supplies. Moreover, the chosen ventilation system for a building can cause SBS, especially if the intake of fresh air is located close to a source of pollution. Other causes of SBS are the occupants. A zone with a large number of occupants present over a long period of time has an increased risk of experienced SBS. (Redlich et al. 1997)

Chapter 3

Building ventilation

Ventilation of buildings is a necessary measure to achieve and maintain a satisfactory indoor environment experienced by occupants, while not compromising the health or productivity of the building users (Nystad 2017). The following chapter will present a general introduction of the strategies of ventilation. This includes both natural, mechanical and hybrid ventilation. The mathematical models of the ventilation strategies will be presented, including prediction methods and energy demand calculations. Further, some main methods of air distribution will be presented, including displacement and mixing ventilation. Different controllers and classification of ventilated air rates will be discussed to some extent. Finally, a state of the art review of energy efficient ventilation is presented, including a short case study of Nydalen Vy.

3.1 Strategies of ventilation

The strategies of ventilation can be sectioned into three main categories. Ventilation can occur due to natural forces, such as temperature and wind, mechanics, or a combination of natural and mechanical forces (Etheridge & Sandberg 1996). These categories are referred to as natural, mechanical and hybrid ventilation, respectively. The following three subsections will further describe these strategies.

3.1.1 Natural Ventilation

Natural ventilation is the result of air flows due to pressure differences created by buoyancy and/or wind effects (Etheridge & Sandberg 1996). The strategy of natural ventilation is based on the fact that acceptable indoor air quality can be achieved by diluting the concentration of contaminants in a zone by supplying ambient air (Allard et al. 1998).

When natural ventilation is the chosen strategy, the air is supplied to a building through openings on the building facade, such as windows, doors, hatches and smaller cracks. Air will exhaust the building through the same openings as the air is supplied.

There are several advantages of natural ventilation, in terms of both energy demand and costs. Due to natural ventilation occurring through windows and other facade openings, the operating energy demand is close to zero. However, some energy demand may occur if the windows or doors are motorized. Furthermore, a natural ventilation strategy entails low costs, space, and maintenance. A study of an office building located in the United Kingdom indicates that the implementation of natural ventilation can reduce the total energy cost by 10% (Emmerich et al. 2001).

A natural ventilation strategy does, however, have some disadvantages. No mechanics are implemented. Thus, there is a lack of filtering air and heat recovery. The supplied air quality is variable, both in terms of contaminants and temperature. Furthermore, natural ventilation is a strategy with unstable efficiency. The efficiency has a direct relation to the ambient surroundings. A great temperature difference between the internal and external temperature causes a large air flow. However, if the internal temperature of a building is close to the ambient temperature while no wind is present natural ventilation won't occur. This will be further discussed when presenting the mathematical models of natural ventilation. Moreover, natural ventilation can lead to an inferior indoor environment. Draught can be experienced from the openings and noise from the surroundings can among others be a problem. (Emmerich et al. 2001)

3.1.2 Mechanical Ventilation

The strategy of mechanical ventilation implements mechanical fans to displace air through a building by forcing air to be supplied to or extracted from a zone. A *mechanical ventilation system* is achieved if the fans are connected to adjacent rooms through ducts (Etheridge & Sandberg 1996). Forcing a desirable amount of air in and out of a building can demand the supply and exhaust fans to provide over 1000 Pa each (Dokka et al. 2003).

There are several advantages to implementing mechanical ventilation. Mechanical ventilation provides the opportunity to control the amount of air supplied and extracted from a building. Hence, the amount of air supplied can be controlled by demand (Dokka et al. 2003). In addition to the installation of filters, demand-controlled mechanical ventilation ensures a satisfactory indoor environment when dimensioned correctly. Heat recovery can be installed with the mechanical ventilation system so that heat from the exhaust air is utilized. Such heat recovery can minimize the demand for heating energy to the supply air (Emmerich et al. 2001).

A mechanical ventilation system demands energy to operate, which is one of the most significant disadvantages. Further, the energy demand of such a system increases rapidly when there is a cooling demand in the building (Dokka et al. 2003). A mechanical ventilation system will require installation and maintenance, which can cause an increment of costs. Some noise from the fans can be experienced, which would decrease the quality of the indoor environment.

3.1.3 Hybrid Ventilation

A hybrid ventilation strategy utilizes both natural and mechanical forces with the intent of decreasing the usage of energy (Dokka et al. 2003). Hence, a hybrid ventilation system is an energy efficient combination of natural and mechanical ventilation.

Hybrid ventilation presents the opportunity to provide an acceptable indoor environment in an energy efficient manner. Such a ventilation system intends to provide a comfortable internal environment while taking maximum advantage of the ambient conditions at all times (Jagpal 2015).

A ventilated building can utilize hybrid ventilation within three different categories (Lie 2015). Natural ventilation can be assisted with mechanical fans, which is known as *fan assisted natural ventilation*. Mechanical ventilation can utilize natural forces, such as buoyancy, to ensure ventilation of an entire tall building. This is referred to as *mechanical ventilation with support from natural forces*. The third category is *mixed mode ventilation*. Mixed mode ventilation entails a hybrid ventilation system where the energy demand and operating costs are minimized while the use of natural and mechanical ventilation is optimized (CBE 2013). A mixed mode hybrid ventilation strategy will be further discussed in the following subsection.

Mixed mode ventilation

A mixed mode ventilation system can switch from natural to mechanical ventilation. An intelligent building with an automation system can change between mechanical and natural ventilation automatically, dependent on the internal properties of the building combined with the ambient surroundings (Jagpal 2015).

Mixed mode ventilation can occur in a building through different modes. Natural and mechanical ventilation can operate together in the same zone, operate at different times in the same zone, or operate at different times in different zones (CBE 2013).

Concurrent mode A *concurrent mode* mode implies that natural and mechanical ventilation operate together, at the same place in the same zone, as presented in Fig. 3.1. In this mode, both natural and mechanical ventilation can be used to cover the base load ventilation of the zone, depending on preference, season and ambient surroundings (CBE 2013).

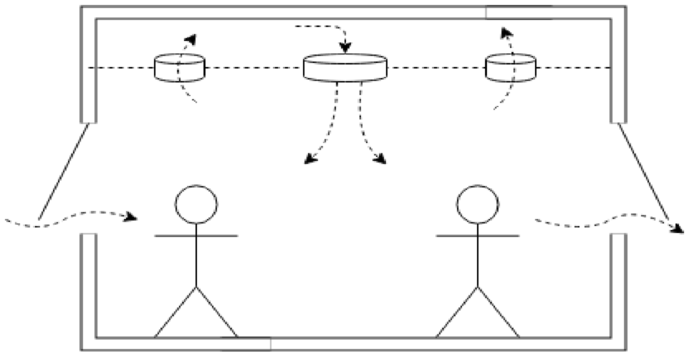


Fig.: 3.1 Concurrent mixed-mode ventilation (reproduced from CBE (2013)).

Change-over mode A *change-over ventilation mode* implies that the ventilation strategy switches between mechanical and natural ventilation (CBE 2013). The transition between the ventilation strategies can be based on preference, season, or the internal and external surroundings of the building. An example of such an operating mode is when the mechanical ventilation is automatically turned off when windows are open.

A simple representation of change-over mode, with active mechanical ventilation, is presented in Fig. 3.2.

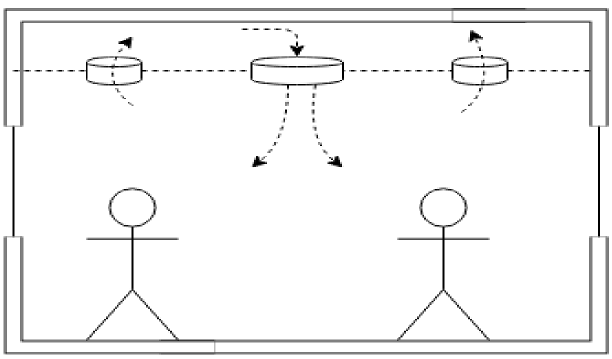


Fig.: 3.2 Change-over mixed-mode ventilation (reproduced from CBE (2013)).

Zoned mode A *zoned mode* implies that different zones in a building operate with different ventilation strategies, as presented in Fig. 3.3 (CBE 2013). An example of such an operating mode is when an office is naturally ventilated, while a classroom in the same building is mechanically ventilated.

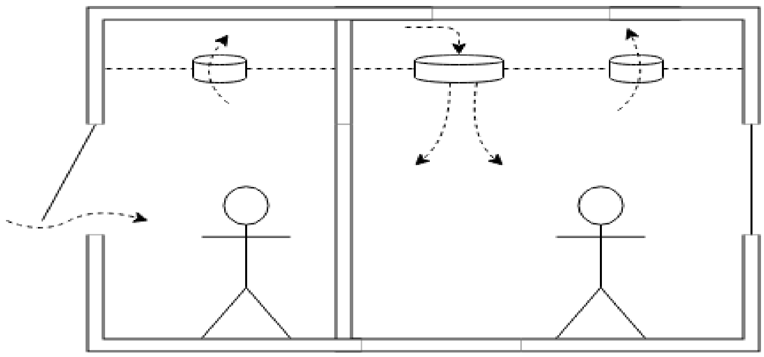


Fig.: 3.3 Zoned mixed-mode ventilation (reproduced from CBE (2013)).

3.2 Mathematical models of ventilation

During the work with the previously completed Project Thesis, *Optimal use of natural ventilation in ZEB Flexible Lab*, several mathematical models and approaches to natural ventilation were reviewed. Empirical Models, the Network Model, Zonal Modelling and CFD Models were evaluated. Based on a performed literature review, several calculations, and some trial and error, the *Network Model* was chosen to be a suitable approach to ventilation.

3.2.1 The Network Model

In the Network Model, a building is represented by a grid with several nodes and interconnections. A node can be external representing the ambient surroundings, or internal representing a room. An interconnection represents an opening between two nodes. (Allard et al. 1998)

A simplified graphical presentation of the Network Model applied to a simple building is presented in Fig. 3.4

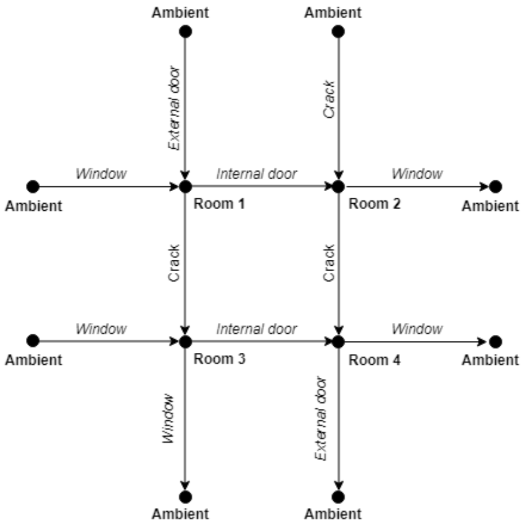


Fig.: 3.4 A graphical presentation of the Network Model applied to a simple building.

Network Modelling is based on the assumption that air flows are non-viscid and incompressible while mass balance is achieved, as in Eq. (3.1), and uniform air temperature profiles are present in each zone (Allard et al. 1998).

$$\sum_{k=1}^{j} \dot{m}_k = \sum_{k=1}^{j} \rho_i Q_{ik} = 0 \tag{3.1}$$

When analyzing a multi-zone building with *N* zones, a number of *N* dependent equations will describe and establish the Network Model of the building (Asfour & Gadi 2007). Hence, the Network Model is based on a set of equations that must be solved iteratively. Due to the assumption of mass balance, as presented in Eq. (3.1), the air volume flow to and from each node must be determined. The *Power Law*, Eq. (3.2), describes a relation between the volume flow, *Q*, and a resulting pressure difference, ΔP, over an interconnection (Etheridge & Sandberg 1996).

$$Q = K\Delta P^n \tag{3.2}$$

The flow coefficient, *K*, and the flow exponent, *n*, are constants describing the geometrical properties of an opening, and vary with Reynolds number (Etheridge & Sandberg 1996).

The combination of Eq. (3.1) and (3.2) will lead to an equation expressing the relation between pressure drops and volume air flows, which can describe the interconnections in the Network Model. Such a relation can also be obtained through the usage of *The square root law* (Etheridge & Sandberg 1996). The square root law is an adaption of Bernoulli's equation, presented in Eq. (3.3) describing a streamline from a point *i* to a point *j* (Stensaas 1986).

$$P_i + \frac{1}{2}\rho U_i^2 + \rho g z_i = P_j + \frac{1}{2}\rho U_j^2 + \rho g z_j + \Delta P_{i-j} \tag{3.3}$$

The square root law assumes a constant elevation of a streamline, with a negligible initial velocity and pressure loss through an opening with an area equal A and discharge coefficient equal C_d, resulting in the relation between pressure drop and volume air flow as in Eq. (3.4) (Stensaas 1986).

$$Q = C_d \cdot A \cdot \sqrt{\frac{2 \cdot \Delta P}{\rho}} \tag{3.4}$$

The pressure difference over an opening resulting from the natural forces of temperature differences and wind must be obtained to solve the Network Model. Further, in a mechanical or hybrid ventilation system the air flows due to mechanical fans must be obtained to predict the movement of air by the Network Model.

Pressure difference due to temperature differences

The density of air varies with the air temperature. Heated air has a lower density and is lighter than cooler air, as described in Eq. (3.5) (Hamrick 2012).

$$\rho = \rho_0 \frac{T_0}{T} \tag{3.5}$$

Hence, heated air will rise to higher levels, while cooled air will sink down to lower levels. This is referred to as *buoyancy* or *the stack effect* (Stensaas 1986). Eq. (3.6) describes pressure occurring in a zone due to stack only, P_s, at an elevation equal to z when static pressure at a zero elevation in the zone is P_0 (Etheridge & Sandberg 1996).

$$P_s = P_0 - \rho g z \tag{3.6}$$

Furthermore, the *pressure difference* due to the stack effect between two zones is described by Eq. (3.7) (Etheridge & Sandberg 1996).

$$\Delta P_s = P_{1,0} - P_{2,0} + (\rho_1 - \rho_2) g z \tag{3.7}$$

Such pressure difference, dependent on density, static pressure, and elevation can be described graphically by a *pressure profile* (Li et al. 2000). Fig. 3.5 presents a general pressure profile with an internal and an external pressure gradient. It's assumed that the external temperature is at a lower level than the internal temperature, and both temperature levels are constant and independent of height.

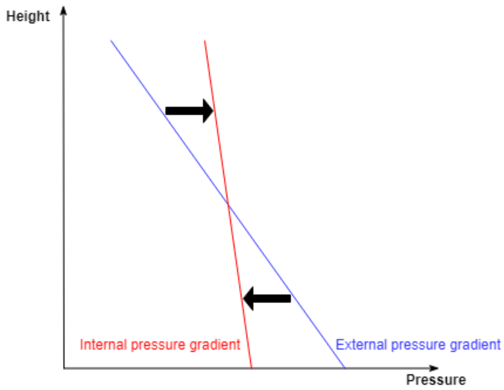
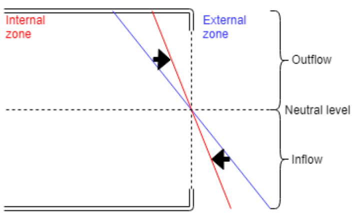


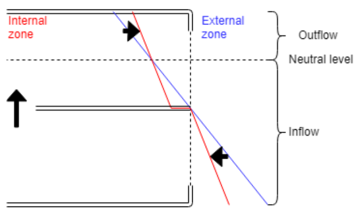
Fig.: 3.5 General pressure profile resulting from internal internal temperature larger than external temperature (inspired by Li et al. (2000)).

Fig. 3.5 shows that at a low elevation, the internal pressure will be lower than the external. Hence, air will flow into the internal zone. At higher elevations, external pressure is lower than the internal. The air flow will therefore reverse, and air will flow out of the internal zone. At a given level, the internal and external pressure will be equal. This level is referred to as the *neutral level*, where air movements aren't affected by temperature differences (Li et al. 2000).

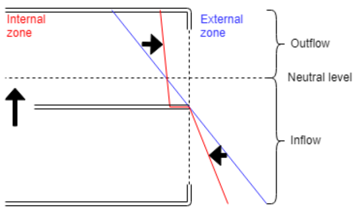
Pressure profiles resulting from temperature differences over a building facade are affected by the interior properties of the building, such as internal temperature variations, zonal division and the presence of dividing floors (Jo et al. 2007). Fig. 3.6 presents three different pressure profiles as a result of temperature differences, assuming higher internal temperatures than external temperatures, and variable interior properties.



(a) Open zone building with higher internal temperature than external temperature



(b) A two floor building with higher internal temperature than external temperature



(c) A two floor building with different internal temperature higher than the external temperature

Fig.: 3.6 Pressure profiles resulting from temperature differences over different building facades (inspired by Jo et al. (2007)).

Fig 3.6 (a) shows the resulting pressure profile of an open zone building, similar to Fig. 3.5. If the building consists of two floors connected by a staircase as in Fig. 3.6 (b), the pressure profile on the second floor will shift due to the internal pressure difference (Jo et al. 2007). Further, the neutral level will be elevated, leading to smaller air flow out of the upper zone (Li et al. 2000). The stack effect causes heated air to rise, and an increase of the temperature in the upper part of the building occurs as in Fig 3.6 (c). Hence, the internal pressure gradient achieves a larger slope in the upper part of the building (Li et al. 2000), leading to a lowering of the neutral level and a larger air flow out of the upper zone.

Pressure differences due to effects of wind

Ventilation caused by the effects of wind is dependent on the velocity and the direction of the wind (Walker 2006). Positive pressure will occur at the windward side of a building while the leeward facade experiences suction regions. This leads to a pressure difference as in Eq. (3.8). Wind will therefore ventilate air from the windward to the leeward facade (Allard et al. 1998). Eq. (3.8) is a deriving of Bernoulli's equation, Eq. (3.3), assuming equal openings at the opposite facades (Walker 2006).

$$\Delta P_w = \frac{1}{2}\Delta C_p \rho U_0^2 \tag{3.8}$$

ΔC_p is equal to the difference in wind pressure coefficient over the building, while the air density, ρ, and the velocity of the wind at a reference height, U_0 (Allard et al. 1998). The reference height normally equals the height of the building.

A pressure profile describing the resulting pressure difference from the effects of wind is presented in Fig. 3.7. The resulting pressure over the windward side is at a larger level than the pressure over the leeward side. However, there is a small increase of pressure with height. The resulting pressure gradient over each facade is parallel with each other (Walker 2006).

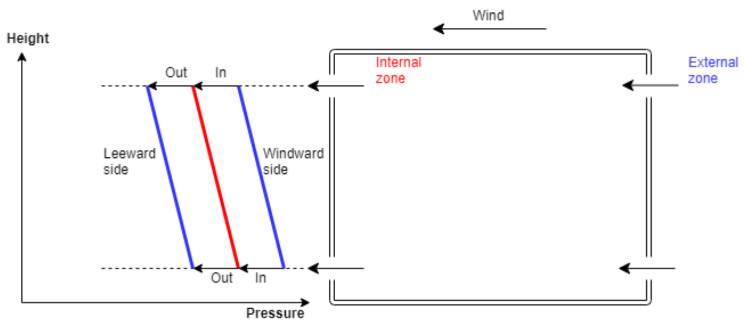


Fig.: 3.7 Resulting pressure profile form wind (inspired by (Walker 2006)).

Wind pressure coefficient The wind pressure coefficient, C_p, is a dimensionless coefficient describing the ratio of the wind pressure at a given point *x* (Gullbrekken et al. 2018). The coefficient can be described by Eq. (3.9), where P_{dyn} represents the dynamic pressure in the free wind. However, the determination of the wind pressure coefficient is a complicated affair and requires wind tunnel tests of small scale neighborhoods or actual measuring of buildings (Allard et al. 1998).

$$C_{px} = \frac{P_x - P_0}{P_{dyn}} \tag{3.9}$$

The wind pressure coefficient is often assumed to vary with the approach angle of the wind, which has been experimentally proven in wind tunnels (Allard et al. 1998). This assumption has been used in the development of the database *Aerodynamic Database of Low-rise Building* provided by the Tokyo Polytechnic University, a database proving wind pressure coefficients for a selection of different building models (Tokyo Polytechnich University 2007).

Pressure difference due to temperature and the effects of wind combined

Ventilation created by a combination of temperature differences and wind leads a larger pressure difference over the building. The resulting pressure difference equals the sum of the pressure difference caused by the stack effect, ΔP_s, and wind effect, ΔP_w (Allard et al. 1998). The total pressure difference, ΔP_{total}, is presented in Eq. (3.10).

$$\Delta P_{total} = \Delta P_s + \Delta P_w \tag{3.10}$$

The resulting total pressure profile over a building due to natural forces is presented in Fig. 3.8. Fig. 3.8 shows that the resulting pressure difference, due to both stack and wind effects, leads to a different elevation of the neutral level on the windward and leeward facade, causing a possible change of the air flow direction (Walker 2006).

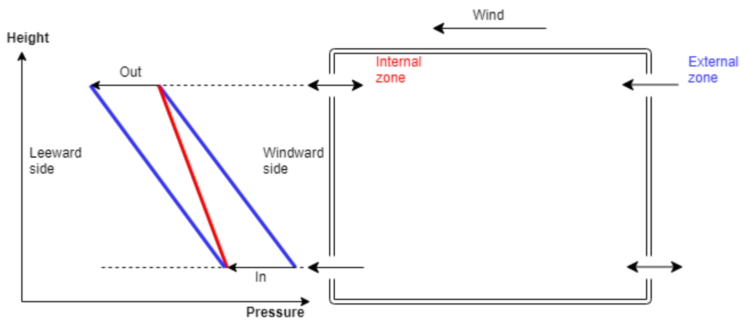


Fig.: 3.8 Resulting pressure profile form the effects of stack and wind (inspired by Walker (2006)).

Air flows due to fans

Mechanical ventilation refers to ventilation due to fans and generates the same pressure over all openings in a building assuming no temperature differences or wind effects present (Etheridge & Sandberg 1996).

Fans used for ventilation purposes can mainly be divided into *centrifugal fans* and *axial fans* causing different pressure and flow characteristics (Nystad 2017). The characteristics of a fan are usually stated by the fan manufacturer, describing the relation between the pressure difference over a fan and the resulting volume flow as presented in Eq. (3.11) (Etheridge & Sandberg 1996).

$$Q_{fan} = f_{fan}(\Delta P_{fab}) \tag{3.11}$$

The function f_{fan} are often second order polynomial equations dependent of empirical constants K_i, as described in Eq. (3.12) (Etheridge & Sandberg 1996).

$$Q_{fan} = K_1 + K_2 \cdot \Delta P_{fan} + K_3 \cdot P_{fan}^2 \tag{3.12}$$

3.3 Distribution of ventilated air

A mechanical ventilation strategy can distribute air throughout a zone in different ways. The air distribution depends, among others, on the location of the supply and exhaust ducts, and the supply velocity. In the following subsections two different strategies of air distribution, displacement and mixing ventilation, will be presented.

3.3.1 Displacement ventilation

Displacement ventilation, or source ventilation, utilizes zonal heat sources and the resulting natural convective air flows as the main driving force (Etheridge & Sandberg 1996).

Traditionally, a displacement ventilation system supplies a room with air at a lower temperature than the room temperature, from an inlet located close to the floor, directly into an occupied zone (Yuan et al. 1998). The supplied, cooler air, will distribute evenly throughout the floor of the room. Zonal heat sources, such as occupants and technical equipment, will heat the supplied air resulting in a *thermal plume*. A thermal plume is the term of convective currents that occur above a heated object caused by buoyancy (Hamrick 2012). Fig. 3.9 presents a simple graphical presentation of a thermal plume, with associated temperature and velocity profiles.

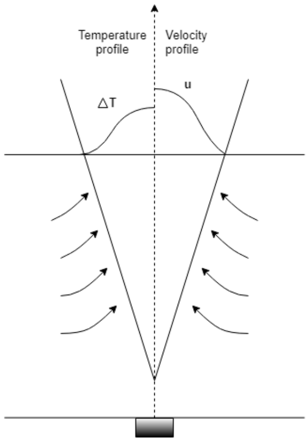


Fig.: 3.9 A thermal plume with associated temperature and velocity profile (reproduced from Kofoed (1991)).

As presented in Fig. 3.9 the volume of the thermal plume increases with the distance from the heat source, hence the thermal plume merges with the surrounding air. However, the velocity and the temperature of the plume will decrease with the increasing distance from the heat source (Hamrick 2012). The thermal plume creates a vertical air motion, transferring heat with associated contaminants toward the upper part of the room (Etheridge & Sandberg 1996). Further, heated and contaminated air can be removed from the room through an exhaust duct placed at the ceiling level. The level of contaminants in the exhaust will be higher than the contaminant level in the occupied zone.

The vertical motion of air creates a stratification. Hence, heated and light air with contaminants will be carried by a layer of colder and clean air. When a displacement ventilation system is dimensioned correctly, the heated and contaminated air will be located in an unoccupied zone of the room (Wachenfeldt et al. 2007).

A simplified graphical presentation of a traditional displacement ventilation system is presented in Fig. 3.10.

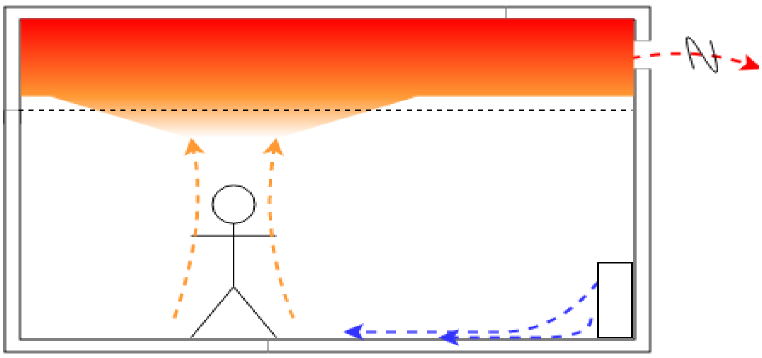


Fig.: 3.10 Displacement ventilation (inspired by Etheridge & Sandberg (1996)).

The efficiency, the containment removal, and perceived air quality of displacement ventilation depends on supply air temperature, room design, and occupant load (Yuan et al. 1998). The temperature of the supplied air must be lower than the room temperature to ensure the transmission of heat and no occurrence of a short circuit of the ventilation. The room must be designed with such a ceiling height that an unoccupied zone is present. This ensures that a collection of contaminants doesn't have any poor consequences for the occupants. Further, occupants and technical equipment must be present and act as a heat source to ensure a movement of the air (Etheridge & Sandberg 1996).

A displacement ventilation system can achieve good contaminant removal and air change rate, without any risk of draught when designed correctly (Bottolfsen 2014).

3.3.2 Mixing ventilation

In contrary to traditional displacement ventilation, air can be supplied into the unoccupied part of the room. A mixing ventilation system supplies a room with air, at a high initial velocity as a jet (Stensaas 1986). The supply is located at ceiling height, minimizing the risk of experienced draught. The high supply velocity ensures complete mixing of the air, diluting the temperature and contaminants to an even level throughout the room. Hence, the concentration of contaminants and the air temperature is equal in the occupied zone and in the exhaust (Stensaas 1986).

A simplified graphical presentation of a traditional mixing ventilation system is presented in Fig. 3.11.

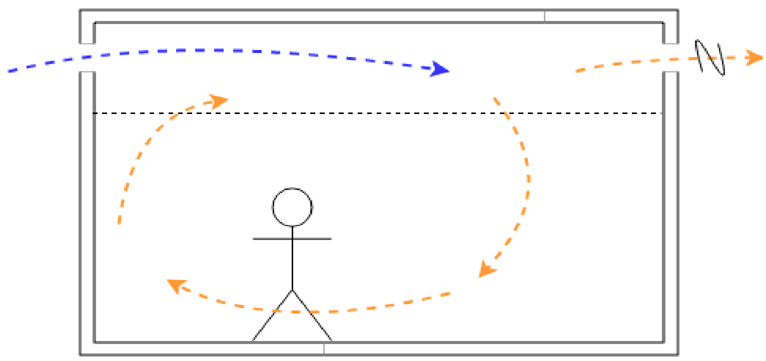


Fig.: 3.11 Mixing ventilation (inspired by Etheridge & Sandberg (1996)).

Steady air supply in mixing ventilation ensures a uniform temperature profile. Thus, the risk of dissatisfaction regarding the thermal environment is minimized (Bottolfsen 2014).

A disadvantage of mixing ventilation is the risk of low efficiencies when combined with natural ventilation. The opening of a window can disrupt the uniform temperature profile, while decrease the contaminant removal rate (Bottolfsen 2014). Hence, a hybrid ventilation system including mixing ventilation can be unfavorable.

3.4 Controllers of ventilation

A mechanical ventilation system can be managed by controlling the amount of supplied air, the temperature of the supplied air, or by the demand of air. These management systems are referred to as *Constant Air Volume*, *Variable Air Volume*, and *Demand Controlled Ventilation*. The three following subsections briefly present these management systems.

3.4.1 CAV

Constant Air Volume, CAV is a collective term describing management systems that operate with a constant amount of air during the operational hours for the entire air handling unit (Mysen & Schild 2014). Further, the heating and cooling demand of the building are covered by heating or cooling the supplied air (Stensaas 1986).

CAV ventilation systems are often installed in modern Norwegian schools, with a constant air flow rate dimensioned to cover the maximum pollution load from both the building envelope and the occupants during the operating hours (Wachenfeldt et al. 2007). The maximum ventilation rate is referred to as mode *on*. Further, the mode *off* refers to the ventilation rate outside operational hours, which equals the air flow rate demanded to cover pollution from the building materials (Mysen & Schild 2014). The switch between the two modes can be preset by a schedule.

A CAV ventilation system is a simple system, easily controlled and maintained. However, studies have shown that the amount of energy demanded by a CAV system is up to twice as high as the energy demand of a more complex management system (Mysen & Schild 2014).

3.4.2 VAV

Variable Air Volume, VAV, is a collective term referring to all ventilation systems where the amount of supplied air is variable Mysen & Schild (2014). The heating and cooling demand in a zone is covered by a change in the supplied air, while the supply air temperature is constant (Stensaas 1986).

A system implemented by VAV changes the supplied air based on demand. The amount of air supplied to a zone can be varied by a sensor detecting the presence in a room and changing the position of the damper to a predetermined position (Mysen & Schild 2014). The predetermined positions of the damper can be decided based on performed calculations when assuming the future number of occupants and taking national standards and regulations into consideration. This ensures a lower energy demand compared to a CAV ventilation system.

3.4.3 DCV

Demand Controlled Ventilation, DCV, is the collective term describing ventilation system where the ventilation rate, and the heating and cooling effect of the ventilation is automatically and continuously controlled. The management is based on measurements regarding the fresh air demand in the room. (Kolokotroni & Heiselberg 1997)

The amount of air supplied to a zone can be regulated based on a continuous measure of occupants present with a feedback loop to the control system (Ehrlich 2015). Hence, DVC is well suited for zones with an occasional large number of occupants. Such a ventilation system supplies air only when needed, resulting in a minimized energy demand (Mysen & Schild 2014).

Fig. 3.12 presents a simplification of a DCV system in a traditional HVAC installation in an office.

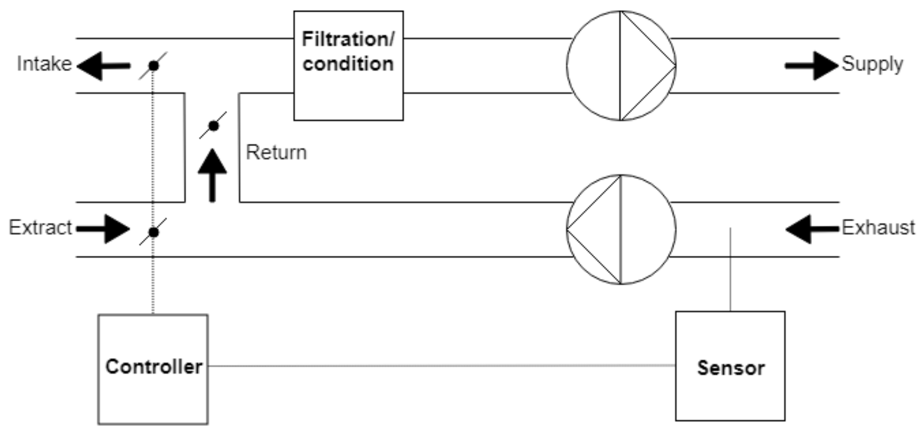


Fig.: 3.12 A simple DCV system (reproduced from Kolokotroni & Heiselberg (1997)).

The sensor presented in Fig. 3.12 measures the air quality in the room, by factors such as CO_2 level and temperature. The sensor will continuously feed the controller with information. Further, the controller will, in this case, change the position of the dampers in a satisfactory matter. As a result, the pressure in the ducts will change. This is a pressure change the controller can equalize by changing the rotation per minute of the fans. This is referred to as *pressure control* and is a common principle in DCV (Mysen & Schild 2014).

Proportional controller

The controller implemented in a CAV system can operate as a *Proportional controller*, a P-controller.

A P-controller amplifies an input value to a static output value by a proportional constant, while no dynamical change occurs, as presented in Fig. 3.13 (Novakovic et al. 1996). The input value to the controller can be equal to the deviation between the measured value and the desired value.

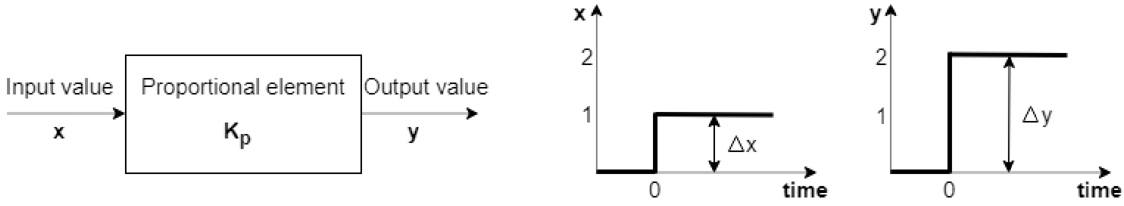


Fig.: 3.13 A graphical presentation of a P-controller (reproduced from Novakovic et al. (1996)).

The input value, *x*, into the controller may equal a deviation of a measured value and a desirable value. An example, a sensor measures the CO_2 level in the exhaust air. The measured CO_2 level is compared to a desirable value. The deviation, *x*, is sent as a signal to the P-controller. The P-controller amplifies the input signal with a proportional constant of K_p. The output value, *y*, equals the change of the valve position. Hence, the amount of fresh air supplied is continuous and automatically altered to a desirable level. (Novakovic et al. 1996)

3.5 Classification of ventilation

When analyzing a ventilation system several factors can be taken into consideration. However, ventilation must ensure a good indoor environment in terms of air quality. The air quality depends, as previously discussed, on the amount of fresh air supplied and levels of contaminants. The following subsections will present different possibilities to classify a ventilation system.

3.5.1 Age of air

Age of air is a concept proven to be a useful tool to classify the efficiency of a ventilation system. The age of air is the time frame from a given amount of air enters the building until the same amount leaves the building. (Mundt et al. 2004)

Assuming a zone with one air inlet and one air outlet, as presented in Fig. 3.14, the air will pass a point *P* at a given time. The time gone by from air enters the zone to it reaches this point is referred to as the *local age of air*, τ_p. The *local mean age of air*, $\overline{\tau_p}$, equals the mean local air of every air streamline entering the room. The local mean age of air in the exhaust is a constant value, referred to as the *nominal time constant*, τ_n. (Mundt et al. 2004)

τ_n equals the ratio of the room volume to the ventilation rate, Q_V, as described in Eq. (3.13), and is the shortest possible time for an air change of an entire room (Etheridge & Sandberg 1996).

$$\tau_n = \frac{V}{Q_V} \tag{3.13}$$

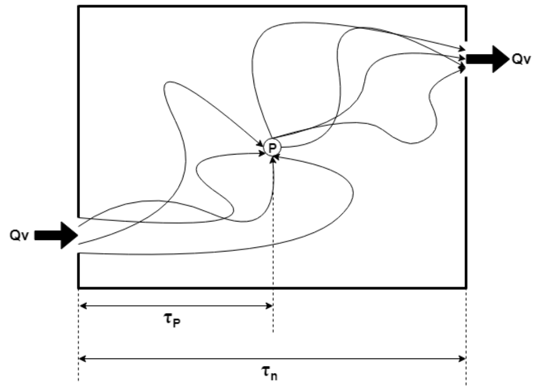


Fig.: 3.14 Definition of age of air (reproduced from Etheridge & Sandberg (1996)).

The average age of the air in an exhaust is by definition equal to the mean residence time of the air in the room, $\overline{\tau_r}$ Etheridge & Sandberg (1996). Furthermore, the mean residence time is half of the *mean age of air in the room*, $\langle\overline{\tau}\rangle$, as described in Eq. (3.14) (Mundt et al. 2004).

$$\overline{\tau_r} = 2\langle\overline{\tau}\rangle \tag{3.14}$$

Due to the fact that the nominal time constant is a constant value, it can be used to evaluate the ventilation efficiency and detect some dimensional errors. If the nominal time constant is of a value smaller than the mean room age of air a short circuit of the ventilation may have occurred. When a room is completely mixed, the nominal air constant will equal the room mean age of air (Mundt et al. 2004).

Air change efficiency

The air change of an entire room is an important indicator of the experienced air freshness of a room Etheridge & Sandberg (1996). The age of air in a room can determine the *air change efficiency*, $\langle\varepsilon_a\rangle$, as presented in Eq. (3.15) (Mundt et al. 2004).

$$\varepsilon_a = \frac{\tau_n}{\tau_r} = \frac{\tau_n}{2\langle\overline{\tau}\rangle} \tag{3.15}$$

The air change efficiency is, as described in Eq. (3.15), the ratio between the shortest possible time of air change and the actual air change time (Etheridge & Sandberg 1996).

Containment removal effectiveness

The *contaminant removal effectiveness*, how exposed occupants are to airborne contaminants, is a suitable indicator of the effectiveness of a ventilation system (Etheridge & Sandberg 1996). The contaminant removal effectiveness can be described as the ratio of the contaminant level in the exhaust, c_e, to the mean concentration of the room, $\langle c \rangle$, as described in Eq. (3.16) (Mundt et al. 2004).

$$\varepsilon^c = \frac{c_e}{\langle c \rangle} \tag{3.16}$$

If a room is supplied with a fully mixed flow, the concentration of contaminants will be equal throughout the entire room, hence a contaminant removal effectiveness will obtain a value of 50%.

3.6 Energy demand for ventilation systems

Due to the fact that natural ventilation is operated by natural forces, no power demand occurs operating the ventilation system. However, ambient air entering a building can cause a power demand in terms of heating. A lower the ambient temperature, compared to the internal building temperature, will lead to a higher heating demand as presented in Eq. (3.17). (Nystad 2017)

$$P = \dot{m} \cdot c_p \cdot \Delta T \tag{3.17}$$

The demanded heating power, P, is dependent of the mass air flow, $\dot{m}$, the specific heat capasity of air, c_p, and the internal and external temperature difference, ΔT.

The operation of a mechanical ventilation system has a power demand occurring from the heating of air and running the installed fans (Nystad 2017). However, an advantage of a mechanical ventilation system is the possibility of heat recovery, leading to a lower heat power demand (Stensaas 1986). Assuming a heat recovery with an efficiency of η, leads to a heat power demand as presented in Eq. (3.18) (Nystad 2017).

$$P = \dot{m} \cdot c_p \cdot \Delta T \cdot (1 - \eta) \tag{3.18}$$

Specific Fan Power, SFP, indicates the energy efficiency of a mechanical ventilation system, by presenting the ratio of the combined demanded fan power and the gross amount of circulated air. SFP can be derived from Eq. (3.19) (Nystad 2017). Hence, a low SFP value is desirable.

$$SFP = \frac{\sum P_{fan}}{Q} \tag{3.19}$$

3.7 A state of the art review of energy efficient ventilation

The Energy Performance of Building Directive has required that all buildings that are to be constructed after 2020 must achieve a level of nZEB, leading to the demand of new energy and cost-efficient solutions in the building sector (Breesch et al. 2018).

The following sections present some important finds from the performed literature review regarding *state of the art* ventilation strategies to increase the energy efficiency of ventilation of buildings.

3.7.1 Ventilative cooling

The building sector is responsible for more than 60% of the total energy demand in the world, due to the energy required for heating, cooling and ventilation (Cuce & Riffat 2016). Hence, the state of the art solutions, especially regarding HVAC systems, may be crucial to lower the energy demands in future buildings with an nZEB vision.

Buildings with a vision of achieving nZEB are well insulated and highly airtight, leading to the risk of overheating during the summer and increased cooling demand to maintain thermal comfort (Breesch et al. 2018).

The definition of ventilative cooling is *"the application of the cooling capacity of the outdoor air flow by ventilation to reduce or even eliminate the cooling loads and/or the energy use by mechanical cooling in buildings, while guaranteeing a comfortable thermal environment"* (Kolokotroni & Heiselberg 2015). Hence, ventilative cooling is an important method to utilize ensuring the lowest possible energy demand and maintain a satisfactory indoor environment regarding thermal comfort.

Passive cooling by ventilation

A state of the art review concerning passive cooling techniques has been performed by Sanatoriums and Kolokotsa in 2013, reviewing the effect and potential of *night time ventilation* implemented in office, education, and residential buildings (Santamouris & Kolokotsa 2013). The review states that passive cooling aims to improve the thermal comfort through heat dissipation and heat control with a low or no energy demand. Night time ventilation utilizes the low air temperature at night to remove some or all of the heat absorbed by a building during the day. This leads to a decrease or the abatement of temperature peaks during the occupied hours during the day. Further, the review states that the implementation of passive cooling may cause an energy saving of 70% compared traditional solutions, but the effect is highly dependent of the rate and duration of the ventilation, the building mass, and climate conditions. A study regarding an office building located in the north of China suggests that a night ventilation rate of ten air changes per hour causes a decrease of 3.90°C of the mean radiant temperature of the internal surfaces. However, the report created by Sanatoriums and Kolokotsa suggests that the implementation of nighttime ventilation leads to an uncertainty regarding the thermal comfort, causing some unwillingness to implement such solutions.

Annex 61, A State of the Art Review regarding Ventilative Cooling, performed by the Energy in Buildings and Communities Programme concerns the potential and limitations of ventilative cooling (Kolokotroni & Heiselberg 2015). The annex suggests, by the degree-hour method, that passive cooling, achieved by night time ventilation, is to be an applicable implementation in buildings located in the north of Europe. Nighttime ventilation may be driven by natural forces, or be supplemented by some fan power, causing a low energy demand. The review presents that the ventilation system of a Norwegian kindergarten located in Larvik implemented with night time ventilation during the summer season. The review states that the internal temperature is kept at a low and satisfactory level, without increasing the energy consumption due to the passive cooling technique. However, the review states that the thermal comfort of other buildings with other locations, building structure, and building mass, might be compromised by the implementation of night time ventilation. Furthermore, the low-temperature difference between internal and external temperature during the summer season will decrease the potential of passive ventilative cooling.

A study regarding hybrid ventilation and predictive control performed at Concordia University in 2016 evaluates the potential and effect of nighttime ventilation to some extent in a modern office building, The Concordia EV, by the creation of numerical models (Yuan et al. 2018). The report states that the building was implemented with a hybrid ventilation system, with motorized opening, fan assist, and night time ventilation. The results of the study show that the natural ventilation system can cover 13% of the cooling demand during the summer season without compromising the thermal comfort. This when assuming the building is unoccupied during the four hours of night ventilation, and that the air temperature is lowered to a level of 8.00°C.

3.7.2 Building automation and ventilation control

While buildings worldwide are responsible 20% of the total CO_2 emissions, a major share of these amounts are due to wrongly dimensioned automation units and error in the overall building management systems (Lazarova-Molnar et al. 2016). Further, installations of automation units alone may not ensure a low energy demand or a higher level of indoor environment due to the behavior of the occupants - office workers often work outside the presumed working hours leading to a high internal heat gain and a higher demand of ventilated air (D'Oca et al. 2018). The implementation of natural ventilation is an increasingly popular technology, due to the possible decreasing of energy and improving indoor environment (Chen et al. 2019).

A study performed by Chen et al. evaluated the resulting natural ventilation, energy saving, indoor thermal comfort, and operating time of different control systems of a hybrid ventilation system including windows and an HVAC system (Chen et al. 2019). The resulting report of the study states that to ensure a natural ventilation system operating with low energy demand, while achieving a satisfactory indoor environment, the operation of the windows is a major factor. Furthermore, the operating of windows is especially important in hybrid, mixed-mode, buildings with a variable degree of automation from manual control to fully automatic control. The study evaluated three different control systems in a simulated model: manually controlled windows based on thermal comfort, informed manual controlled windows, and a fully automatic system for the windows and HVAC system with model predicting control, MPC. The study concludes that a fully automatic control system is the only system achieving a continuous satisfying indoor air temperature. However, an improper automatically system may cause energy waste and thermal discomfort.

An understanding of occupant behavior is crucial to correctly dimension the controller of a ventilation system, due to the fact that manually opening windows will affect the thermal performance of a building (Sorgato et al. 2016). Occupants open windows for a longer period of time during the summer than the winter, and windows are more likely to be opened in the afternoon (Chen et al. 2019). Building automation opening windows must consider the ambient surroundings, when these properties affect the result of natural ventilation (Chen et al. 2018). Hence, the variable occupant behavior and ambient surroundings during one year must be accounted for when dimensioning a ventilative controller for a hybrid system. A *reinforced learning control*, a system with continuously climate adapted control for motorized windows and HVAC systems, are proven to be a satisfactory controller with up to 23% lower energy consumption compared to a traditional *heuristic control system* with preset criteria (Chen et al. 2018).

3.7.3 Nydalen Vy

FutureBuilt is a program created in 2010 in Oslo, Norway, intending to act as a showcase of the most ambitious and climate neutral actors in the building sector (FutureBuilt 2016). The program has the aim of developing 50 buildings and projects with the level of nZEB by 2020, by giving building developers access to experts on given fields (Rote 2017). One of the current ambitious projects of FutureBuilt is *Nydalen Vy*, a building consisting of office units, residential units, and industrial units (FutureBuilt 2018).

According to FutureBuilt, Nydalen Vy has the ambition of achieving a status of nZEB, while the office section of Nydalen Vy will only be implemented with clean natural ventilation as the first office building in Norway (FutureBuilt 2018). Further, FutureBuilt states that Nydalen Vy will implement the status of *TripleZero*, hence no energy will be demanded from the grid powering the ventilation, heating, or cooling of the building (Hegli 2018). Furthermore, on-site production of heat, cooling, and electricity will occur through geothermal production, geothermal cooling and PV-panels in the building facade (FutureBuilt 2018).

No mechanical ventilation, fans, ducts, or pipes will be implemented in the office section of the building (Kirkebøen 2017). The natural ventilative system will be supplied by *WindowMaster*. According to WindowMaster (WindowMaster 2017) natural ventilation will be automatically implemented in the building by motorized external openings. WindowMaster further states that the controller of the windows and hatches will be controlled according to ambient and internal air temperature, wind velocity and wind direction, in addition to the external and internal level of CO_2.

Nydalen Vy is a Norwegian showcase project, inspired by the ambitious and successfully constructed TripleZero office building, located in Lustenau Austria, *2226* (Berg 2018). The building is named according to the required comfortable indoor temperature range from 22 to 26°C, to ensure a satisfactory indoor climate without mechanical heating, cooling, or ventilation (Halderaker 2016).

The internal heat gain of 2226 results from lighting, computers, and occupants, while natural ventilation occurs through manually or motorized controlled windows according to the internal CO_2 levels. The heavy building mass ensures passive cooling, and deep window frames ensure solar shielding and no overheating. (Stoknes 2018)

The concept of 2226 has been proven to be successful. A satisfactory indoor environment has been achieved, with a CO_2 level mostly below 1200 ppm, internal temperature in the required range from 22.0 to 26.0 °C. Furthermore, a zero energy demand due to heating, cooling, or mechanical ventilation. (Halderaker 2016)

However, the climate in Norway differs from the climate in Austria, leading to a need for some constructional changes with innovative solutions (Berg 2018). With that an uncertainty of the resulting quality of the indoor environment in Nydalen Vy arises.

Chapter 4

Presentation of ZEB Laboratory

The objective of this Master's Thesis is to find the optimal combination of natural and mechanical ventilation in ZEB Laboratory. General knowledge concerning the building is therefore essential. The following section will present the vision, structure, and predetermined ventilation strategies of ZEB Laboratory.

4.1 Zero Emission Buildings

The Norwegian ZEB Definition Guideline defines a Zero Emission Building as a building that compensates for greenhouse gas equivalent emissions during the lifetime of the building by on-site renewable energy generation (Fufa et al. 2016). In this Master's Thesis, this definition of ZEB according to the Norwegian ZEB Definition Guideline will be used.

There are six defined levels of ZEB, ranking from ZEB-O to ZEB-Complete. When a level of ZEB-O is achieved, the renewable energy production compensates for greenhouse gas equivalent emissions from the operational phase of the building. A ZEB-Complete building generates renewable energy to compensate for the greenhouse gas emissions occurring during the entire lifespan of the building. This includes the lifespan from the production of the building materials to the deconstruction of the building including the disposal of the used materials. (Fufa et al. 2016)

The vision of ZEB Laboratory is to achieve the fourth level of ZEB, ZEB-COM (Time 2016). A building achieving ZEB-COM generates renewable energy to compensate for greenhouse gas equivalent emissions occurring from the production stage, the construction process stage, replacement of materials, operational energy use and from the deconstruction and disposal stage (Fufa et al. 2016).

4.2 ZEB Laboratory

ZEB Laboratory is an office and educational building under construction, located at Gløshaugen, Trondheim. The building is a result of the collaboration between NTNU and SINTEF. (SINTEF 2017*b*)

4.2.1 Ambition level

As previously mentioned, ZEB Laboratory has the ambition of achieving the level of ZEB-COM. The building will function as a *living Lab* (Time 2016). Hence, ZEB Laboratory will be suitable for further studies and will be analyzed while occupied by real occupants, such as workers who will use the building as their office.

According to researchers at SINTEF, (Time 2016), ZEB Laboratory aims to answer the following questions:

- Which technical and architectural solutions are needed to achieve good office and education conditions in a Zero Emission Building?
- How do users influence the energy consumption in the building and how do they adapt ZEB technologies?

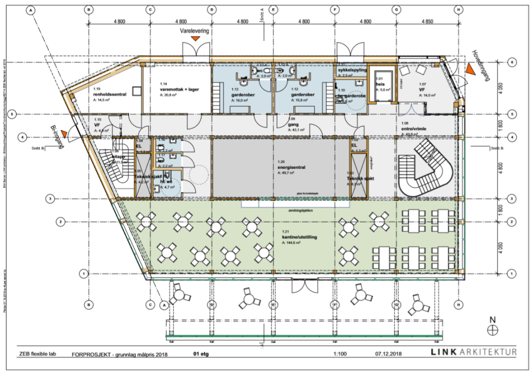
In addition to achieving the level of ZEB-COM, ZEB Laboratory is constructed with the ambition to act as a role model for the future projects regarding architectural qualities, future use of materials, building techniques and technology. This includes having a suitable and flexible energy and climatization system and a flexible workplace design while being a building adapted to the climate. (Time 2016)

4.2.2 Building structure

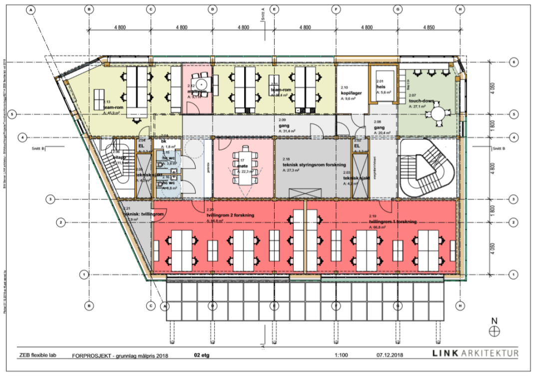
ZEB Laboratory is a 2000 square meters, four floors high, office and education building under construction located at Gløshaugen, an NTNU campus, in Trondheim.

The floors including the zonal division of each floor are presented in Fig. 4.1, and in Appendix A. Larger images of each floor is presented in Appendix A.

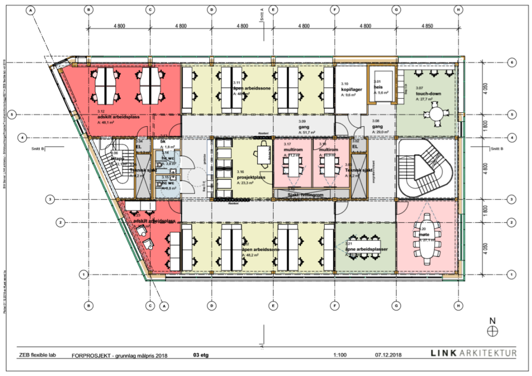
The first floor of the building will consist of the entrances, wardrobes, toilets, a cafeteria with seating and an energy plant. The second floor will consist of two identical classrooms, team rooms, meeting rooms and toilets. The identical classrooms will enable further study the energy use and degree of satisfied occupants. The third floor will consist of closed and open work-spaces, meeting rooms and toilets. Both the second a third floor will consist of flexible areas with a possibility to vary the workplace design. At the fourth floor, there will be classrooms, toilets and a technical room. The technical room will act as a "showroom" presenting the technical solutions of the building. (SINTEF 2017*b*)



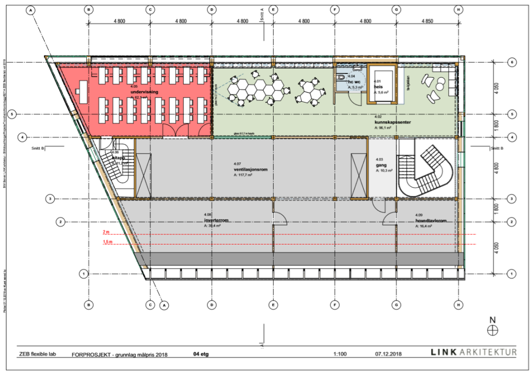
(a) First floor



(b) Second Floor



(c) Third Floor



(d) Fourth Floor

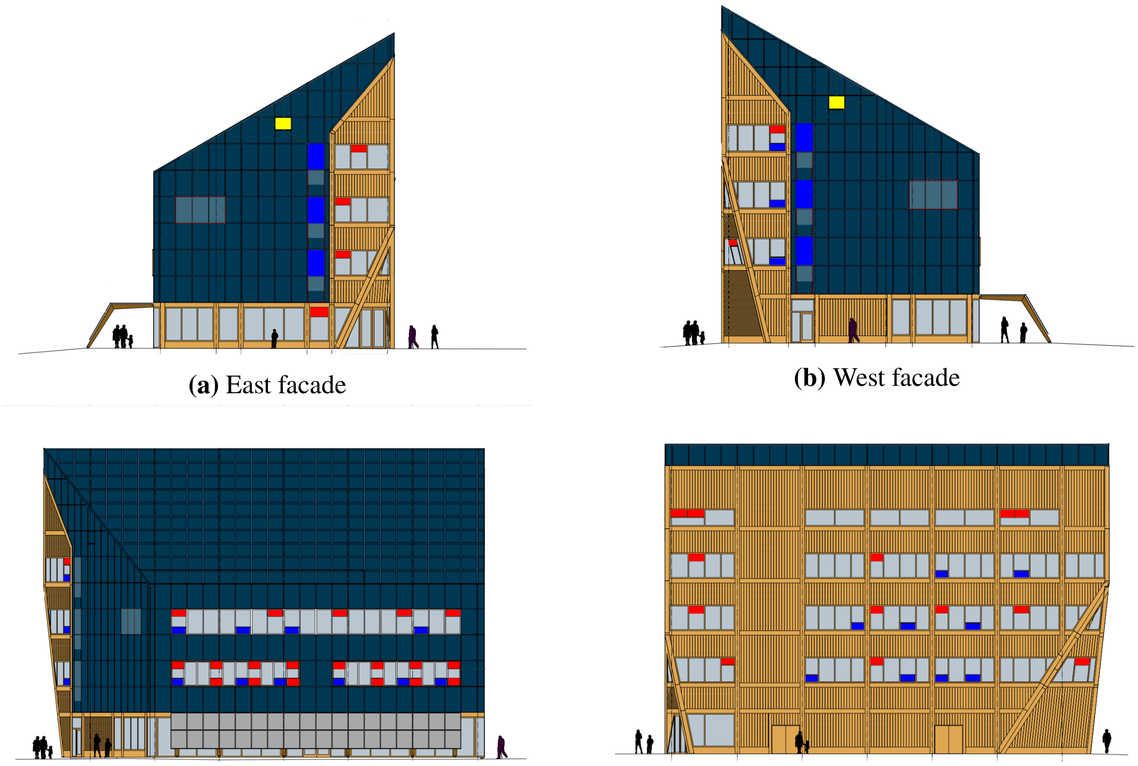
Fig.: 4.1 Architectural drawing of the floors of ZEB Laboratory (permission for display given by Cecilie Schei, Civil Architect, Link Arkitektur).

To ensure a satisfactory on-site renewable energy generation, the facades of the building will be implemented with a photovoltaic, PV, system. The south, east and west facades, in addition to the pitched roof, will be integrated with PV-panels. This results in over 1200 square meters of implemented PV-panels, with an assumed efficiency in the rate from 16 to 21% (Førland-Larsen 2017*b*). Fig. 4.2 presents the facades of ZEB Laboratory. This figure will be discussed further in the upcoming section. Larger images of the building facade are presented in Appendix B.

4.2.3 Windows, doors and hatches

A large part of the facade, about 28% which equals to 488 square meters, will be windows. A large share of the windows will not be able to open. However, the openable windows will both be automatically and manually controlled. The opening area of the openable windows are limited respectively to 60% and 20% of the geometric area of the windows. (Førland-Larsen 2017*b*)

Fig. 4.2 presents the facade of ZEB Laboratory, which can also be seen in Appendix B.



(a) East facade

(b) West facade

(c) South facade

(d) North facade

Fig.: 4.2 The facades of ZEB Laboratory with openable windows marked as blue, red and yellow (permission for display given by Cecilie Schei, Civil Architect, Link Arkitektur).

The red squares in Fig. 4.2 represent the part of the windows that are automatically controlled, while the blue squares represent the windows that are manually controlled. Generally, the upper parts of windows are motorized, while the lower parts of a window are manually controlled. The yellow squares represent the motor controlled fire hatches.

4.2.4 Usage

ZEB Laboratory will be a fully operating office and educational building with, among others, office spaces and classrooms. The building is assumed to be occupied to some degree during the period from 07:00 to 20:00, with main usage from 08:00 to 16:00 (Førland-Larsen 2017*b*).

The number of occupants will vary, and mainly be in the range from 70 to 100 persons including students (Time 2016). However, the number of occupants can both increase and decrease during some periods of the day.

The overall dimensional lifetime of the entire building is estimated to be 60 years (Time 2016).

4.3 Ventilation in ZEB Laboratory

Although ZEB Laboratory is under construction, a provisional decision has been made for ventilation systems of the building. This includes both mechanical and natural ventilation principles, utilized in various functions. The overall intent is to initially utilize a system with the least possible technical installations in terms of ventilation, heating and cooling (Time 2016). Further experiments and experimental studies related to ventilation can be performed.

4.3.1 Mechanical ventilation

Different principles of displacement ventilation will be implemented on each of the four floors.

The first floor will have displacement ventilation through floor vents. The second floor will have installed displacement ventilation from the ceiling through stone plates with holes. The third floor will have displacement ventilation from the ceiling as well, but through slots in trox discs. The fourth floor will have traditional displacement ventilation from a ventilator installed. (SINTEF 2017*a*)

In the mechanical ventilation system, the exhaust air will be removed from the building envelope through exhaust ducts in the wardrobes, toilets, and through the main exhaust duct connected to the stairwell located at the fourth-floor (SINTEF 2017*a*).

4.3.2 Natural ventilation

Natural ventilation will be implemented in ZEB Laboratory through the opening of doors, hatches, and windows. The openings will be manually or automatically controlled. Several principles cornering natural ventilation are planned to be implemented in ZEB Laboratory.

Morning fresh air

Morning fresh air entails the opening of the motor controlled windows immediately before the occupants arrive the building (SINTEF 2017*a*). This is with the intent to ensure the sensation of fresh and clean indoor air when the building is occupied.

Whether the principle of *morning fresh air* should be carried out a given day depends on the season and ambient temperature (SINTEF 2017*a*).

Pulse ventilation

Pulse ventilation includes the principle of opening the windows for a very short period of time, this to affect the air change rate of the building to a minimum (SINTEF 2017*a*). Hence, *pulse ventilation* is very suitable for periods with a low ambient temperature.

Whether the principle of *pulse ventilation* should be carried out a given day depends on the season, ambient temperature and occupants present in the given zone (SINTEF 2017*a*).

Slot ventilation

Slot ventilation describes the opening of a window by 10.0 to 20.0 millimeters, during the occupied hours, with the intent of ensuring a continuous air change rate. Whether the principle of *slot ventilation* should be performed at a given day depends on the internal and ambient temperature, along with the given season.

4.3.3 Ventilation modes

Given that ZEB Laboratory has the ambition to achieve the level of ZEB-COM, a minimal energy consumption during operation is necessary. Passive measures with natural driving forces for ventilation, heating, and cooling are needed (Time 2016). ZEB Laboratory will be implemented with a hybrid ventilation system to maximize natural ventilation.

The ventilation mode carried out in the building can be strictly mechanical or natural, or a hybrid ventilation mode. The hybrid ventilation system operates different during the winter and the summer seasons.

During *mechanical ventilation mode*, mechanical ventilation is the only ventilation implemented in the building. Natural ventilation is only implemented through manually controlled windows. The automatically controlled windows are not active. *Natural ventilation mode* only involves the automatically and manually opening of the windows. No mechanical ventilation is active. *Hybrid ventilation summer mode* entails natural ventilation as its preference, with mechanical ventilation as a supplement when the indoor climate is unsatisfactory. However, *hybrid ventilation winter mode* uses mechanical ventilation as its preference, with natural ventilation as a supplement when needed. (SINTEF 2017*a*)

4.3.4 Ventilation control

The ventilation system in ZEB Laboratory will be a balanced mechanical ventilation system (Førland-Larsen 2017*b*).

Each floor will be divided into four regulation zones, except the fourth floor that will be divided into two regulation zones. In each zone, the air pressure will be regulated. The position of the dampers will be controlled to achieve a stable pressure. In addition, sensors monitoring the internal and ambient temperatures, levels of CO_2, occupancy, and season are placed in each zone. (SINTEF 2016)

Chapter 5

The structure of the models and cases in CONTAM

The chapter presents the chosen simulation tool CONTAM, including a validation and description of the simulation program. Further, the structure of the building model constructed in CONTAM will be presented. Three seasons will be implemented in the simulations. The seasons are winter, summer, and the transition season, from now on referred to as *cases*.

The simulations aimed to create a close to life like model of ZEB Laboratory in different seasons and thus a lifelike model of the air flows through the building.

5.1 The simulation tool

As the objective of this Master's Thesis is to find the optimal combination of natural and mechanical ventilation, in ZEB Laboratory, transient simulations of air flows through a model of the building is a suitable approach. The simulation tool must be able to account for transient ambient surroundings, occupant load with an associated pollution generation, as well as ventilation occurring due to both natural and mechanical force. Furthermore, the simulation tool must have the possibility to create a close to life like model of ZEB Laboratory. This includes building structure, zonal division, external openings, HVAC systems, and the possibility to add any control units managing the building. Furthermore, the chosen simulation tool must present the resulting air flows, pressure difference, and CO_2 levels, allowing the possibility for further energy demand calculations and evaluation of the internal environment.

Several simulation tools can carry out the mentioned simulations and supply the user with the desired results, among others TRNSYS and EnergyPlus. However, such tools demand complicated codes and input values to create a complete and lifelike model.(Woloszyn & Rode 2008)

CONTAM is a computer program developed by NIST, that can be used to determine the indoor air quality and ventilation of a multi-zone building. CONTAM allows the input of transient weather files, occupants, pollution generation, as well as a model of a building consisting of several zones, levels, internal and external openings, in addition to the possibility to create different HVAC systems and controllers. CONTAM takes both natural, including wind and buoyancy, and mechanical induced air flows into consideration. Some of the simulation results that can be collected from CONTAM are the amount of air entering and exiting a zone, the air change rate of the modeled building, the resulting CO_2 level, and the age of the internal air. (Dols & Polidoro 2015)

5.1.1 Validation of CONTAM

According to the creators of CONTAM, the program can be used to determine indoor air quality and the ventilation rate in a building based on several equations according to the Network Model that are solved by iterations (Dols & Polidoro 2015).

A verification of CONTAM was performed during the work with the former Project Thesis. During the Project Thesis, several simplified models of ZEB Laboratory were created. This included a building with open floors and several orifice openings at different heights. This model of ZEB Laboratory was simulated in CONTAM with varying ambient surroundings, including different external temperatures and wind conditions. The resulting air flows from CONTAM was compared with a mathematical model of the building. The mathematical model used equations to describe the nodal model. The resulting simulated air flows and the calculated air flows were close to equal, regardless of the ambient surroundings.

5.2 The structure of the model of ZEB Flexibel Lab

The *building model* describes the building structure, zonal division, internal conditions, and the mechanical installations in ZEB Laboratory. The structure of the building model is presented in the following subsections.

5.2.1 Building structure

CONTAM includes a simple sketch tool, *SketchPad*. This sketch tool provides the possibility to create a simple multi-zone, multi-story building with internal, and external openings. SketchPad is not able to create a building with corners other than 90°. Hence, ZEB Flexible will be simulated as a rectangular building with a floor area of 400 square meters with a flat top roof.

SketchPad includes the possibility to include flow paths, as both external and internal openings in a building. The external openings, the openings at the building facade of ZEB Laboratory, are defined as external doors, windows, and hatches. Fig. 5.1 presents a simplification of ZEB Laboratory which will be simulated, where the different external openings are displayed in different colors. The motorized controlled openings are presented as red squares, the manually controlled openings are presented as blue squares and the doors as grey squares.

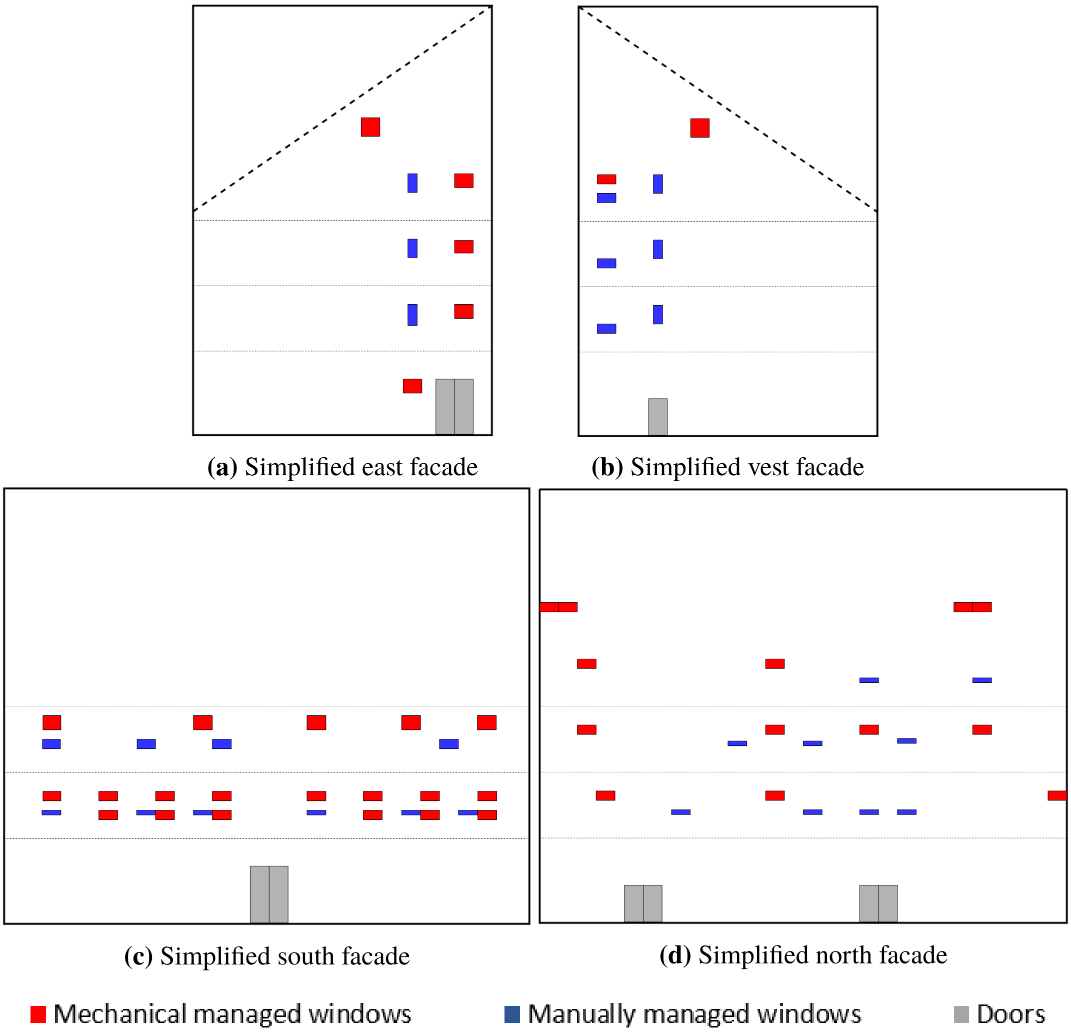


Fig.: 5.1 The facades of the building model of ZEB Laboratory with openabale windows and doors implemented in the building model.

The first floor is assumed to have a ceiling height of 4.45 meters. The second and third floors are assumed to both have a ceiling height of 3.85 meters. As previously mentioned CONTAM is not able to simulate a building with a pitched roof. Hence, the entire fourth floor is modeled with a ceiling height of 11.85 meters. This to achieve good utilization of the buoyancy effect. Following, the model of the building created in SketchPad has a total height of 24.0 meters.

5.2.2 External openings

The external openings of ZEB Laboratory consist of doors, windows, and hatches. The following subsection presents the properties of these openings that will be implemented in the building model. It's assumed that the control of some of the windows and all of the hatches are motorized.

External doors

Two different types of external doors will be implemented in the building model of ZEB Laboratory, *tall doors* and *short doors*. The tall doors will have a height of 2.99 meters, and a width of 1.00 meter. The short doors will have a height of 2.09 meters, and a width of 1.00 meter. The external doors will be defined as *two way flow paths*, with a relative elevation equal to half of the door height. The doors are marked as gray in Fig. 5.1.

The external doors are assumed to be opened according to a schedule, dependent on the season. The entry doors will be modeled to open during the time period from 08:00 to 10:00 and during the period from 15:00 to 17:00. The external entry doors will open 50% during the winter season, and 100% during the transition and summer season. The external doors in the cafeteria area are assumed to be opened during the time period from 11:00 to 13:00, at 50% during the summer and 10% during the winter. The external doors placed in the first-floor storage area and the bike room are assumed to be opened 100% during the period from 08:00 to 17:00 during all seasons.

Windows

As previously discussed ZEB Laboratory consists of windows with both motorized and manual opening areas. Fig. 5.1 defines the motorized windows as red, and the manual windows as blue.

The motorized windows can be opened 60% of the geometrical area, while the manual windows can achieve an opening area of 20% of the total geometrical area (Førland-Larsen 2017*b*). The simulation are based on seven main categories of windows. These categories are defined as *the motorized first floor window*, *manually and motorized small windows*, *manually and motorized large windows*, *manually side windows* and *motorized fire hatches*. Table 5.1 presents the dimensions and properties of each of the windows.

Table: 5.1 Dimension and properties of windows inserted in the building model of ZEB Laboratory.

	Category	Openable height [m]	Openable width [m]	Area [m^2]
Manually controlled window	**Small window**	0.08	1.00	0.08
	Large window	0.10	1.00	0.10
	Side window	1.00	0.40	0.40
Motorized controlled window	**Small window**	0.24	1.00	0.24
	Large window	0.30	1.00	0.30
	First floor window	0.40	1.00	0.40
	Fire hatch	1.00	1.00	1.00

The total elevation of a window equals the distance from the ground level to the center of the opening. Further, the relative elevation of a window is equal to the distance between the given floor to the center of the opening. Both the total and the relative elevation are important factors to determine the stack effect through a building and will be implemented in the building model.

As presented in Fig. 5.1 some openings on the same floor are assumed to be placed vertically compared to each other. The relative elevation of the windows is unaffected by how the opening are controlled and whether the windows are categorized as *small* or *large*. The total and relative elevation of each opening is presented in Table 5.2.

Table: 5.2 Total and relative elevation of height of openings inserted in the building model of ZEB Laboratory.

		Total elevation [m]	Relative elevation [m]
First floor	**Upper opening**	2.70	2.70
Second floor	**Lower opening**	5.90	1.60
	Upper opening	7.10	2.80
	Side window	6.50	2.20
Third floor	**Lower opening**	9.90	1.60
	Upper opening	11.1	2.80
	Side window	10.5	2.20
Fourth floor	**Lower opening**	13.9	1.60
	Upper opening	15.1	2.80
	Side window	14.5	2.20
	Fire hatches	17.1	4.95

The windows will be defined as *two way flow paths* in the building model, creating the opportunity to simulate the occurrence of possible neutral levels.

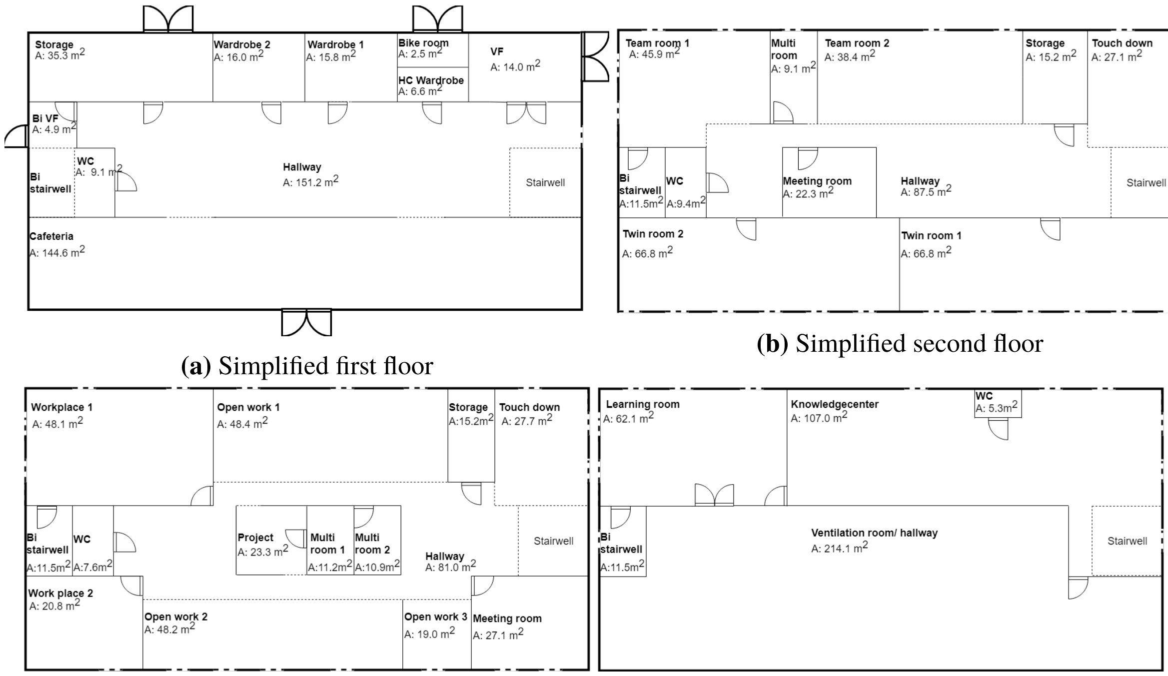
The rate and magnitude of the opening of the motorized controlled windows are assumed to be controlled by an automation system. This will be implemented in the building model and will be further described later in this chapter. The manually controlled windows are assumed to be opened by the occupants according to a schedule, which will be implemented in the model. The manually controlled windows are assumed to be opened 20% of the total possible opening area, for one hour, four times a day. A graphical presentation of the schedule for manual opening of the windows is presented in Appendix D.

Cracks and small openings

Some infiltration and exfiltration will occur through the building facade although the doors, windows, and hatches are closed. These air flows are assumed to occur through small openings in the facade. This movement of air will be implemented in the base model as *external and internal cracks*. These cracks are simulated with a length and width equal to respectively 1.00 meter and 1.00 millimeter. The cracks are assumed to be placed at the bottom of the windows, hatches and external and internal doors.

5.2.3 Zonal division

To achieve a realistic simulation of the air flows through ZEB Laboratory, several zones must be created at each floor. Fig. 5.2 presents a simplification of the different zones at each floor that will be implemented in CONTAM using SketchPad. Fig. 5.2 is based on the architectural drawings of ZEB Laboratory, presented in Chapter 4.2. The dotted lines on the external facade represent the windows and hatches, while the internal dotted lines represent the assumed boundary between two zones.



(a) Simplified first floor

(b) Simplified second floor

(c) Simplified third floor

(d) Simplifies fourth floor

Fig.: 5.2 The floor plans of the building model of ZEB Laboratory implemented in the building model.

The first floor, presented in Fig. 5.2 (a), will consist of the entries, a hallway, the cafeteria, wardrobes, and restrooms. The second floor, as described in Fig. 5.2 (b), will consist of two identical twin rooms, team rooms, a touchdown area, a multi-room, a restroom and a hallway. Fig. 5.2 (c) presents the third floor, consisting of several working areas, a meeting room, two multi-rooms, a touchdown area, along with a restroom and a hallway. The fourth floor, presented in Fig. 5.2 (d), will consist of a learning room, a large knowledge center, a restroom, along with a ventilation room and a hallway.

5.2.4 Internal openings

The internal openings, the openings between two internal zones, will be implemented as two way flows in the building model. All of the internal doors are assumed to have an area of 2.00 square meters. The internal doors will be simulated to be opened 20% during the time period from 08:00 to 17:00, and to be completely closed outside working hours, as presented in Appendix D.

The cases where two zones aren't separated by any doors or internal walls, such as the Hallway and Team Room 1 on the second floor, will be taken account for in the model. A door opening will be implemented, and further multiplied with a factor so that the correct opening area is achieved. Such openings are completely open during the entire simulation. This because two zones can be assumed to have different temperatures, pollution rate, and number of occupants even though there is no physical separation between the zones.

5.2.5 Internal temperature levels

The internal temperature varies from one zone to another. Constant and desirable temperature levels are assumed to be maintained during the working hours. The internal temperature levels are unaffected by the external temperature levels, this because the simulation tool CONTAM alone doesn't calculate such changes in temperature Dols & Polidoro (2015). However, the different temperature levels are important to include to get a realistic model of ventilation due to temperature differences.

Table 5.3 presents the different internal temperatures that will be included in the model of ZEB Laboratory, based on the preferred temperature levels presented by *Norwegian Standard* (Standard Norge 2007). Zones referred to as *Working spaces* include areas where sedentary work will be performed.

Table: 5.3 Internal zonal temperatures in the building model of ZEB Laboratory.

Zone	**Temperature level [°C]**
Working spaces	23.0
Cafeteria	23.0
Restrooms and wardrobes	26.0
Storage	20.0

The temperature levels presented in Table 5.3, are valid both during and outside the working hours, and will be implemented in the building model.

5.2.6 Occupants

ZEB Laboratory will be occupied by both students and office workers. The average number of occupants present during a workday will vary from 70 to 100 (Time 2016). The occupant load is assumed to exceed this average during some hours of the day, due to a large presence of students during lectures.

The number of occupants present and the schedules describing the movement of the occupants must be included in the simulations. An average number of occupants present in a given zone during a given time will be implemented in the building model. Table 5.4 presents the assumed average number of occupants in the different zones of ZEB Laboratory. It's assumed that ZEB Laboratory is occupied during the time period from 07:50 to 17:10.

Table: 5.4 Average number of occupants in a given zone during a given time present in the building model of ZEB Laboratory implemented in the building model.

	Zone	Time period	Number of occupants
First Floor	VF	07:50-10:00 & 16:00-17:10	2
	BiVF	07:50-10:00 & 16:00-17:00	0.2
	Hallway	07:50-17:00/10:45-13:15*	5/20*
	Warderobe 1	08:00-08:20 & 16:40-17:00	5
	Warderobe 2	08:00-08:20 & 16:40-17:00	5
	HC Wardrobe	08:00-08:30 & 15:30-16:30	1
	WC	09:00-15:00	1
	Cafeteria	11:00-13:00	30
Second Floor	Hallway	07:55-16:55	3
	WC	08:00-16:00	0.5
	Team room 1	09:00-10:00 & 14:00-16:00	7
	Muli room	10:00-12:00	4
	Team room 2	08:00-10:00	4
	Touch down	12:00-13:00	4
	Twin room 1	10:00-12:00 & 14:00-16:00	10
	Twin room 2	10:00-12:00 & 14:00-16:00	10
	Meeting room	10:00-12:00/13:00-15:00*	7/4*
Third Floor	Hallway	08:00-16:50	3
	WC	08:00-16:00	0.5
	Workplace 1	08:00-12:00 & 14:00-16:00	8
	Workplace 2	08:00-12:00 & 14:00-16:00	5
	Open work 1	08:30-12:00 & 14:00-16:30	10
	Open work 2	08:30-11:30	6
	Open work 3	13:30-16:30	6
	Meeting room	13:00-14:00	8
	Project	13:00-14:00	10
	Multiroom 1	13:00-14:00	5
	Multiroom 2	16:00-17:00	5
Fourth Floor	WC	10:00-14:00	0.5
	Knowledgecenter	10:00-12:00	30
	Learning room	12:00-14:00	30

*Zones are to be occupied by a different number of occupants at different hours.

5.2.7 Levels and generation of pollution

CO_2 will, as the only pollution, be implemented in the model with occupants as the internal source. This is a simplification of reality when both external and other internal sources are neglected. The external pollution level of CO_2 is assumed to be constant with a value of 400 ppm. The properties of CO_2, which will be implemented in the model, are presented in Table 5.5 and are based on values suggested by the creators of CONTAM (Dols & Polidoro 2015).

Table: 5.5 The properties of CO_2 within the building model of ZEB Laboratory implemented in the building model (Dols & Polidoro 2015).

Molar weight [$\frac{kg}{mol}$]	**Diffusion coefficient [$\frac{m^2}{s}$]**	**Mean diameter [μm]**	**Effective density [$\frac{kg}{m^3}$]**	**Specific heat [$\frac{J}{kgK}$]**	**Default [ppm]**
44	2 e-005	0.00033	1.977	850	400

The generation of CO_2 by the occupants is assumed to only vary with the activity. Table 5.6 presents the level of CO_2 which is implemented in the base model.

Table: 5.6 Inserted CO_2 generation of the occupants in the building model of ZEB Laboratory.

	CO_2 **generation [$\frac{L}{s}$]**
Walking	0.005
Sedentary work	0.004
Restroom breaks	0.006

5.2.8 Mechanical ventilation

A mechanical ventilation system will be implemented in the building model as a simple air handling unit with both supply and return points.

The air flow exhaust rate is implemented in the model as a constant value, unaffected by the possible presence of occupants. Table 5.7 presents the exhaust rates of the toilets and the wardrobes. These ratios are based on values recommended by the standard NS 15251 (Standard Norge 2007). The mechanical fan system is assumed to entail an SFP value of 1.00 $\frac{kW}{m^3/s}$ and to be connected to a heat exchanger with the efficiency of 85% as previously performed in SIMIEN by Førland-Larsen (Førland-Larsen 2017*a*).

Table: 5.7 Recommended and implemented values of exhaust air flow rates in the building model of ZEB Laboratory (Standard Norge 2007).

	Air flow exhaust[$\frac{L}{s}$]
WC	10.0
Wardrobe	15.0

The air flow rates of supply that are to be implemented in the model are presented in Table 5.8. These air flow rates are based on the recommended values according to the standard NS15251 (Standard Norge 2007). The air flow rates of supply vary with the presence of occupants.

Table: 5.8 Recommended and implemented values of air flow rates in the building model of ZEB Laboratory (Standard Norge 2007).

	Zone	Air flow supply unoccupied [$\frac{L}{s}$]	Air flow supply occupied [$\frac{L}{s}$]
First Floor	VF	4.90	18.90
	BiVF	1.715	3.115
	Hallway	52.92	87.92/192.92*
	Cafeteria	50.61	260.61
Second Floor	Hallway	30.63	51.63
	Team room 1	16.065	65.065
	Team room 2	13.44	41.44
	Multi room	3.185	31.185
	Touch down	9.485	37.485
	Twin room 1	23.38	93.38
	Twin room 2	23.38	93.38
	Meeting room	7.805	56.805/35.805*
Third Floor	Hallway	28.49	49.49
	Workplace 1	16.835	72.835
	Workplace 2	7.28	42.28
	Open work 1	16.94	86.94
	Open work 2	16.87	58.87
	Open work 3	6.65	48.65
	Meeting room	9.485	65.485
	Project	8.155	78.155
	Multi room 1	3.92	38.92
	Multi room 2	3.815	38.815
Fourth Floor	Knowledgecenter	37.45	247.45
	Learning room	21.735	231.735

*The two different amounts of air flow supply are caused by the different number of occupants present at different times. See Table 5.4.

There are supply points in every occupied zone. The elevation of these points depend on the preliminary chosen air distribution of the floor. Therefore, the supply points on the first and fourth floor are placed at floor level, while the supply points on the second and third floor are at the ceiling level.

Duct work

A part of the mechanical ventilation system is assumed to be the *main return ducts*. The main return ducts will be located on the fourth floor, mainly in the ventilation room, and act as the main return of the air handling unit. The following subsection describes the ductwork that will be implemented in the building model.

The duct work will consist of one *main exhaust duct* connected to three smaller ducts. The main exhaust duct will be placed in the ventilation room and carries exhaust air out of the building. The air will leave the building at an elevation of 11.85 meters relative to the fourth level. The main exhaust duct is assumed to have a rectangular shape, with a width and height of 0.70 meters, and will be connected to three smaller ducts. The *main staircase duct* has its inlet 3.85 meters above the main staircase at the fourth floor. The main staircase duct is assumed to be rectangular with a width and height of 0.50 meter. Two smaller and rectangular shaped ducts with a width and height of 0.10 meter will be connected to the ductwork. These ducts will be referred to as *bi staircase ducts*, with one inlet 3.85 meters above the bi staircase, and one inlet 3.85 meters above the floor in the ventilation room. The entire ductwork is assumed to have a roughness 0.09 millimeter, as suggested by the simulation program (Dols & Polidoro 2015).

Fig. 5.3 presents a simple sketch of the main return ductwork placed on the fourth floor.

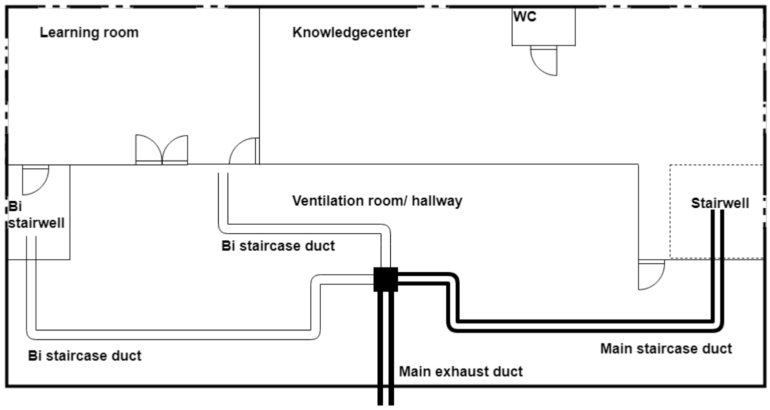


Fig.: 5.3 Simple presentation of the main return duct work within the building model of ZEB Laboratory.

According to Førland-Larsen, the amount of air in and out of the building will be 15 $\frac{m^3}{hm^2}$ during work hours, and otherwise 0 $\frac{M^3}{hm^2}$ (Førland-Larsen 2017*a*). Hence, each of the main and bi staircase ducts will be implemented as a *constant volume flow* of 500 and 2500 $\frac{m^3}{h}$, respectively. The ducts will be connected to a schedule, ensuring no air flow outside working hours.

5.2.9 Automation systems

The building model consists of some automation and controllers. The automation systems will consist of schedules for the motorized windows and mechanical air supply, as well as P-controllers managing the natural and mechanical ventilation system. The controllers that are to be implemented in the building model will be described in the four following subsections.

Scheduled controllers of the natural ventilation system

The opening of the motorized controlled windows will, in addition to a controller, be managed according to a schedule. The schedule able to control the motorized windows will automatically open the windows with an opening degree of 100% during a given time period from 06:00 to 08:00. Hence, the windows can be opened and closed automatically before any occupants are present in the building. This to achieve a satisfactory perceived indoor air quality. The schedule is based on the previously described principle referred to as *Night time aeration*.

Scheduled controllers of the mechanical ventilation system

The mechanical ventilation system supplies air at different rates depending on the presence of occupants. This gives the basis for the scheduled control of mechanical ventilation. The scheduled control of mechanical ventilation is preset, according to the assumed presence of occupants. Once occupants enter a zone, the peak ventilation rate covering the load of the occupants is turned on. Similarly, the peak ventilation is turned off once the occupant is scheduled to leave the zone. This control schedule will be implemented in the building model.

Proportional controllers of natural and mechanical ventilation systems

The automation system of the building model will consist of a *proportional controller*, P-controller, managing the opening rate and magnitude of the motorized windows, in addition to the rate of supplied mechanical air. The P-controller will act based on the CO_2 level in the given zone. P-controllers with different ranges will be implemented in the building model. The different P-controllers will change the modes of the ventilation system when the CO_2 level reaches given levels. CONTAM allows the controllers to be implemented as a network of different elements (Dols & Polidoro 2015). The current subsection will further describe a general P-controller as implemented in CONTAM.

A description on a general P-controller with the range from a *lower limit* to a *upper limit*, and a rate from 0 to 100% is graphically described in Fig. 5.4.

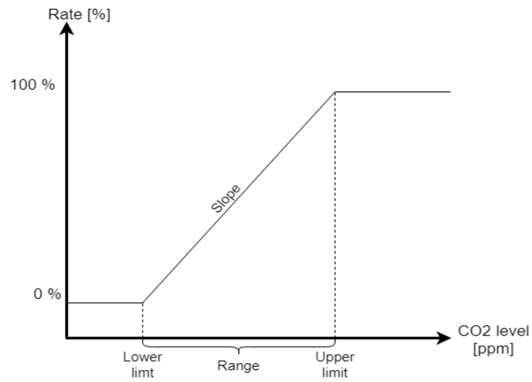


Fig.: 5.4 Graphical presentation of a general P-controller with a range from a lower to an upper limit.

As Fig. 5.4 presents the P-controller will only manage the system when the CO_2 level reaches the given lower limit. As an example, motorized windows will stay closed until the CO_2 level exceeds the given lower limit. The opening rate of the window will be proportional to the increase of CO_2, leading to a 100% opening if the CO_2 level exceeds the given upper limit.

A set of equations describing the window opening rate, varying from 0 to 100%, is described in Eq. (5.1).

$$Rate = \begin{cases} 0\% & \textit{if the } CO_2\textit{-level is below the lower limit} \\ \frac{100\%}{Range} \cdot CO_2 \; level - \frac{Range}{Lower \; limit} & \textit{if the } CO_2 \textit{ level is the the given range} \\ 100\% & \textit{if the } CO_2\textit{-level is above the upper limit} \end{cases} \tag{5.1}$$

To transfer the function described in Fig. 5.4 and Eq. (5.1) to a P-controller, a CO_2-sensor must be placed in each zone. Further, the measured CO_2 level must be modified to a value that can be multiplied with a constant proportional coefficient. The coefficient is equal to the slope of the graphical presentation of the P-controller. A block diagram describing the general P-controller with the associated elements and control loop implemented in the building model is presented in Fig. 5.5.

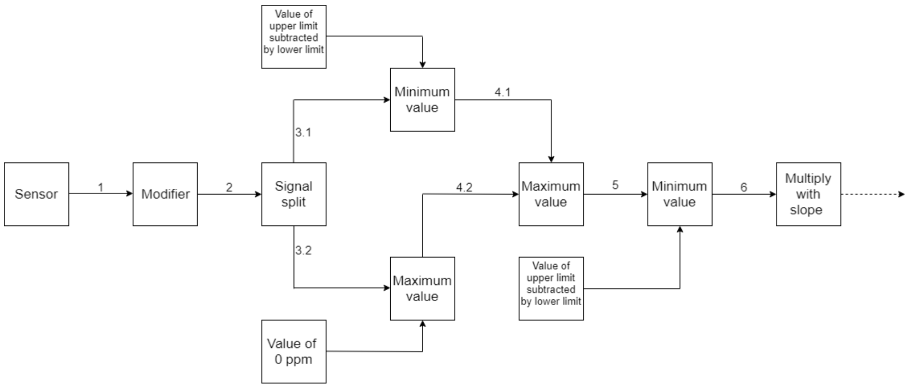


Fig.: 5.5 Block diagram of a general P-controller with the range from a lower to an upper limit, with the proportional coefficient equal the slope, with associated modifier and control loop.

A simple description of the signals in the P-controller described in the block diagram presented in Fig. 5.5 will now follow.

Signal 1 The CO_2 level registered by a zone sensor

Signal 2 The modified CO_2 level in the zone

Signal 3.1 Equal to Signal 2

Signal 3.2 Equal to Signal 2

Signal 4.1 The minimum value of Signal 3.1 and the difference between the upper and lower limit

Signal 4.2 The maximum value of Signal 3.2 and a constant value of 0 ppm

Signal 5 The maximum value of Signal 4.1 and Signal 4.2

Signal 6 The minimum value of Signal 5 and the difference between the upper and lower limit

The resulting signal is multiplied with the slope and further manage the ventilation system

All of the motorized external openings and the mechanical supply of air will be connected to a P-controller. Two P-controllers are implemented in the model building. One with the range from 600 ppm to 800 ppm, and one with the range from 800 ppm to 1100 ppm. The structure of these P-controllers are presented in Appendix E and Appendix F, respectively.

5.3 The properties of the ambient conditions

The building model will be simulated based on three different cases. The three cases are the *winter week*, the *transition week*, and the *summer week*. The different cases that will be simulated surrounding the building model is based on the ambient conditions of ZEB Laboratory. The following subsections will describe the conditions and the properties of the three different cases.

To achieve a realistic indoor environment and resulting ventilation of ZEB Laboratory a transient simulation must be completed. Transient weather files must be created and included in each case. CONTAM takes the ambient air temperature and pressure, humidity ratio, wind velocity, and wind direction into consideration (Dols & Polidoro 2015). The created weather files will be produced based on values measured in 2018 and 2019 at a weather station placed at Voll in Trondheim, presented by Yr (Yr 2018).

5.3.1 Location

ZEB Laboratory will be located at NTNU, Gløshaugen Campus, in Trondheim. The same location will be implemented in the simulation in CONTAM. This is equal a latitude of 63.24° North and a longitude of 10.24° East (Timein 2015). ZEB Laboratory is assumed to have an elevation of 45 meters above sea level (Yr 2019).

5.3.2 Air temperature

The detailed ambient air temperature that will be describing each case is presented graphically in Fig. 5.6. The temperature is based on measurements performed each hour, over one week (Yr 2018).

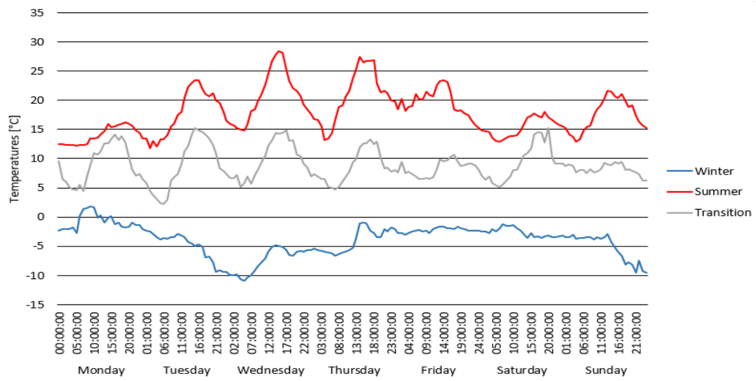


Fig.: 5.6 Ambient air temperatures implemented in the simulations (based on measurements performed by Yr (2018)).

As presented in Fig. 5.6, and as expected, the temperature is at the highest level during the summer and at the lowest level during the winter. The temperature levels undergo some variations during each week.

5.3.3 Humidity ratio

A detailed file describing the humidity ratio will be implemented in the weather file for each case. These humidity ratios are presented graphically in Fig. 5.7, and are the result of measurements performed by Yr (Yr 2018).

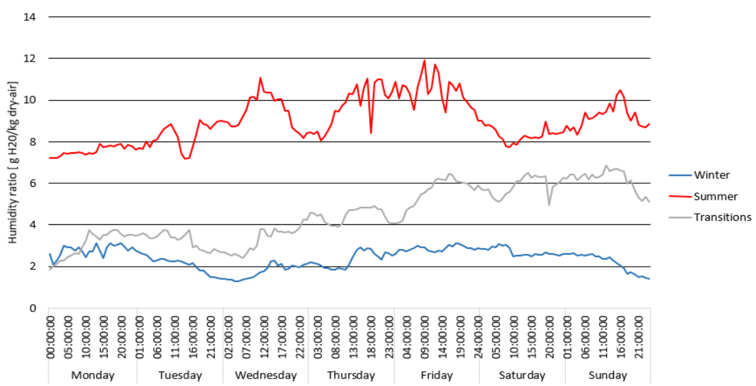
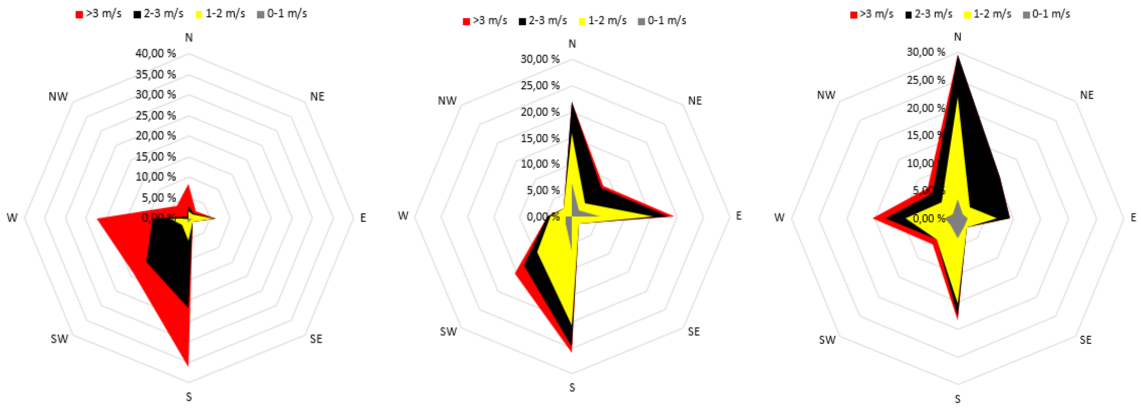


Fig.: 5.7 Ambient humidity ratio implemented in the simulations (based on measurements performed by Yr (2018)).

During the summer week the humidity ratio achieves the highest level. Further, the humidity ratio is close to equal at during the start of the transition and winter week.

5.3.4 Wind

As previously mentioned, CONTAM takes both wind velocity and wind direction, as well as the wind pressure coefficient into consideration. Each case must be implemented by the properties of wind. The wind velocity and the approach angle of the wind measured by Yr are presented as *wind roses* in Fig. 5.8 (Yr 2018). A wind rose describes the velocity and the approach angle of the wind in a merged diagram. The properties of the wind presented in Fig. 5.8 will be implemented in the cases simulated in CONTAM.



(a) Winter week **(b)** Transition week **(c)** Summer week

Fig.: 5.8 Wind roses describing the properties of wind implemented in CONTAM (based on measurements performed by Yr (2018)).

According to Fig. 5.8 the wind maintains a higher velocity level during the winter. The wind mainly approaches from the south during the winter and the transition week, and from the north during the summer.

The wind pressure coefficient is an important factor affecting the natural ventilation caused by wind (Allard et al. 1998). An accurate wind pressure coefficient profile is hard to estimate for ZEB Laboratory when an accurate pressure profile is achieved through measurements of an actual building (Verma et al. 2013).

According to research completed by L. Gullbrekken et al. in 2018, Tokyo Polytechnic University has produced a detailed database correctly describing the wind load of low rise buildings (Gullbrekken et al. 2018). This database does not describe the wind load of buildings with a height larger than the depth of the building, neither buildings with a diagonal pitched roof (Tokyo Polytechnich University 2007). However, the database from Tokyo Polytechnic University describes a building with a depth and width ratio of 2, and a pitched roof of 30.00° (Tokyo Polytechnich University 2007). This data will be implemented in the simulations, and is graphically presented in Fig. 5.9.

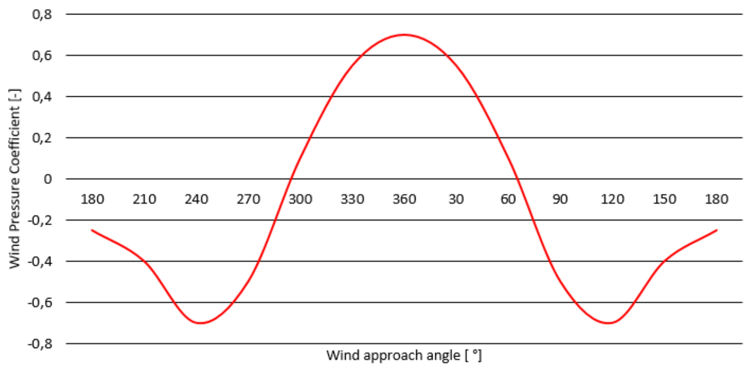


Fig.: 5.9 Wind pressure coefficients implemented in the simulations (based on measurements performed by Tokyo Polytechnich University (2007)).

5.4 The structure of the basic and corrected models

The previous description of the building model and the three different weather cases formes a basis for further development of corrected models. Three *basic models* will be defined in the following and consist of three different ventilation modes: A) Natural ventilation mode, B) Mechanical ventilation mode, and C) Hybrid ventilation mode.

5.4.1 Model A: Only natural ventilation

Model A will be simulated to include a clean natural ventilation system. Mechanical ventilation will be turned off. This includes removal of the supply and exhaust points, in addition to the main exhaust duct placed on the fourth floor. The natural ventilation will occur through manually and automatically controlled external openings, in addition to infiltration and exfiltration.

A clean natural ventilation system forms a basis for two further corrected models, *Model A.1* and *Model A.2*. These differ from each other by having different controllers connected to the motorized windows and hatches. Model A.1 will be implemented with a P-controller with the range from 600 to 1000 ppm, while the P-controller implemented in Model A.2 will have a range of 800 to 1100 ppm.

5.4.2 Model B: Only mechanical ventilation

Model B will be simulated as a clean mechanical ventilation building model. All of the doors, windows, and hatches will be closed during the entire week. However, some infiltration and exfiltration may still occur through the small openings and cracks on the building facade.

The mechanical ventilated building model forms basis for two different models, *Model B.1* and *Model B.2*. These only differ from each other by having different regulators connected to the supply ducts. Both models will supply the mechanically ventilated zones with air covering the base ventilation load of the building. However, the peak ventilation rate of Model B.1 will be controlled according to a preset schedule, while the peak ventilation load of Model B.2 will gradually be turned on and off according to a P-controller with the range from 600 to 1000 ppm.

5.4.3 Model C: Hybrid ventilation

Model C will be simulated as a building model implemented with a hybrid ventilation system, including both natural and mechanical ventilation. Natural ventilated air may occur through the building facade while air is mechanically supplied and extracted from the building.

Several hybrid ventilation building models can be created with the basis of Model A.1, Model A.2, Model B.1, and Model B.2. Hence, mixing mode ventilation can occur with the possibility of concurrent, change-over, and zonal ventilation.

5.4.4 Summary of simulated building models

Table 5.9 presents a tabular summary of the corrected models to be simulated in CONTAM.

Table: 5.9 A tabular summary of the corrected building models of ZEB Laboratory.

		Controller of windows	**Controller of mechanical supply**
Natural ventilation	**A.1**	P-controller with range from 600 to 1000 ppm	-
	A.2	P-controller with range from 800 to 1100 ppm	-
Mechanical ventilation	**B.1**	-	Preset scheduled control
	B.2	-	P-controller with range from 600 to 1000 ppm
Hybrid ventilation	**A.1+B.1**	P-controller with range from 600 to 1000 ppm	Preset scheduled control
	A.1+B.2	P-controller with range from 600 to 1000 ppm	P-controller with range from 600 to 1000 ppm
	A.2+B.1	P-controller with range from 800 to 1100 ppm	Preset scheduled control
	A.2+B.2	P-controller with range from 800 to 1100 ppm	P-controller with range from 600 to 1000 ppm

Chapter 6

Presentation and discussion of the results

The following section contains relevant and important results from the simulations and calculations. The results are tabular and graphical displayed, and further discussed, described and compared. The indoor environment is evaluated based on the air change rate, CO_2 levels, age of air, and ambient air supply. The energy demand associated with ventilation is described according to energy heating demand and required fan power.

The resulting indoor environment and energy demands are evaluated in detail in four chosen zones. The four zones are found at four different floors and have moderately different design and occupant load. These zones are the Cafeteria on the first floor, the Meeting Room on the second floor, Workplace 1 on the third floor, and the Learning room on the top floor. The Cafeteria can be supplied with mechanical ventilated air and natural ventilated ambient air through the external doors in the zone. The Cafeteria is connected to the first-floor Hallway. The second-floor Meeting Room is designed with a mechanical supply of air, but has no openings connecting to ambient surroundings. The third-floor Workplace 1 and the fourth-floor Learning room both have external openings and can be supplied with both natural and mechanical ventilated air.

Appendix G to I presents the resulting air change rate and the internal CO_2 level of the building model implemented with each ventilation mode during the entire year. These results are the product of several simulations performed to obtain an optimal combination of natural and mechanical ventilation.

6.1 Case 1: Winter week

Large differences between internal and external temperatures occur throughout the winter. Large rates of air change appear in naturally ventilated buildings. This is presented in Fig. G.1 in Appendix G. The resulting energy demand for heating ambient air entering a building is proportional to the air change rate. Hence, a clean naturally ventilated building requires a large amount of heating energy during the winter. No building models including only natural ventilation will be presented in this section. The upcoming presented results are associated with the mechanical models, Model B.1 and Model B.2, in addition to the hybrid combination of Model A.2+B.1 and Model A.2+B.2.

An essential result from the simulation of the winter week, is the power and energy demand. Demand for power and energy results from the heating of air and work performed by the fans. Low energy consumption is, as previously discussed, crucial to achieving a level of ZEB. The required power and energy from the chosen models will be presented in addition to some indoor environmental results.

Appendix G presents the air change rates and resulting CO_2 levels over the entire winter week for the whole building for each of the possible ventilation systems. An important find is that natural ventilation will lead to satisfactory levels of CO_2 in ZEB Laboratory during the entire winter week.

6.1.1 Energy heating demand

The maximum required power, due to the heating of ambient air entering the building envelope, is presented in Fig. 6.1. The energy demand is calculated according to the procedure presented in Chapter 4.6.

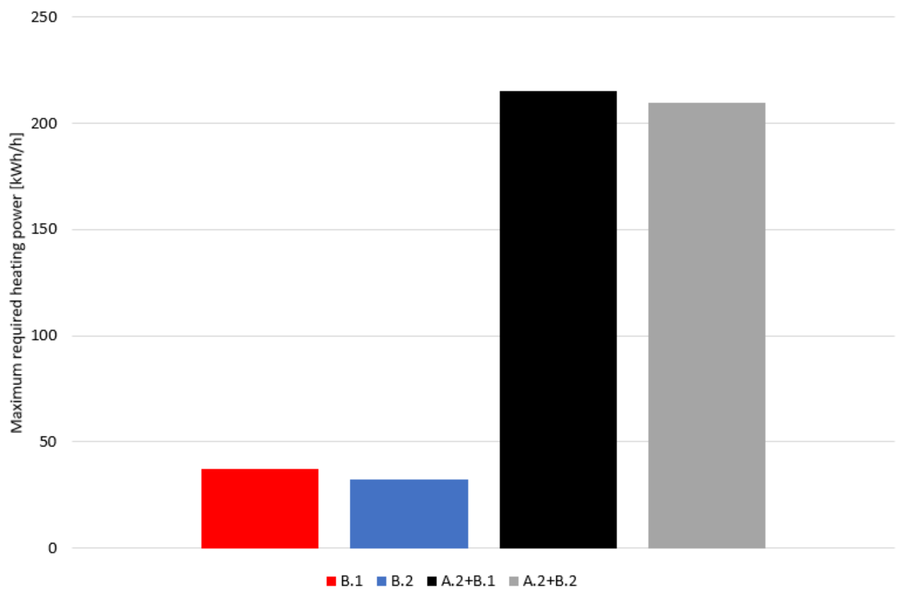
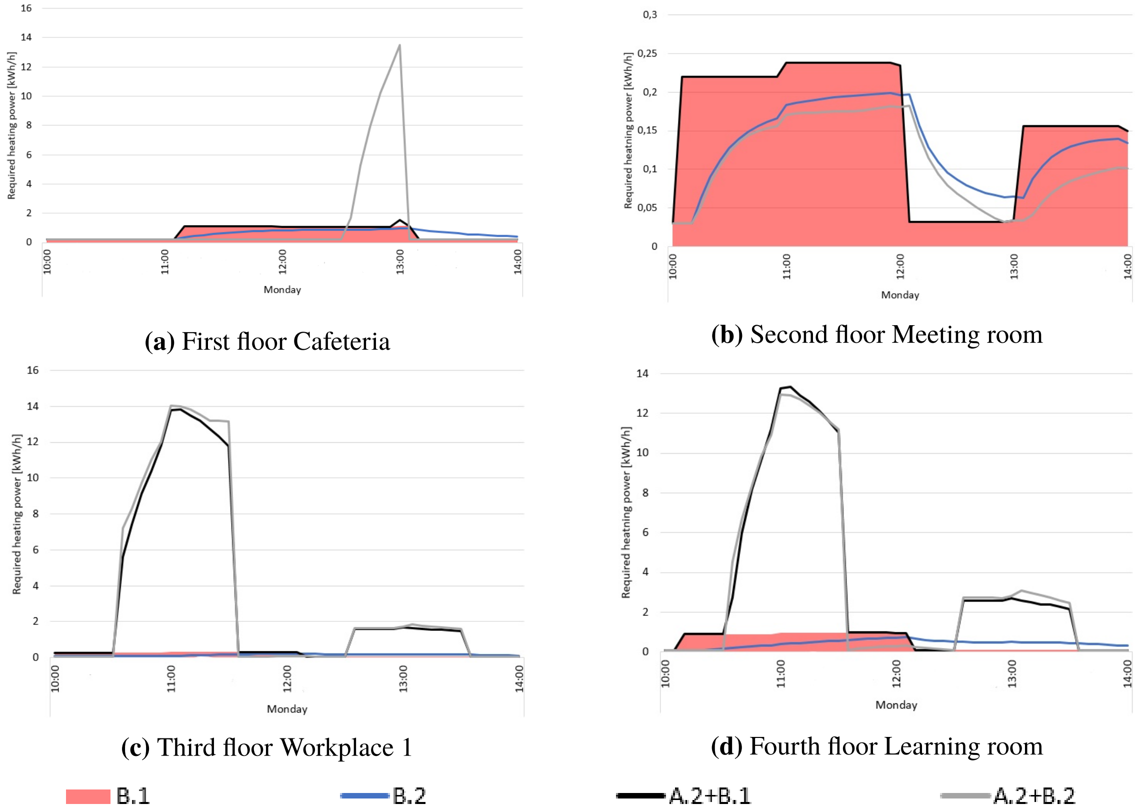


Fig.: 6.1 Maximum heating power required to heat ambient air during the winter week.

Fig. 6.1 shows that the models implemented with a hybrid ventilation system have an enormous demand for heating power compared to the models only implemented with mechanical ventilation. Hence, the overall heating power required by the building is larger in the hybrid models, and a clean mechanical ventilation solution is more energy efficient when only analyzing the heating demand of the entire building.

Fig. 6.2 presents the heating power required of the four chosen zones in ZEB Laboratory. The plotted graphs describe the required heating power in the time period between 10:00 and 14:00 for each of the zones. The area beneath the lines correspond to the resulting energy heating demand. The total energy demand due to heating during the entire winter week is presented in Table 6.1.



(**a**) First floor Cafeteria

(**b**) Second floor Meeting room

(**c**) Third floor Workplace 1

(**d**) Fourth floor Learning room

Fig.: 6.2 The resulting required heating power of ambient air entering four given zones during the winter week.

Table: 6.1 The total heat energy demand of air during the winter week in four chosen zones.

	B.1	**B.2**	**A.2+B.1**	**A.2+B.2**
Cafeteria heating demand [kWh]	51.43	51.44	3203	7232
Meeting room heating demand [kWh]	10.05	9.63	10.05	8.92
Workplace 1 heating demand [kWh]	21.78	16.78	43.12	38.75
Learning room heating demand [kWh]	27.88	27.07	43.99	37.58

Fig. 6.2 (a) shows the required heating power of the Cafeteria. The large power demand resulting from the hybrid combination of Model A.2+B.2 may be caused by a large air flow of ambient air into the zone. During lunch hours ambient air will enter the Cafeteria in this model at a rate up to 1.830 $\frac{kg}{s}$, leading to a power demand of 13.50 $\frac{kWh}{h}$. The heating power demanded of the other hybrid model, Model A.2+B.1, is far smaller, as well as the supply of ambient air. This may be caused by the constant supply of peak load ventilation from the mechanical system, creating an overpressure in the zone resulting in outflows of air from the building.

The heating power demanded by the Meeting Room, presented in Fig. 6.2 (b), shows that the energy demand of the mechanical model B.1 causes the same power demand as the hybrid Model A.2+B.1.

In the analyzed zones at the third and fourth floor, presented in Fig. 6.2 (c) and (d), the required heating power is significantly lower for models with only mechanical ventilation. The heating power demand of the hybrid ventilated models is close to equal. This may be a result of equal amount of naturally ventilated air in the hybrid models.

The notion that mechanical ventilation models have a lower power demand is confirmed by the heating energy demand presented in Table 6.1. By analyzing this table it's clear that Model B.2 has the lowest energy demand, independent of the zone. Hence, a clean mechanical ventilation system leads to the most energy efficient building when only evaluating the heat demand of the supplied air to the four chosen zones.

6.1.2 Required fan power

An energy demand due to the running of the fans will occur in buildings implemented with both mechanical and hybrid ventilation systems. This is a parameter that must be taken into consideration when analyzing energy efficient solutions of ventilation.

The required power to run the mechanical fans for each of the four evaluated models is presented in Fig. 6.3. The required power is calculated according to the procedure presented in Chapter 4.6 while assuming an SFP of 1 $\frac{kW}{m^3/s}$.

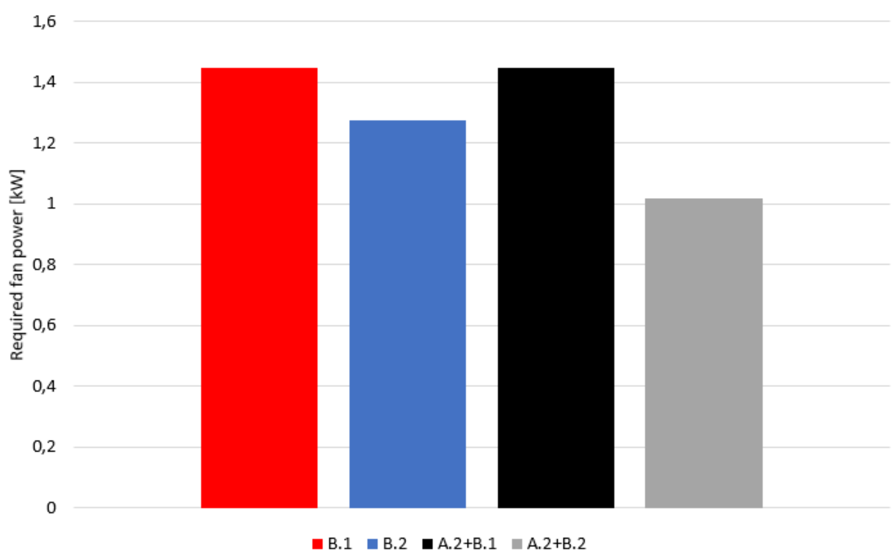


Fig.: 6.3 Power required to run the fans during the winter week.

Fig. 6.3 shows that the fan power required is equal in Model B.1 and Model A.2+B.1. This is expected when the mechanical ventilation system is the same in the two models. However, the model requiring the least amount of fan power is Model A.2+B.2. This is an indication for a smaller amount of mechanical ventilated air in this hybrid model.

When comparing the two clean mechanical ventilated models, Model B.2 has a lower demand for fan power. This indicates that Model B.2 supplies the building with a smaller amount of ventilated air.

6.1.3 Air change rates

Due to overall low demand for heat and fan power in Model B.1 and B.2 these models are further analyzed in this chapter. Fig. 6.4 presents the average air change rate of the entire building in Model B.1, the solid line, and Model B.2, the dotted line, during the winter week. The air change rate in Model A.2+B.1 and A.2+B.2 during the winter is displayed in Fig. G.1 in Appendix G.

The limits corresponding to the *Required air change rate with maximum occupancy* and *Required air change rate when unoccupied* are calculated according to the procedure in Appendix C.

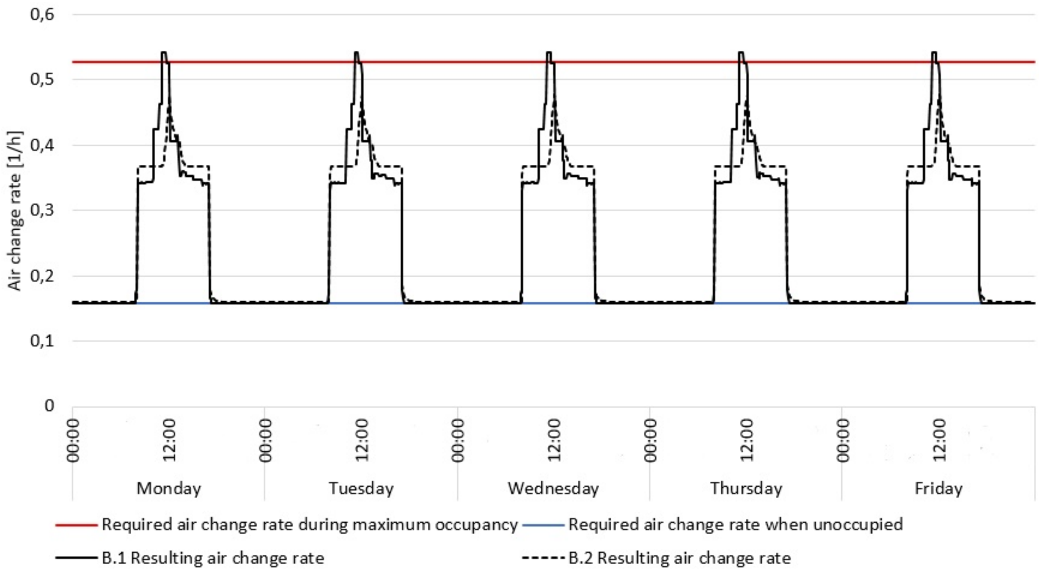


Fig.: 6.4 The resulting air change rate for model B.1 and B.2 in during the winter week.

As shown in Fig. 6.4 the air change rate will be at a satisfactory level during the entire work week, both during the occupied and unoccupied hours for Model B.1. This is expected due to the constant occupant load, and resulting air supply according to NS15251, during the workday. No natural ventilation is needed to compensate for the mechanical system during periods with maximum occupant load, assuming satisfied occupants. The air change rate of Model B.2 is satisfactory during the unoccupied hours, but has a deviation of 0.049 $\frac{1}{h}$, corresponding to 470 $\frac{m^3}{h}$, the required value when occupied. This is due to the structure of the control unit regulating the mechanical ventilation rate, a P-controller with a range from 600 to 1000 ppm. This controller will not turn to maximum capacity as long as the CO_2 level in the building is kept below 1000 ppm.

6.1.4 Age of air vs. CO_2 levels

Fig. 6.5 presents the age of air versus the CO_2 level in Model B.1, the solid line, and Model B.2, the dotted line, at the four chosen zones during working hours. The grey area in the graphs represent the time when the zones are occupied. Hence, the grey areas are the most important and interesting to analyze.

It's important to note that a large age of air doesn't necessary implies a poor indoor climate. It simply represents the time passed, measured from the air entered the building. However, a large age of air implies that the air has been present in the building over a long period of time. Hence, the *freshness*, temperature and pollution load of the air can be compromised.

(a) First floor Cafeteria

(b) Second floor Meeting room

(c) Third floor Workplace 1

(d) Fourth floor Learning room

Fig.: 6.5 The resulting age of air vs. CO_2 levels from simulations of Model B.1 and B.2 during the winter week.

The graphs in Fig. 6.5 show that the age of air decreases and the CO_2 level increases once occupants enter a zone. This is as expected. The peak ventilation rate is turned on once occupants generating CO_2 enter a zone.

According to Fig. 6.5 there are some common features for Model B.1 and Model B.2. The age of air rarely exceeds 2 hours in any of the analyzed zones. Further, the CO_2 level never exceeds 1000 ppm. Hence, the analyzed parameters describing the indoor climate are at a satisfactory level in Model B.1 and Model B.2 during the winter week.

There are few large distinctions when comparing the age of air in Model B.1 and Model B.2. The resulting levels of Model B.2 are smoother in the analyzed time period. This is as expected when the mechanical ventilation rates in this model gradually increases and decreases. The rapid changes within the occupied hours in Model B.1 may occur due to turning off or on the peak ventilation in other zones, leading to a pressure difference propagating through the building. Hence, when the air supply in a zone changes, the age of air in every zone is affected.

There are small variations of the CO_2 levels resulting from the two mechanical models. Some difference occurs due to the different control of the ventilation system. The resulting CO_2 levels of Model B.1 are, as expected, mainly lower. This because no amount of CO_2 must be accumulated before any additional ventilation is turned on.

6.2 Case 2: Transition week

Due to the smaller internal and external temperature differences compared to the winter week, the simulation results from building models implemented with clean natural, clean mechanical, and hybrid ventilation will be presented. Hence, the energy required to heat the air flows is once again an important and interesting result. Further, the ventilation efficiency and the resulting indoor environment of a clean natural ventilated ZEB Laboratory, compared to a mechanical ventilated building, is interesting to evaluate. During the transition period, a somewhat small internal and external temperature difference occurs leading to a possible cooling demand. As previously discussed, nZEB buildings are often passively cooled by aeration at night time or in the morning. The results of a natural ventilated building implemented with morning aeration schedules will be presented.

The resulting air change rate of natural, mechanical and hybrid ventilation are all presented in Appendix H. An important find is that natural ventilation will lead to satisfactory levels of CO_2 in ZEB Laboratory during the entire transition week.

6.2.1 Energy heating demand

The maximum required energy of heating ambient air entering the building is presented in Fig. 6.6. The energy levels are based on the maximum resulting air change rate during the transition week, and are calculated according to Chapter 4.6. The mechanical ventilation system is still assumed to be implemented with a heat exchanger with heat recovery of 85%.

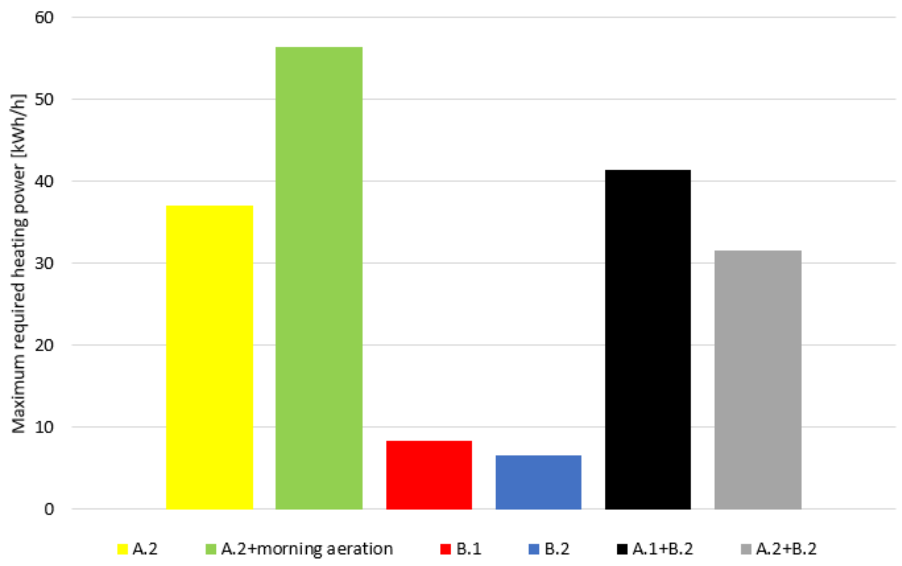
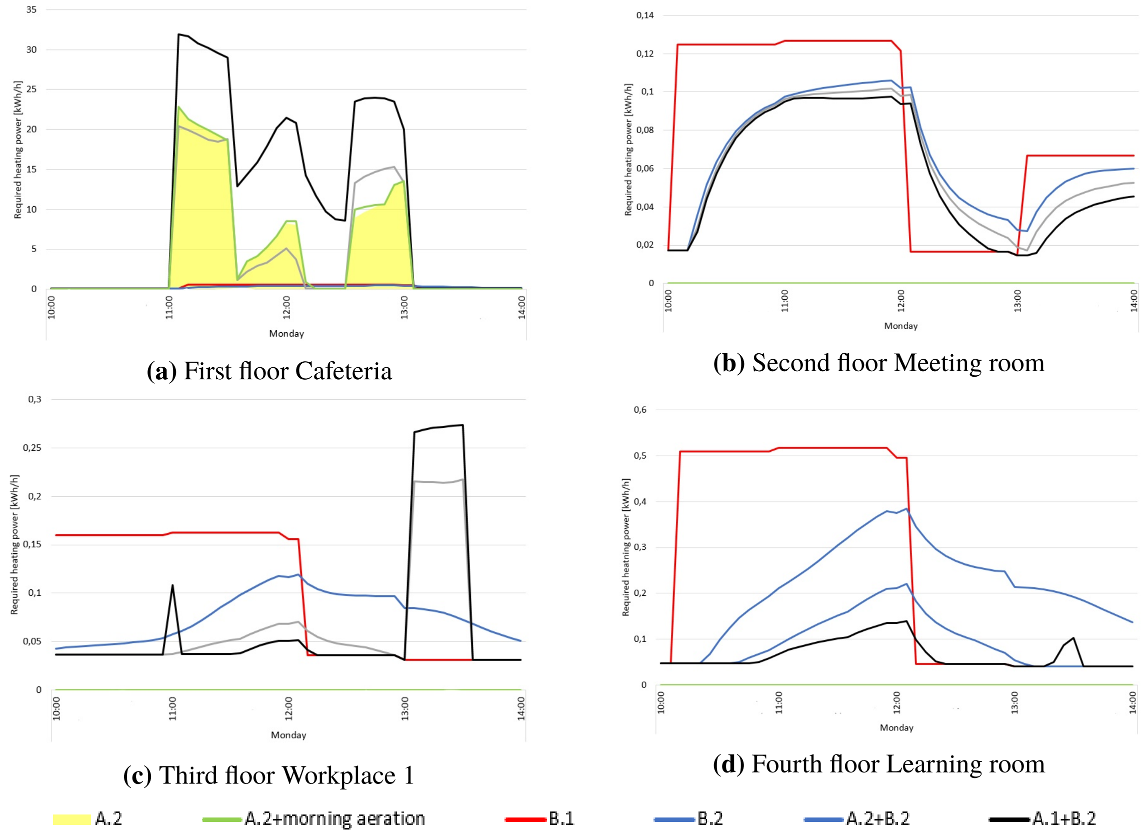


Fig.: 6.6 Maximum heating power required to heat ambient air during the transition week.

Fig. 6.6 shows that the mechanical ventilation system has a lower demand of heating energy. This is probably caused by a lower ventilation rate and the large potential of heat recovery in mechanically ventilated buildings. The amount of air entering the building increases drastically when natural ventilation is added. This is due to a substantial temperature difference, the effect of wind, and the absence of any heat recovery. The largest demand for heating power occurs in a building implemented with natural ventilation with morning aeration. However, the morning aeration takes place outside working hours, so an internal temperature outside the recommended area is acceptable. The model with the lowest demand for heating power is Model B.2. When only evaluating the demanded heating power of the building, the clean mechanical model, Model B.2 is the most energy efficient solution.

Fig. 6.7 presents the heating power required in four zones over the time period from 10:00 to 14:00 resulting from clean natural, clean mechanical and hybrid ventilation. The area below the plotted graphs present the corresponding demanded heat energy over the entire work week. The corresponding demand for heat energy is presented in Table 6.2.



(a) First floor Cafeteria

(b) Second floor Meeting room

(c) Third floor Workplace 1

(d) Fourth floor Learning room

Fig.: 6.7 The resulting required heating power of ambient air entering four given zones during the transition week.

Fig. 6.7 shows that the demand of heating power for the natural ventilated model, Model A.2, is unaffected by morning aeration. Further, the demand for heating power in this model is close to negligible at the second-floor Meeting Room, the third-floor Workplace 1, and in the Learning Room placed at the top floor. This may be an indicator of two things. One, that the CO_2 level doesn't exceed a level causing the P-controller to open the motorized windows in the mentioned zones. Hence, the natural ventilation of the surrounding rooms and the opening of the manually controlled windows are assumed substantial to ensure a satisfactory CO_2 level in the rooms. Or two, that when the windows open, air only flows out of the building. The only exception of this assumption is the second-floor Meeting Room with no external openings or possibilities of natural ventilation.

A general notion of the graphs presented in Fig. 6.7 is the low energy demand resulting from the hybrid model A.1+B.2. This hybrid model is implemented with a P-controller with a range of 600 to 1000 ppm managing the opening rate of windows and the mechanical ventilation system. This hybrid model causes a low heating power demand in the second, third and fourth-floor zones. This may be an indication of a resulting low CO_2 level while no excessive natural or mechanical ventilation occurs. However, Fig. 6.7 shows that the mechanical ventilation system of Model B.2 is an energy efficient solution as well, especially when considering the first-floor Cafeteria.

Table 6.2 presents the corresponding required heat energy needed to heat the ambient air entering the building in the four chosen zones over the entire work week. The energy demand is at a low level at each of the strictly mechanical ventilated models, due to the high heat recovery factor. This is especially visible on the first floor Cafeteria.

Table: 6.2 The total heat energy demand of air during the transition week in four chosen zones.

	A.2	A.2+morning aeration	B.1	B.2	A.1+B.2	A.2+B.2
Cafeteria heating demand [kWh]	149	143	26.67	26.35	163.50	282.19
Meeting room heating demand [kWh]	0	0	5.17	4.88	4.64	4.50
Workplace 1 heating demand [kWh]	0.71	4.69	11.31	8.59	8.33	8.91
Learning room heating demand [kWh]	0	0	14.73	13.76	10.40	9.91

6.2.2 Required fan power

The demanded fan power is calculated based on an SFP factor of 1 $\frac{kW}{m^3/s}$ and as described in Chapter 4.6. The fans will only require power in the hybrid and the mechanical ventilated models. Hence, only these building models are evaluated according to fan power.

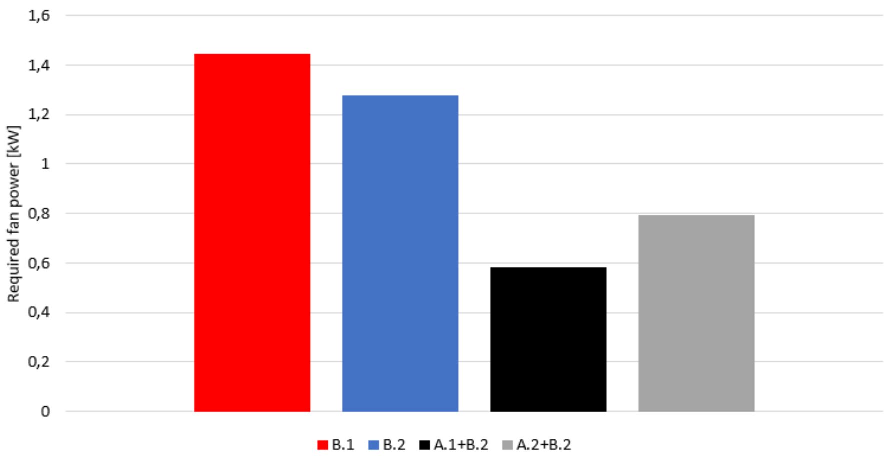


Fig.: 6.8 Power required to run the fans during the transition week.

Fig. 6.8 shows that the model with the lowest required amount of fan power is the hybrid model, Model A.1+B.2. This is somewhat expected. Model A.1+B.2 is implemented with P-controllers managing the opening of the motorized controlled windows and the mechanical ventilation system within the range of 600 to 1000 ppm. While the other models are strictly mechanical or controlled according to schedule, causing a larger amount of mechanical ventilated air. Model A.1+B.2 is the model evaluated with the lowest supply of mechanical ventilated air and the lowest demand for fan power.

When comparing the two strictly mechanical ventilated buildings, Model B.2 has the lowest requirement of fan power. This is due to the implemented P-controller and the resulting air supply rate. Combined with the resulting heating power demand presented in Fig. 6.6 and 6.7 it's assumed that the lowest energy consumption may occur in Model B.2.

6.2.3 Air change rates

Due to the low energy consumption of Model B.2, the resulting indoor environment of this model will be evaluated and compared to the results of the clean natural building model, Model A.2. The air change rate of the two models is presented in Fig. 6.9. The resulting air change rate of Model A.2 is represented by the solid line, while the results of Model B.2 are presented as dotted lines. The resulting air change rate of all the possible building models is shown in Appendix H. The limits corresponding to the *Required air change rate with maximum occupancy* and *Required air change rate when unoccupied* are calculated according to the procedure described in Appendix C.

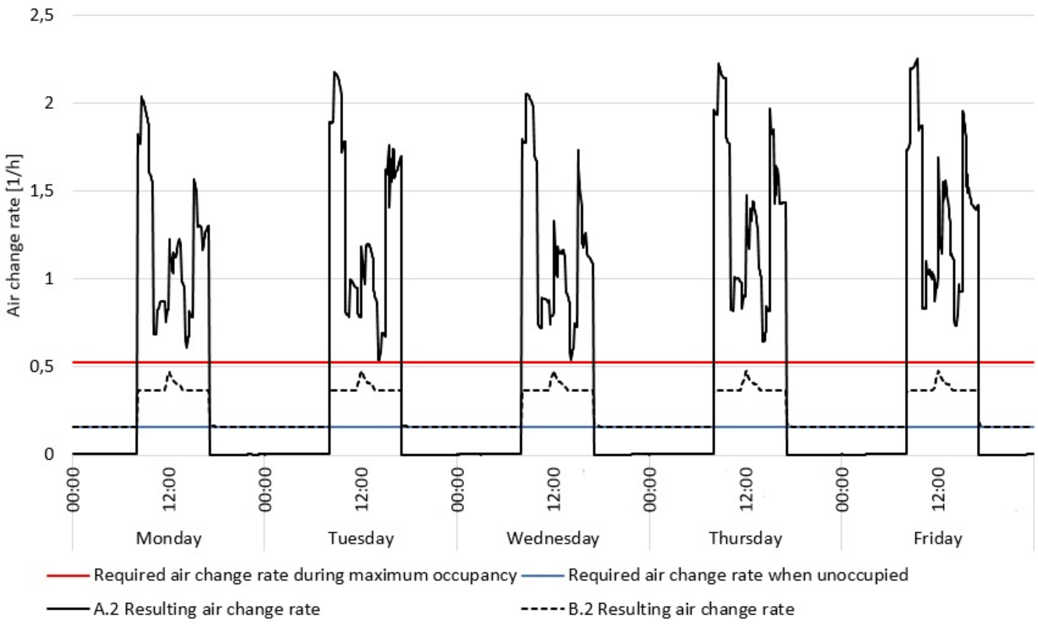
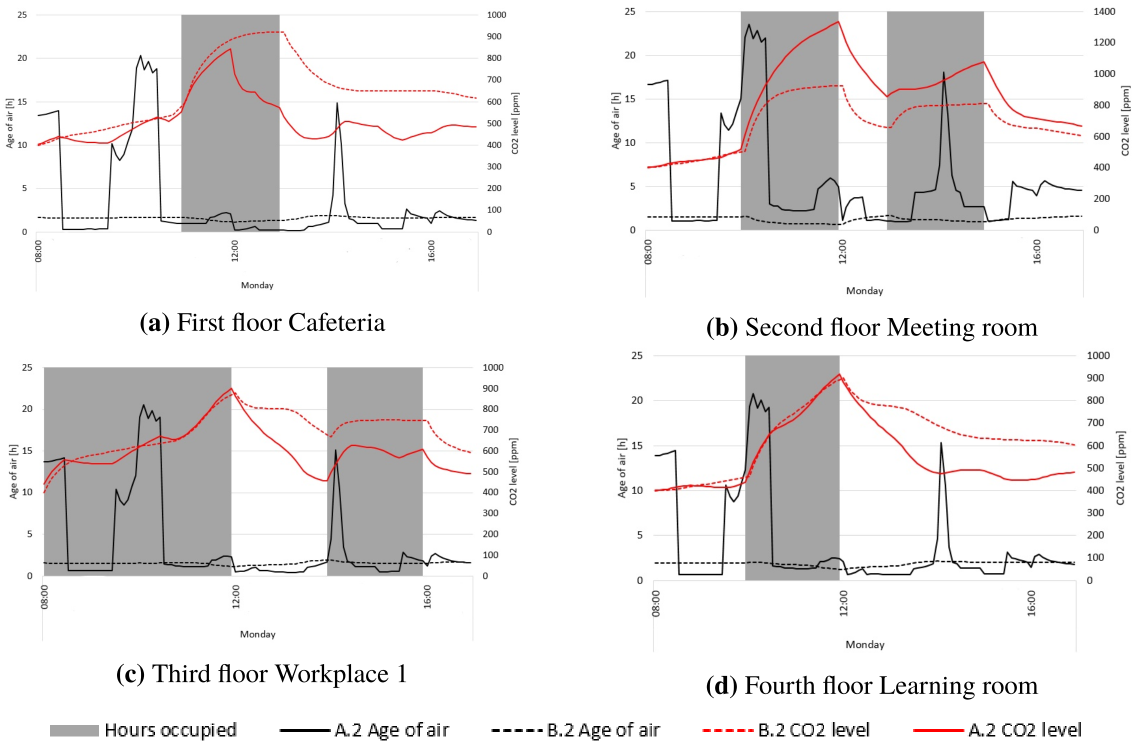


Fig.: 6.9 The resulting air change rate for model A.2 and B.2 during the transition week.

The air change rate of Model B.2 leads a small deviation from the required air change rate during maximum occupancy, as presented in Fig. 6.9. The ventilation in Model B.2 could be compensated with some natural ventilation during the occupied hours to achieve a satisfactory air change rate. Model A.2 surpasses the required air change rate with 1.73 air changes per hour at its maximum. Hence, the large ventilation rate caused by natural forces in Model A.1 can be superfluous, and lead to an unnecessary high demand of heating power.

6.2.4 Age of air vs. CO_2 level

Fig. 6.10 presents the age of air versus the CO_2 level of the four chosen zones for Model A.2, the solid lines, and Model B.2, the dotted lines, over one work day. The grey areas represent the occupied hours of the given zone.



(a) First floor Cafeteria

(b) Second floor Meeting room

(c) Third floor Workplace 1

(d) Fourth floor Learning room

Fig.: 6.10 The resulting age of air vs. CO_2 levels from simulations with Model A.2 and B.2 during the transition week.

Fig. 6.10 shows that both age of air and CO_2 are maintained at a satisfactory level when the mechanical ventilation system of Model B.2 is implemented. The age of air is constantly close to 2 hours, while the CO_2 level never exceeds 1000 ppm.

The level of CO_2 in three of the zones is kept at a level below 1000 ppm when only natural ventilation is used. The only exception is the second-floor Meeting Room with a maximum CO_2 level of 1300 ppm. This is an indication of how a clean natural ventilation system can maintain a satisfactory indoor environment in zones with external openings. Large variations are occurring in the age of air for Model A.2, as presented in Fig. 6.10, with a range from 1.5 up to 25 hours. These variations may be caused by the opening and closing of the manually controlled windows, external wind, and internal pressure changes. The age of air in one zone is affected by the air age in the surrounding zones when internal air flows occur. Therefore, the rapid changes in the age of air may be caused by higher aged air from the surrounding zones.

6.3 Case 3: Summer week

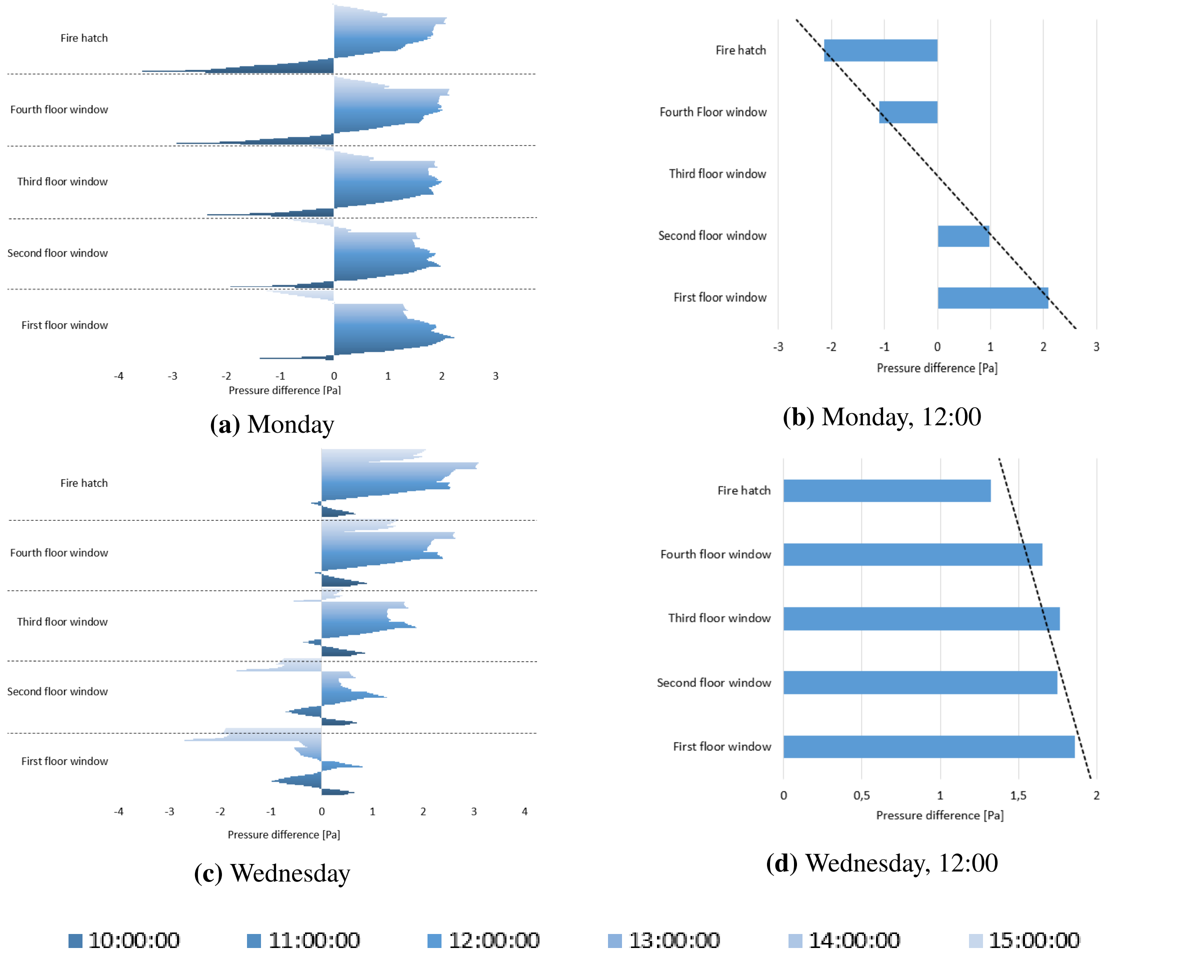
Model A.1 is implemented only with a natural ventilation system. The ventilation system is managed by a P-controller, with range from 600 to 1000 ppm. Further, the manually controlled windows are assumed to be open 20% over a time period of one hour every other hour. Due to a small difference in ambient and internal building temperature during extended periods of the summer, simulation results concerning only Model A.1 will be presented. A close to equal ambient and internal temperature leads to a small demand of heating power. Therefore, no results concerning power or energy demand will be presented. However, a clean natural ventilation system must be able to supply each floor of the building with fresh air. The resulting supply of ambient air, pressure profiles, and the indoor environment are important results.

Appendix I presents several simulation results of the summer week. An important find is that natural ventilation will lead to close to satisfactory levels of CO_2 in ZEB Laboratory during the entire summer week.

6.3.1 Pressure profiles and corresponding air flows

The pressure difference over a facade is as previously described a suitable method to predict air flows through the external openings. A negative pressure difference causes an outflow of air from the building to the ambient surroundings, while a positive pressure difference leads to an inflow of ambient air. If the internal and external pressure is equal, a neutral level occurs. No air flows in or out of the building. Pressure differences over a facade can be presented as a pressure profile.

Fig. 6.11 presents the resulting pressure difference over five openings at the east facade of ZEB Laboratory during the summer week. The pressure differences are simulation results from the time period between 10:00 and 15:00. Each of the evaluated openings are placed at different heights. It's important to note that Fig. 6.11 (a) and (c) are three dimensional, with the pressure differences along the horizontal axis, and both time and elevation along the vertical axis. Hence, for a window at a given elevation the varying pressure difference over time is presented along the vertical axis. Fig. 6.11 (b) and (d) represents the resulting pressure profile at midday.



(a) Monday **(b)** Monday, 12:00 **(c)** Wednesday **(d)** Wednesday, 12:00

Fig.: 6.11 Resulting pressure differences over openings at the east facade of Model A.1 during Monday and Wednesday in the summer week. The horizontal axis describes the pressure difference, while the elevation of the openings are shown on the vertical axis. The color of the graph indicates the time.

As presented in the graphs in Fig. 6.11 both negative and positive pressure differences will occur over each opening during the work week. At noon on Monday, a neutral level will occur in the window on the third floor. At this given time the ambient surroundings have a temperature of 14.1 °C, with wind at 0.9 $\frac{m}{s}$ from north. During the time period from 11:00 to 15:00 on Wednesday the ambient air temperature is at a higher level than the internal temperature. A positive pressure difference will occur, with some deviations due to wind. The resulting air flows on Monday and Wednesday are presented in Fig. 6.12. Note that the second, third and fourth windows are opened according to the window schedule as in Appendix C.

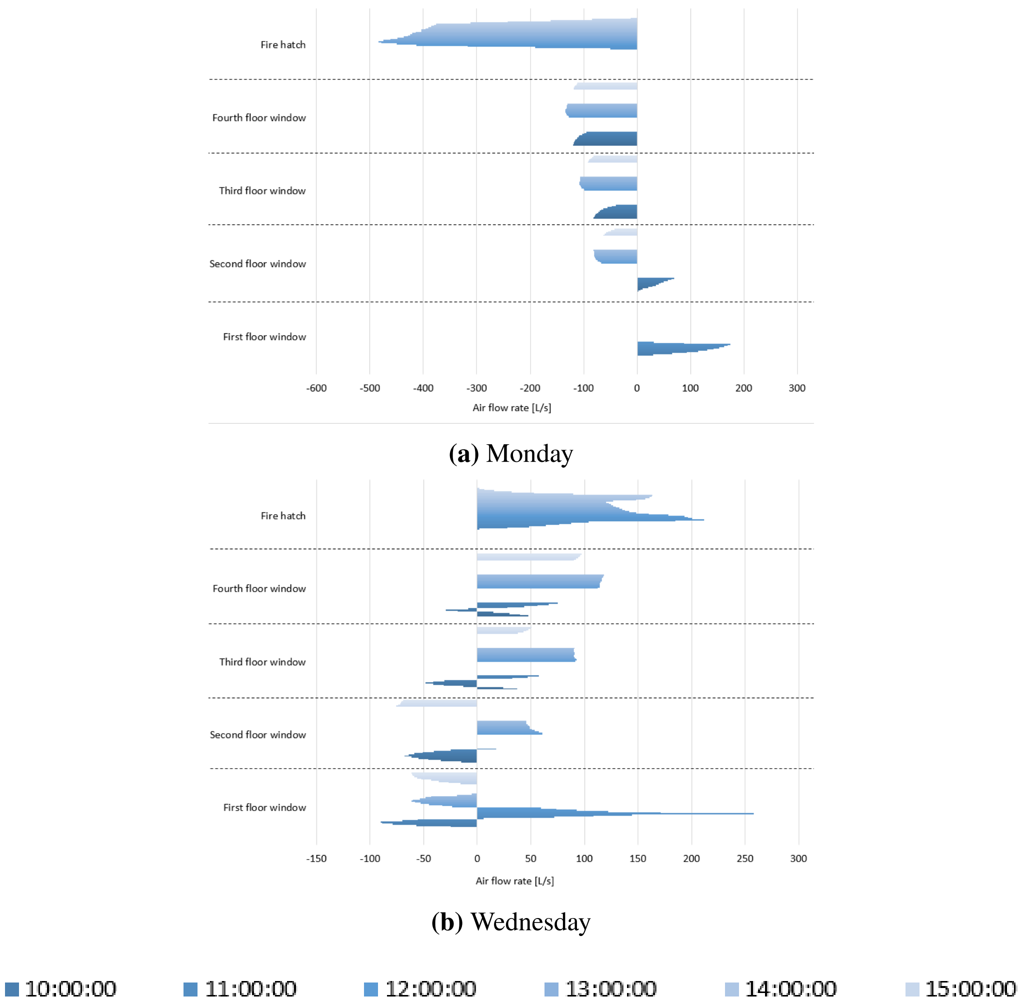


Fig.: 6.12 Resulting air flows through openings at the east facade of Model A.1 during Monday and Wednesday in the summer week. The horizontal axis describes the air flow rate, while the elevation of the openings are shown on the vertical axis. The color of the graph indicates the time.

By comparing the graphs in Fig. 6.11 and 6.12 it's clear that the resulting pressure profiles and air flows are coherent. Ambient temperature below the building temperature causes an inflow of air to the lower floors, while air exits on higher floors. A neutral level is located at the mid-height of the building at noon Monday. Therefore, good circulation of air will occur. However, when the external temperatures are higher than the internal temperatures, the direction of air flow will change. The upper floors of the building will be supplied with a net air amount larger than the lower floors, as presented during Wednesday. On noon Wednesday the neutral level is located below the elevation of the first-floor window. Hence, all of the floors will be supplied with ambient air.

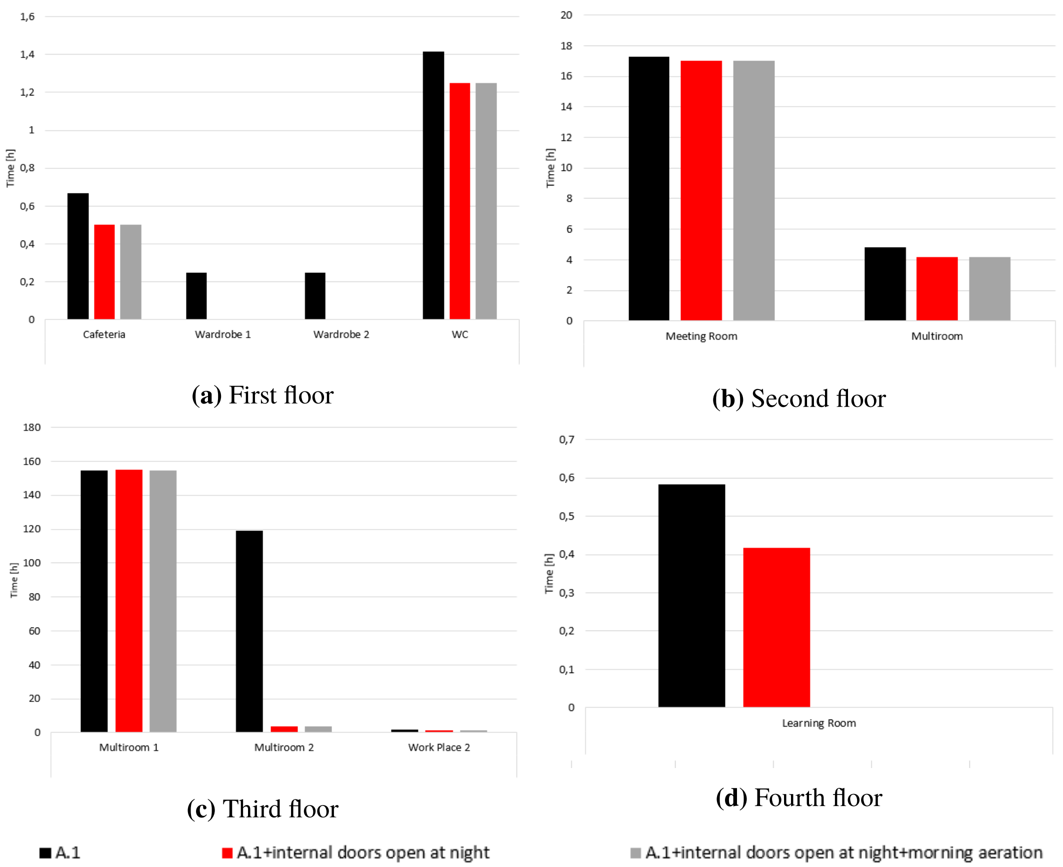
The possible high ambient air temperatures may cause absence of the neutral levels. The risk of the unsatisfactory amount of circulating fresh air occurs. However, the ambient temperature levels outside the work hours are usually at a lower level than the internal temperature. The possibility of passive cooling and good air change rates is present. Further, measures to elevate the neutral level should be considered.

A possibility is to create larger openings on the first floor by somewhat opening the external doors. The resulting pressure profiles and rates of air flow supply occurring during the rest of the work week can be seen in Appendix I.

6.3.2 Atmospherically environment

A risk occurring when implementing a building with clean natural ventilation is, as previously discussed, a low CO_2 removal rate and a poor air change rate. This due to variable conditions of the ambient surroundings. The natural ventilated model, Model A.1, is corrected to evaluate possibilities to improve the indoor environment. First, the model is simulated with the internal doors open during the entire night. This to avoid any collection of CO_2 in the zones. Second, the model is assigned a scheduled opening of the motorized windows ensuring passive cooling of the building before the occupied hours.

A graphical presentation of the time period CO_2 levels exceed 900 ppm in a zone is presented in Fig. 6.13. It's important to take notice that the graphs in Fig. 6.13 don't describe the resulting CO_2 level, only that it's is above 900 ppm. This information can be obtained in Appendix I.

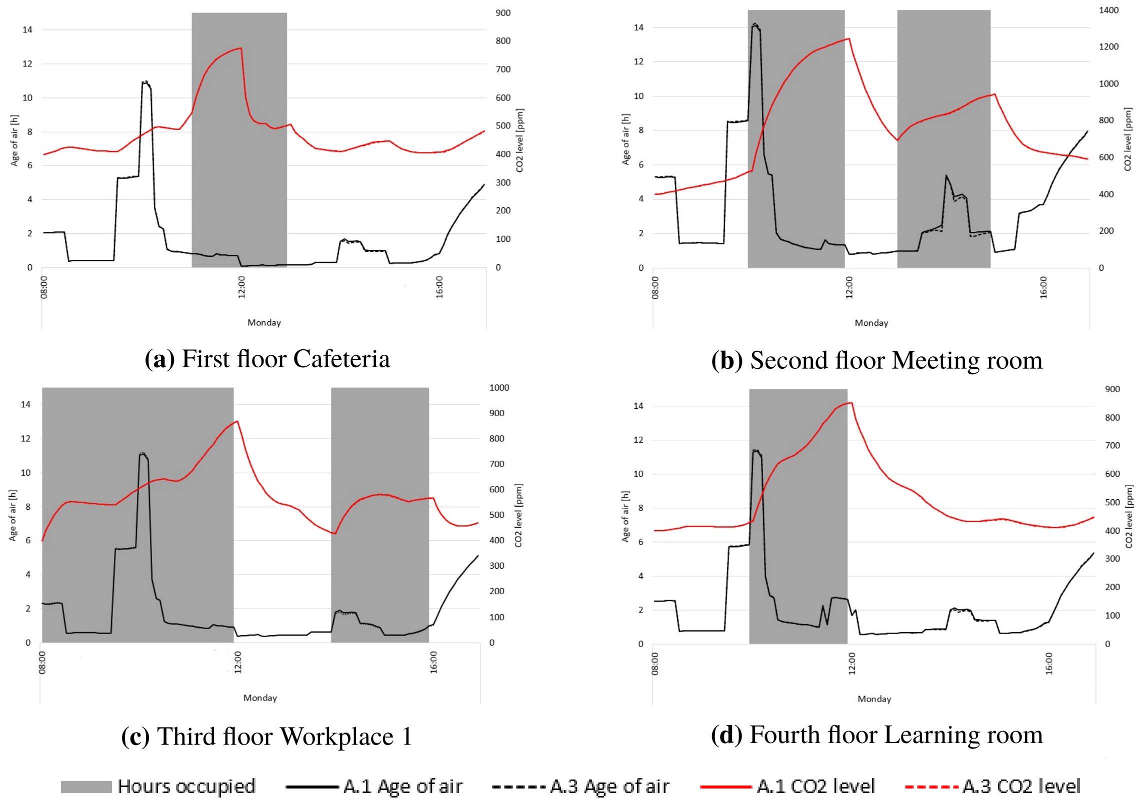


(a) First floor **(b)** Second floor **(c)** Third floor **(d)** Fourth floor

Fig.: 6.13 The time period a zone maintains a CO_2 level above 900 ppm during the summer week.

According to Fig. 6.13 the CO_2 level exceeds 900 ppm at the least amount of time in Model A.1, with night open doors and morning aeration, from now on referred to as Model A.3. It's clear that the implementation of opening the internal doors during unoccupied hours will successfully avoid a collection of CO_2. Note that the major time period the CO_2 level is above 900 ppm in the third floor Multiroom 1 is probably caused by an absence of internal air flows due to no temperature differences compared to the surrounding zones.

To further compare the natural ventilated model, Model A.1 and Model A.3, an evaluation of the resulting age of air and CO_2 levels have been performed. This analysis of the four zones is presented in Fig. 6.14. The black lines represent the age of air, while the red lines represent the CO_2 level. The grey area represents the occupied hours.



(a) First floor Cafeteria

(b) Second floor Meeting room

(c) Third floor Workplace 1

(d) Fourth floor Learning room

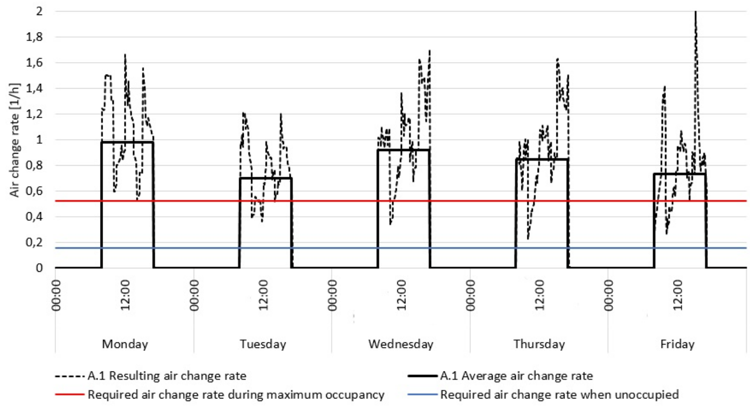
Fig.: 6.14 The resulting age of air vs. CO_2 levels from simulations of Model A.1 and A.3 at Monday during the summer week.

By analyzing the graphs presented in Fig. 6.14 it's clear that the resulting age of air and CO_2 levels of Model A.1 and A.3 are close to equal for all the chosen zones. Hence, an introduction of morning aeration and open internal doors outside working hours won't affect the age of air and CO_2 level during the working hours. The age of air undergoes some rapid changes during the occupied hours. These changes may be caused by pressure changes inside the building resulting from the manually open and closing of windows. The resulting CO_2 levels of the evaluated zones are in a satisfactory range in the first, third and fourth floor, while somewhat high in the second-floor Meeting Room.

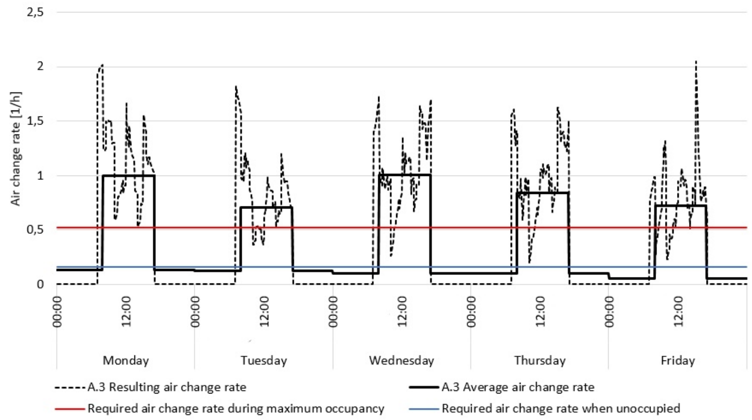
The age of air and CO_2 levels occurring during Wednesday are presented in Appendix I. An interesting discovery is that the resulting age of air and CO_2 levels are somewhat unchanged from Monday to Wednesday, despite the change in the direction of natural ventilated air flows. Natural ventilation causes a satisfactory atmospheric environment independent of the ambient temperature.

6.3.3 Air change rate

The air change rate, the dotted line, and the average air change rate, the solid line, for Model A.1 and Model A.3 is presented in Fig. 6.15. The required air change rates when occupied and unoccupied are calculated according to the procedure in Appendix C.



(a) Model A.1



(b) Model A.3

Fig.: 6.15 The resulting air change rate of Model A.1 and Model A.3 during the summer week.

According to the graphs in Fig. 6.15 it's clear that the average air change rate when not occupied is closer to a satisfactory level when implementing morning aeration as in Model A.3. Hence, Model A.3 is a more indoor environmental friendly solution concerning the average air change rate. It's interesting to observe that the air change rate of the building is close to unaffected by the absence of a neutral level. Accordingly, a high ambient temperature may still induce a satisfactory indoor environment. However, the resulting air change rate is further caused by wind and different pressure profiles over the other facades of the building.

Chapter 7

Discussion

The discussion presented in the following chapter concerns the basis of this thesis, the chosen methods, and the simulation results regarding both energy demand and indoor climate.

This thesis is based on performed literature review considering the indoor environment in offices and education buildings, in addition to a carefully conducted review regarding the ventilation of buildings. The literature available regarding the indoor environment and traditional building ventilation is extensive and available from several conducted theses, studies, reports, and standards. Search engines such as Oria and Google Scholar have been proven to act as a good tool to find relevant information to supplement the review. However, the information regarding how suitable nZEB offices and education buildings are to the Norwegian climate has been difficult to find. This mostly due to the lack of such buildings in operation in similar climates. A nZEB office building that has been proven to be successful is 2226 in Austria. However, the difference in climate makes the results of similar buildings in Norway uncertain.

The simulations performed of the ZEB Laboratory building models, form the basis for the results and conclusion of this thesis, and are an important to discuss. A review of the available information regarding ZEB Laboratory has been a necessary measure to create a close to lifelike simulation model of ZEB Laboratory in the chosen simulation tool CONTAM. The structure of the simulated models are based on the architectural drawings of ZEB Laboratory, including building structure, zonal division, location, and control of internal and external openings. However, the lack of the possibility to create any non-perpendicular corners lead to some changes in the building structure. Further, a simplification of the size of the windows was performed leading to only implement the building with five different window sizes. This simplification was completed to relieve some of the workload, and because the final decision of the windows wasn't available. The occupant load of the building was estimated based on available information of the zones in ZEB Laboratory. The occupant load was assumed to vary during a work day, but the daily occupant load was assumed to be repeated throughout the work week. This is a simplification when the occupant load, which in reality, will change throughout the week.

CONTAM has been proven to be a user-friendly simulation tool regarding simple simulations of air flows occurring due to natural and mechanical forces. The structure of the demanded simulation process is simple to understand, and the CONTAM User Guide, supplied by the creator NIST (Dols & Polidoro 2015), is descriptive and complementary. However, the process of creating a multi-zone building with numerous external and internal pathways, different occupant loads, and several implemented schedules and controllers have been a time-consuming affair due to the demand of manual input of values and restrictions. Besides, the transient weather files, varying each hour over a week, had to be manually implemented in the simulation tool.

A large disadvantage of CONTAM is the absence of including heat transfer and resulting temperature changes in the model. Hence, no temperature changes will occur in the zones as a result of internal or solar heat gain, or air supply. Thus, the temperature difference between zones is constant, causing constant air flows with large velocity and volume. These preconditions may cause an unrealistic high demand for heating power during the simulations of natural and hybrid ventilation systems. This could have been taken account for in the model by either calculation or by using the other simulation tools to simulate the temperature changes. This was however not prioritized due to the time constraint while working with this thesis.

The simulations have been chosen to supply the resulting output values every five minutes to achieve exact and precise simulation results, leading to a major amount of data to analyze. This data has been manually collected, processed, and evaluated. Hence, human errors are a possible source of resulting deviations.

The manually controlled windows were assumed to be opened according to one schedule. This assumption was made based on the problems occurring with CONTAMs ability to calculate the air flows iterative when all or just some windows were open for a short time period. Hence, all of the manually controlled windows were opened the same amount, 20%, at the same time. This leads to a major increase in air change rate and supplied air causing a large demand of heating power, especially during the winter and transition week due to the large temperature differences. The controllers created to manage the motorized windows are all designed to act based on internal CO_2 levels. However, the controllers do not consider ambient conditions. The ambient conditions may be unsuitable for window opening, causing undesirable large air flows into the building. Consequently, the control systems should be designed to take the ambient air temperature, wind speed, and the wind approach angle into consideration.

The mechanical ventilation systems are based on previously described recommendations regarding air supply to a zone when unoccupied and with maximum occupancy. Hence, a required maximum supply of air will occur when occupants are present in a room. The mechanical ventilation system is modeled to be controlled according to a preset schedule or by a P-controller based on the CO_2 level in the given zone. When controlled by a schedule, the maximum amount of air supply is delivered, resulting in a recommended air change rate. However, when the mechanical ventilation system is controlled by a P-controller with a range from 600 to 1000 ppm, the recommendations regarding maximum air flows are rarely achieved. To achieve a recommended air change rate, the P-controller could be given a different range. The supply points are assumed to be placed in each occupied zone, with a varying elevation. The elevation of the supply points in the first and the fourth floor are assumed to be at floor level. While, the supply points in the second and third floor are assumed to be placed at ceiling level. This because of the predetermined air distribution of ZEB Laboratory. The simulations show that a change in the elevation of a supply duct doesn't affect the resulting indoor environment. However, the resulting thermal comfort and experience of draught are uncertain.

The heat recovery efficiency of the mechanical ventilation system was chosen to be at 85%. This is an excellent efficiency, leading to a small demand of additional heating power and may be somewhat unrealistic. Hence, the systems implemented with a mechanical ventilation system will have a low requirement of heating power. The energy calculations performed regarding energy heating demand and fan power are based on several simplifications. No internal heat gains are taken into account, leading to the large energy demand of heating natural ventilated air. Further, no resistance is implemented in the mechanical ductwork, causing a low energy demand for the fans. The demanded fan power is calculated according to a low SFP value and is based on the maximum mechanical induced air change of the building. Hence, the resulting power and energy demand are severe simplifications, which must be taken into consideration when analyzing the results.

No internal heat gains or resulting temperature changes are included in the simulations. This is a simplification of reality. The two main consequences of this simplification is a large energy demand for heating ambient air and large close to constant air flow into and out of the building. The large and close to constant air flows will lead to a larger supply of ambient air to the building and further a larger removal rate of pollution. In reality, the internal temperature will decrease when the cold ambient air is supplied, resulting in a smaller temperature difference and air flows.

The simulations performed shows that a satisfactory indoor environment is possible to achieve when utilizing clean natural ventilation during the entire year in terms of the resulting CO_2 level, air change rate and age of air. However, the simulations assume constant internal temperature and do not consider the risk of draught. This is important to take into consideration when analyzing the entire indoor environment of a building.

It's important to note that the simulation results don't describe the possible environmental impact of the models. A mechanical ventilation system will emit greenhouse gasses during the production, maintenance, decomposition, and transport of materials. Hence, a mechanical ventilation system will cause a larger amount of emission during some phases of its lifespan compared to a clean natural ventilation system.

Chapter 8

Conclusion

The required power and energy demand are major factors affecting the possible achievement of nZEB. Important demands are caused by heating and fan-induced movement of air. During periods with a low ambient temperature and a resulting large external and internal temperature difference, the demanded heating power is substantial compared to the demanded fan power. This is clearly shown from the simulations of the winter and transition week, both when the building is implemented with clean mechanical ventilation and when the building consists of a hybrid ventilation system. However, it's important to note that a clean natural ventilation system can ensure a good indoor environment throughout the entire year.

During the winter season, the most energy efficient solution is to implement the building with a clean mechanical ventilation system. Based on energy calculations the ventilation should be controlled by a P-controller with the range from 600 to 1000 ppm. This ventilation system will ensure a satisfactory indoor environment. The resulting air change rate will be close to the recommended level during the entire work week. The age of air will be at a suitable low level, and the resulting CO_2 level will never surpass 1000 ppm in the occupied zones. Hence, the clean mechanical ventilation system controlled within the range from 600 to 1000 ppm is a suitable solution for ZEB Laboratory during the winter season.

Due to lower temperature differences during the transition season, there will be a lower heating demand. The minimum heating demand of supplied air is achieved when implementing the building with a clean mechanical ventilation system controlled proportionally in the range of 600 to 1000 ppm. However, the lowest demand of fan power is achieved when the building is implemented with a hybrid ventilation system consisting of motorized windows and mechanical ventilated air both controlled by a P-controller with the range from 600 to 1000 ppm. Further, it's shown that the resulting indoor environment of ZEB Laboratory will be close to a satisfactory level when implemented with a clean natural ventilation system controlled by a P-controller with the range of 800 to 1100 ppm. Hence, a hybrid ventilation system is a satisfactory solution for ZEB Laboratory during the transition week.

During the summer season, ZEB Laboratory may experience a cooling demand. By installing the building with a clean natural ventilation system controlled by a P-controller with the range from 600 to 1000 ppm, in addition to a schedule ensuring morning aeration, the indoor environment of the building is within satisfactory conditions. The morning aeration causes passive cooling of the building mass before any occupants are present. The ventilation during the occupied hours will keep the CO_2 levels of all the zones close to a satisfactory amount, and the air change rate above recommended levels. However, measures to elevate neutral levels should be considered to ensure a satisfactory circulation of air.

CONTAM has been proven to be an excellent simulation tool regarding transient simulations of air flows through an occupied, multi-zone building due to natural and mechanical forces. The simulations include the resulting air change rate, age of air and CO_2 levels. However, the exclusion of heat transition affects the results greatly, especially regarding energy and power calculations.

Chapter 9

Further Work

To finally optimize the combination of natural and mechanical ventilation in ZEB Laboratory, concerning both indoor environment and energy demand, further simulations and calculations of ZEB Laboratory must be performed. This includes some further simulations of a corrected model in CONTAM. Correction regarding smaller opening ratios and frequencies of the manually controlled windows, a new design of the mechanical air supply, and generation of different pollutants should be introduced. Further, simulations with controllers considering the ambient temperature should be implemented, in addition to simulations of other hybrid ventilation systems. Such simulations will give the basis to consider the ventilation efficiency of natural ventilation, and the possibilities to lower the amount of mechanically supplied air.

Further, simulations of ZEB Laboratory should be performed with a simulation tool able to simulate heat transfer and the resulting internal temperature. The lack of heat transfer in this thesis may result in inaccurate conclusions. Internal heat gains and resulting heat transfer should be simulated. This is a necessary measure to achieve a lifelike overview of the resulting internal air temperature, and thus air flows and demanded heat and fan power due to ventilation. Such simulation results should be compared to recommended values regarding the indoor environment.

This thesis doesn't evaluate the emissions of greenhouse gasses produced during the production, decomposition, maintenance nor the transport of the ductwork associated with the mechanical ventilation system. This could be of interest when evaluating the total emissions from ZEB Laboratory.

ZEB Laboratory is, as previously discussed, a living lab, creating the possibility to change the ventilation strategy and measuring the resulting indoor environment and energy consumption. Hence, the different ventilation strategies presented in this thesis should be introduced to the building. The resulting heat power demand, fan power required, CO_2 levels, and satisfaction of the occupants should be evaluated.

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Appendix A

Floor plans

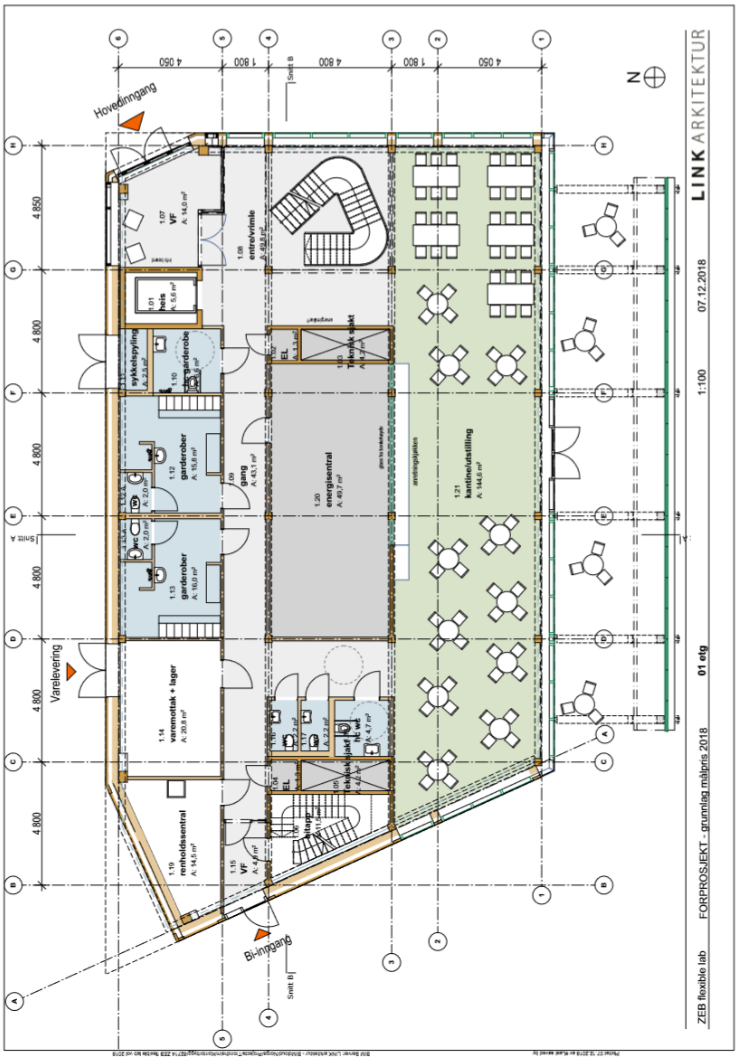


Fig.: A.1 Floor plan of the first floor of ZEB Laboratory.

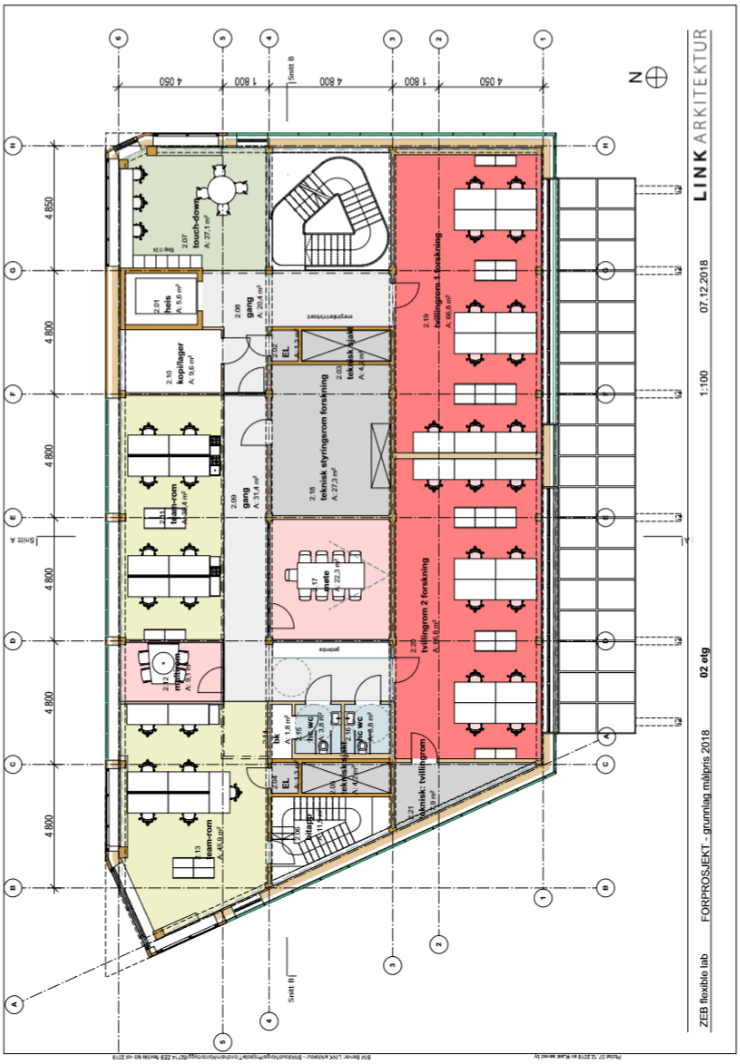


Fig.: A.2 Floor plan of the second floor of ZEB Laboratory.

Fig.: A.3 Floor plan of the third floor of ZEB Laboratory.

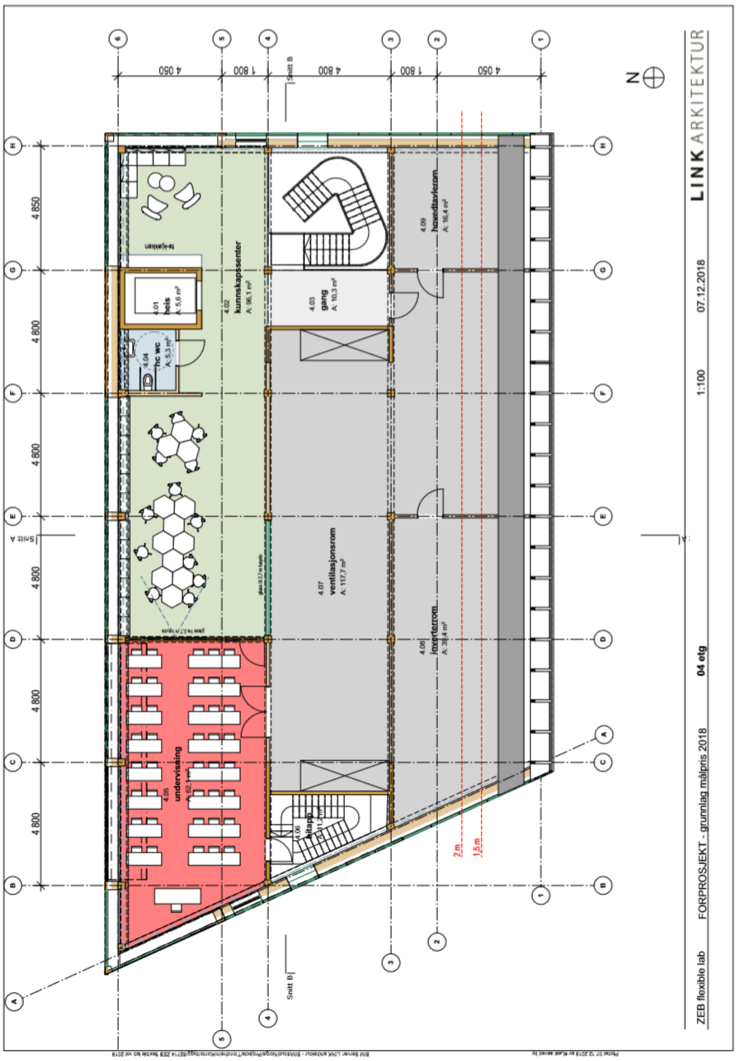


Fig.: A.4 Floor plan of the fourth floor of ZEB Laboratory.

Appendix B

Building facade

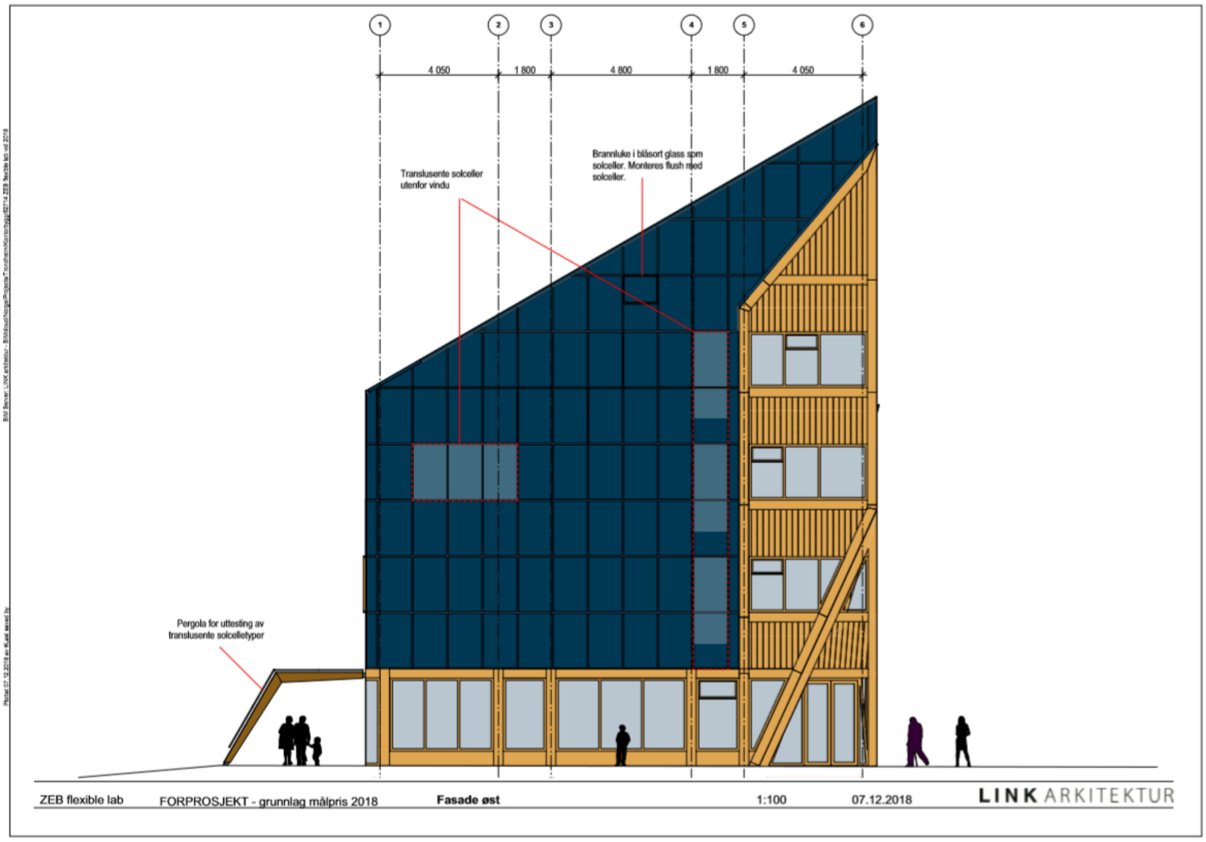


Fig.: B.1 East facade of ZEB Laboratory.

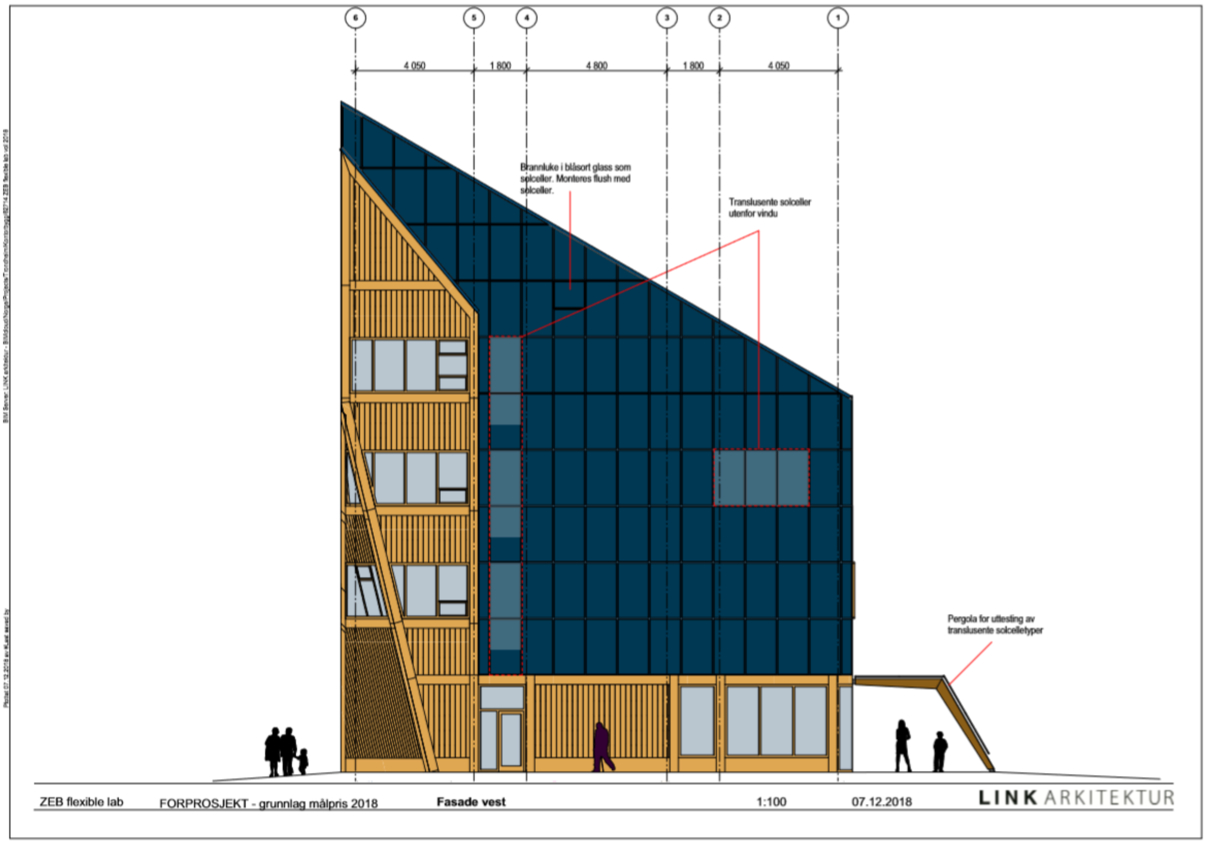


Fig.: B.2 West facade of ZEB Laboratory.

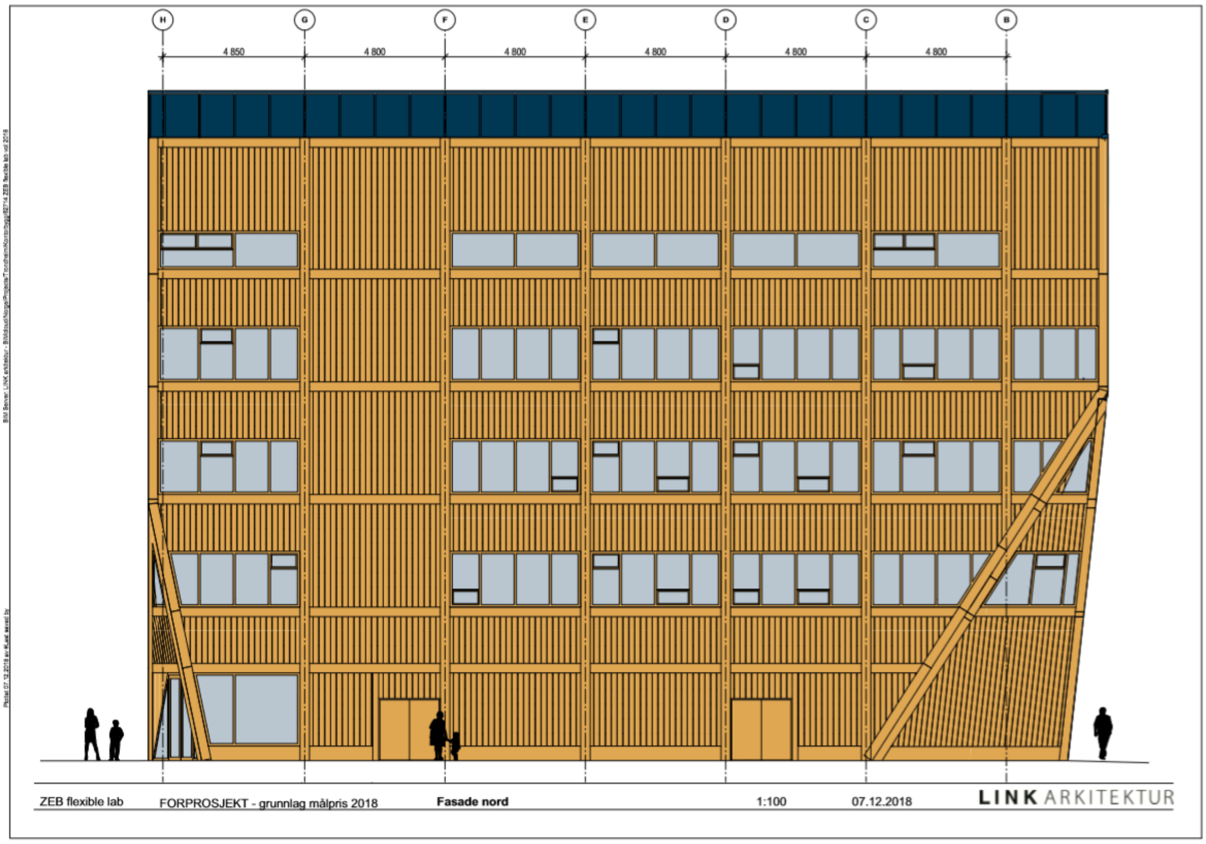


Fig.: B.3 North facade of ZEB Laboratory.

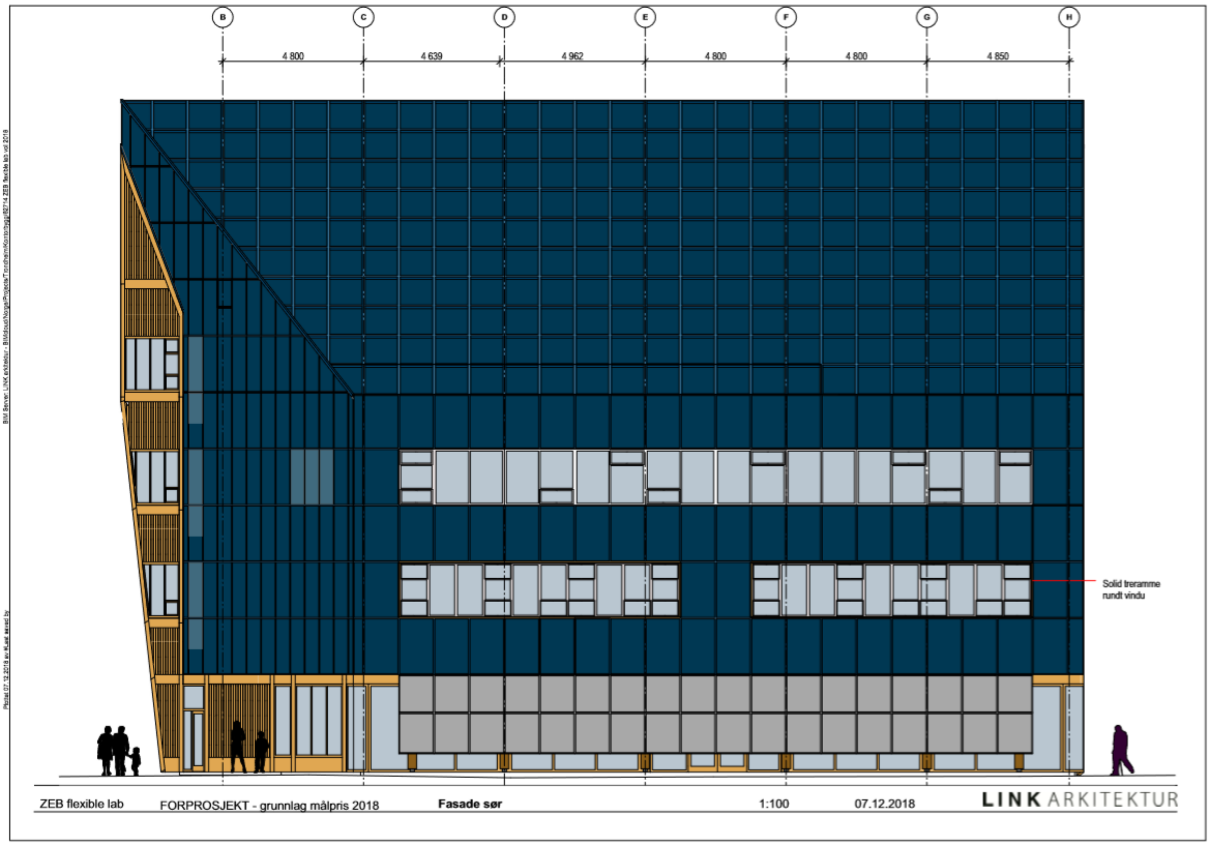


Fig.: B.4 South facade of ZEB Laboratory.

Appendix C

Calculation of air change rate

Table: C.1 Required air flows according to NS15251:2007.

Building category	**Air flow per person [$\frac{L}{s \cdot persons}$]**	**Air flow to very low emitting building [$\frac{L}{s \cdot m^2}$]**
II	7	0.35

Table: C.2 Required air change rate when unoccupied.

Limit value of required air change when unoccupied	
Air flow required per square meter [$\frac{L}{s \cdot m^2}$]	0.35
Air flow required per square meter [$\frac{m^3}{h \cdot m^2}$]	1.26
Air flow required when a building of 1213.4 m^2 is supplied [$\frac{m^3}{h}$]	1528.88
Resulting required air change of a 9600 m^3 building [$\frac{1}{h}$]	**0.159**

Table: C.3 Required air change rate when maximum occupied.

Limit value of required air change when occupied	
Air flow required per person [$\frac{L}{s \cdot persons}$]	7
Air flow required when a building of 1213.4 m^2 occupied by 140 persons [$\frac{L}{s}$]	1404.69
Air flow required when a building of 1213.4 m^2 occupied by 140 persons [$\frac{m^3}{h}$]	5056.88
Resulting required air change of a 9600 m^3 building [$\frac{1}{h}$]	**0.527**

Appendix D

Schedule for opening of windows and doors

Fig. D.1 presents the schedules opening of the manually controlled external entry doors, manually controlled windows and motorized windows for morning aeration.

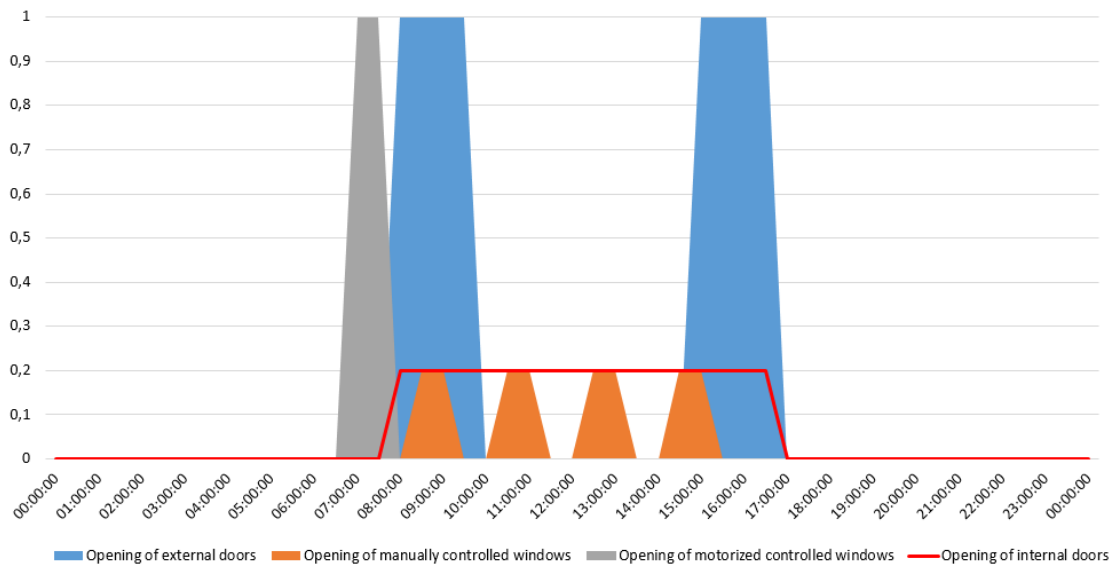


Fig.: D.1 Scheduled opening of manually controlled doors, windows and motorized windows for morning aeration.

Appendix E

P-controller with range from 600 to 1000 ppm

Fig. E.1, E.2 and E.3 presents the P-controllers with the range of 600 to 1000 ppm implemented in the basic building model managing both the mechanical ventilation system and the motorized controlled windows.

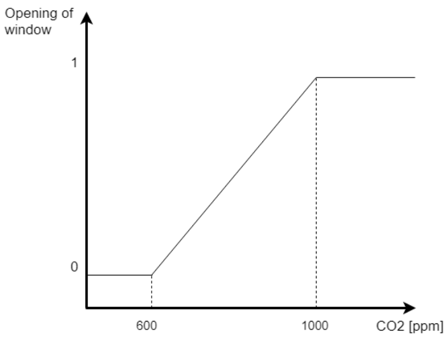


Fig.: E.1 Graphical presentation of P-controller with range from 600 to 1000 ppm.

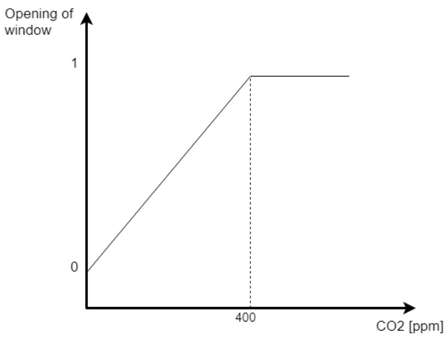


Fig.: E.2 Modified graphical presentation of P-controller with range from 600 to 1000 ppm.

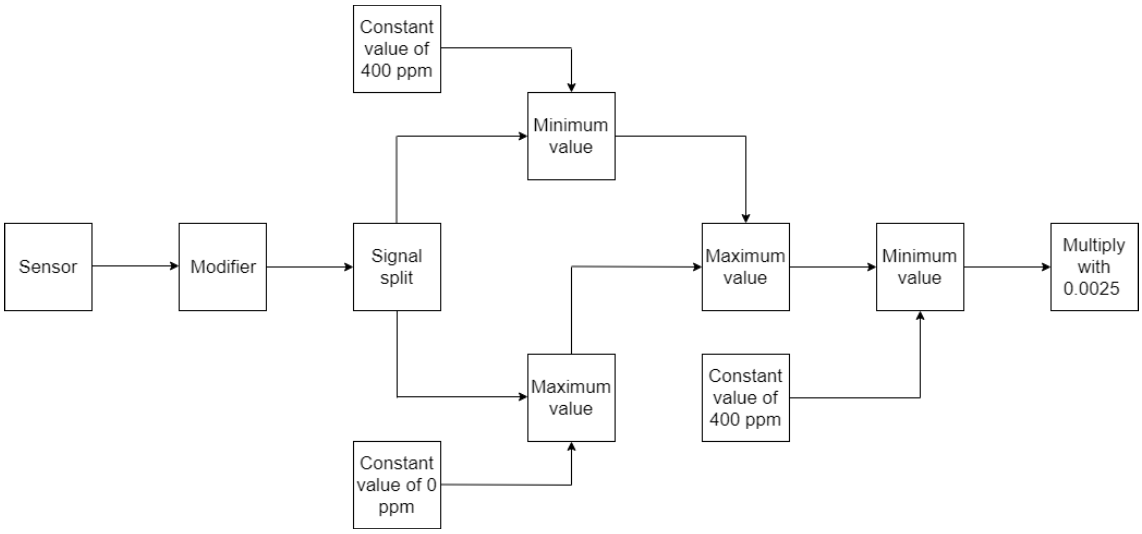


Fig.: E.3 Block diagram describing a P-controller with range from 600 to 1000 ppm.

Appendix F

P-controller with range from 800 to 1100 ppm

Fig. F.1, F.2 and F.3 presents the P-controllers with the range of 800 to 1100 ppm implemented in the basic building model managing both the mechanical ventilation system and the motorized controlled windows.

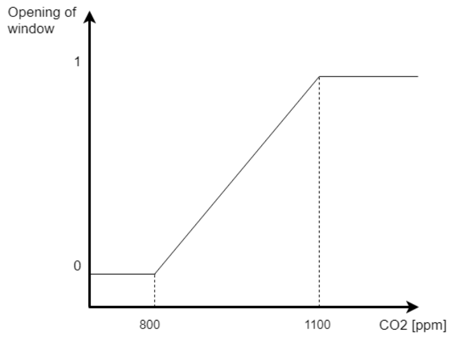


Fig.: F.1 Graphical presentation of P-controller with range from 800 to 1100 ppm.

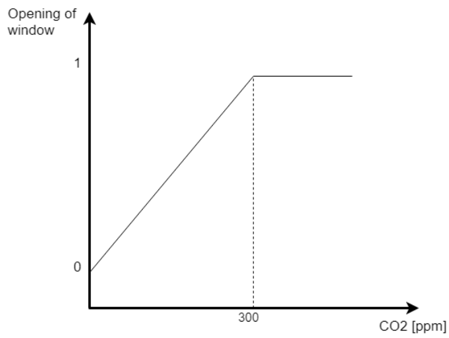


Fig.: F.2 Modified graphical presentation of P-controller with range from 800 to 1100 ppm.

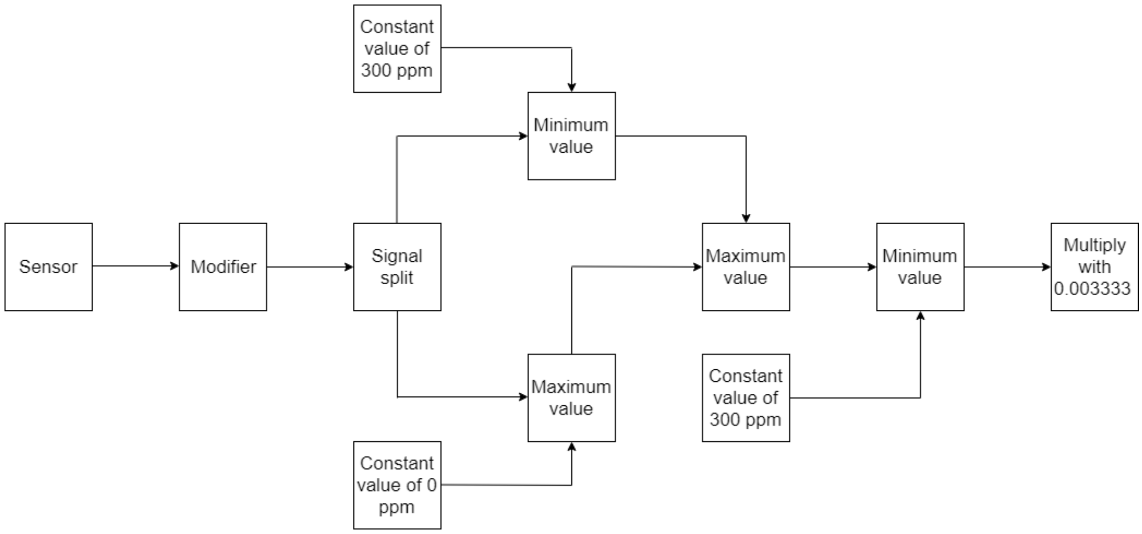


Fig.: F.3 Block diagram describing a P-controller with range from 800 to 1100 ppm.

Appendix G

Winter week results

G.1 Resulting air change rate from simulations

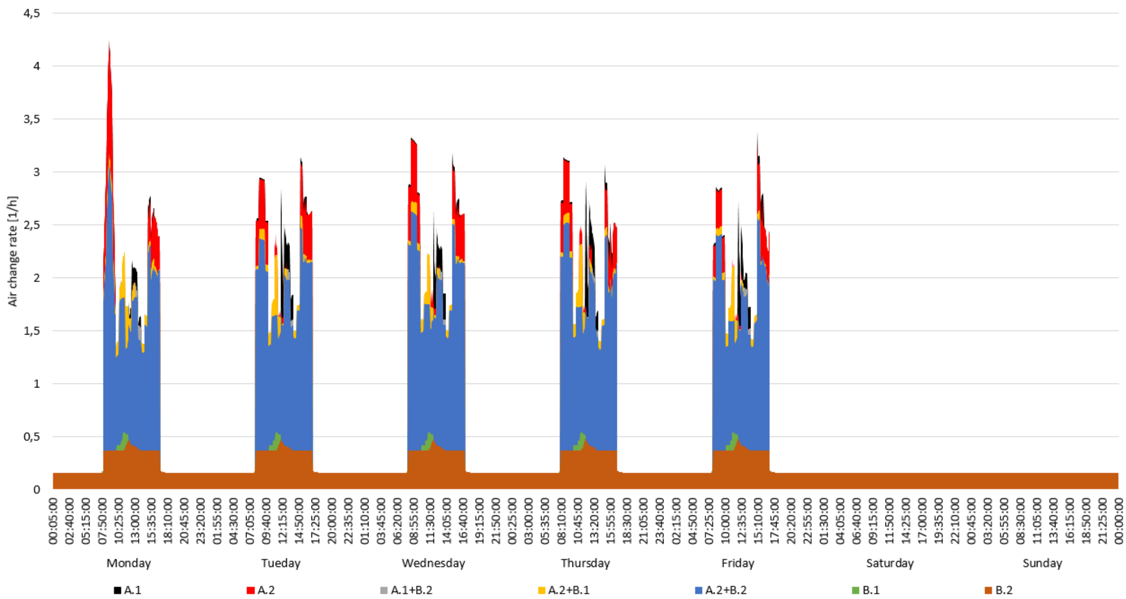
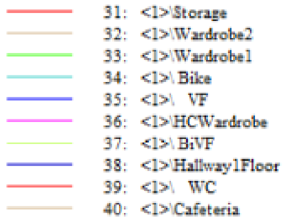
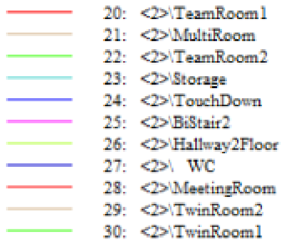


Fig.: G.1 The resulting air changes rates of different corrected building models simulated during the winter season.

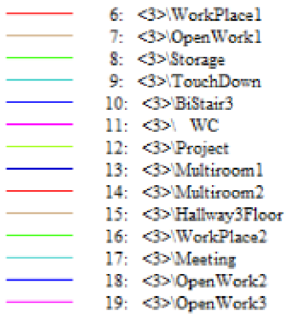
G.2 Resulting CO_2 levels from the simulations



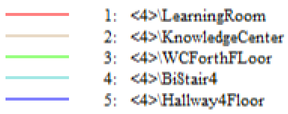
(a) First floor labels.



(b) Second floor labels.



(c) Third floor labels.



(d) Fourth floor labels.

Fig.: G.2 Labels describing the resulting CO_2 levels from the simulations.

Model A.1

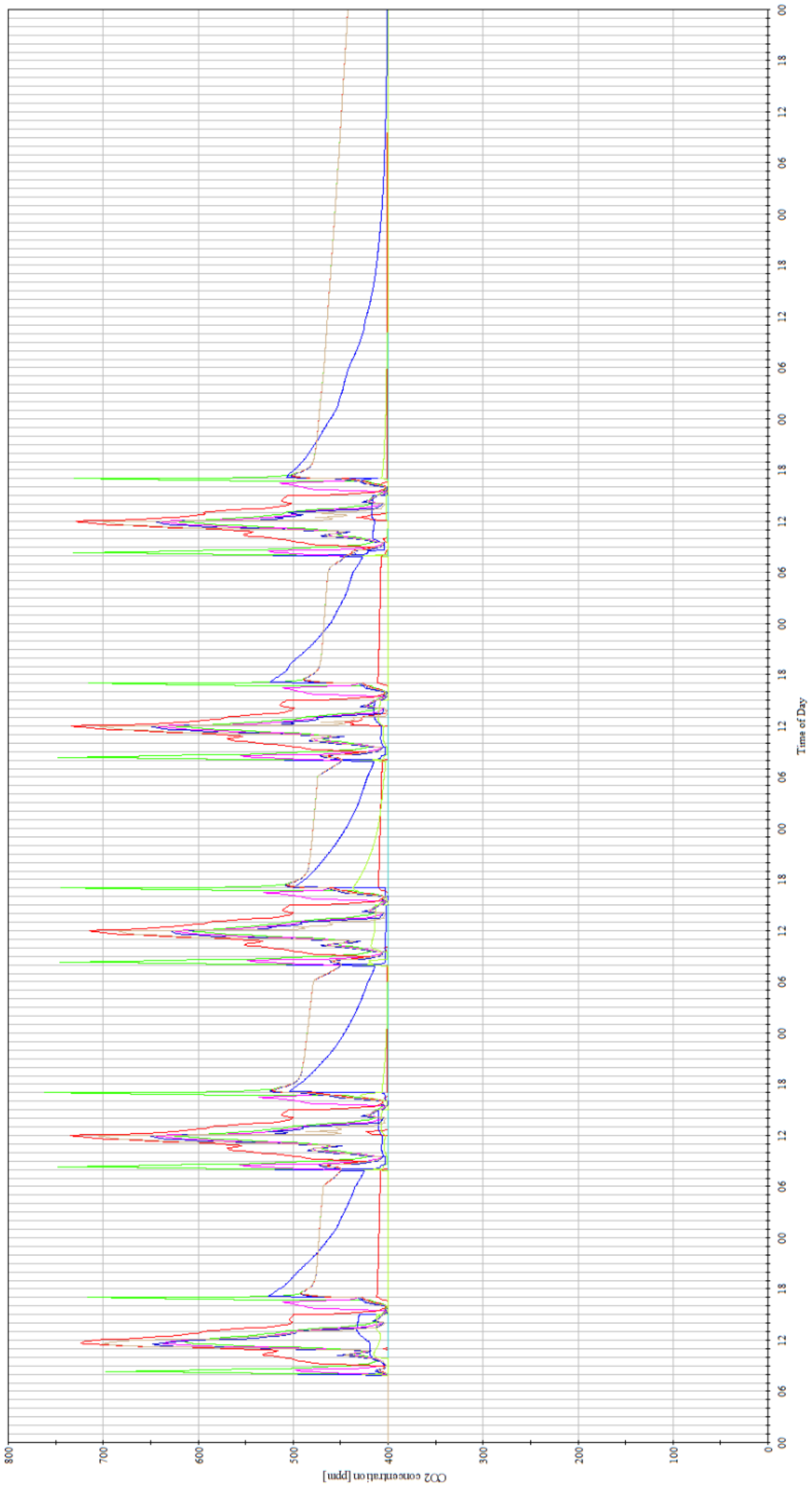


Fig.: G.3 Resulting CO_2 in the first floor when simulating building model A.1 during the winter.

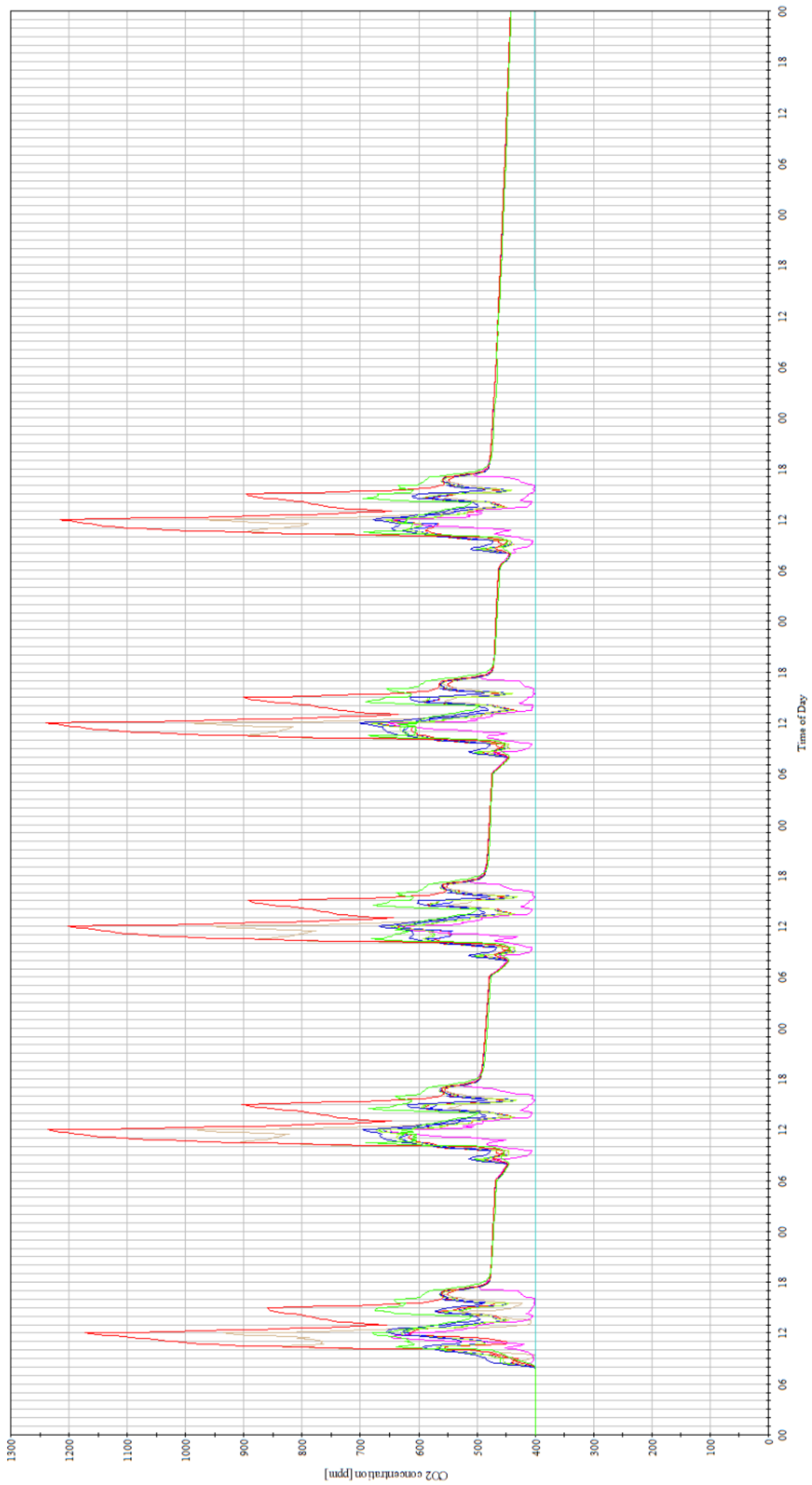


Fig.: G.4 Resulting CO_2 in the second floor when simulating building model A.1 during the winter.

Fig.: G.5 Resulting CO_2 in the third floor when simulating building model A.1 during the winter.

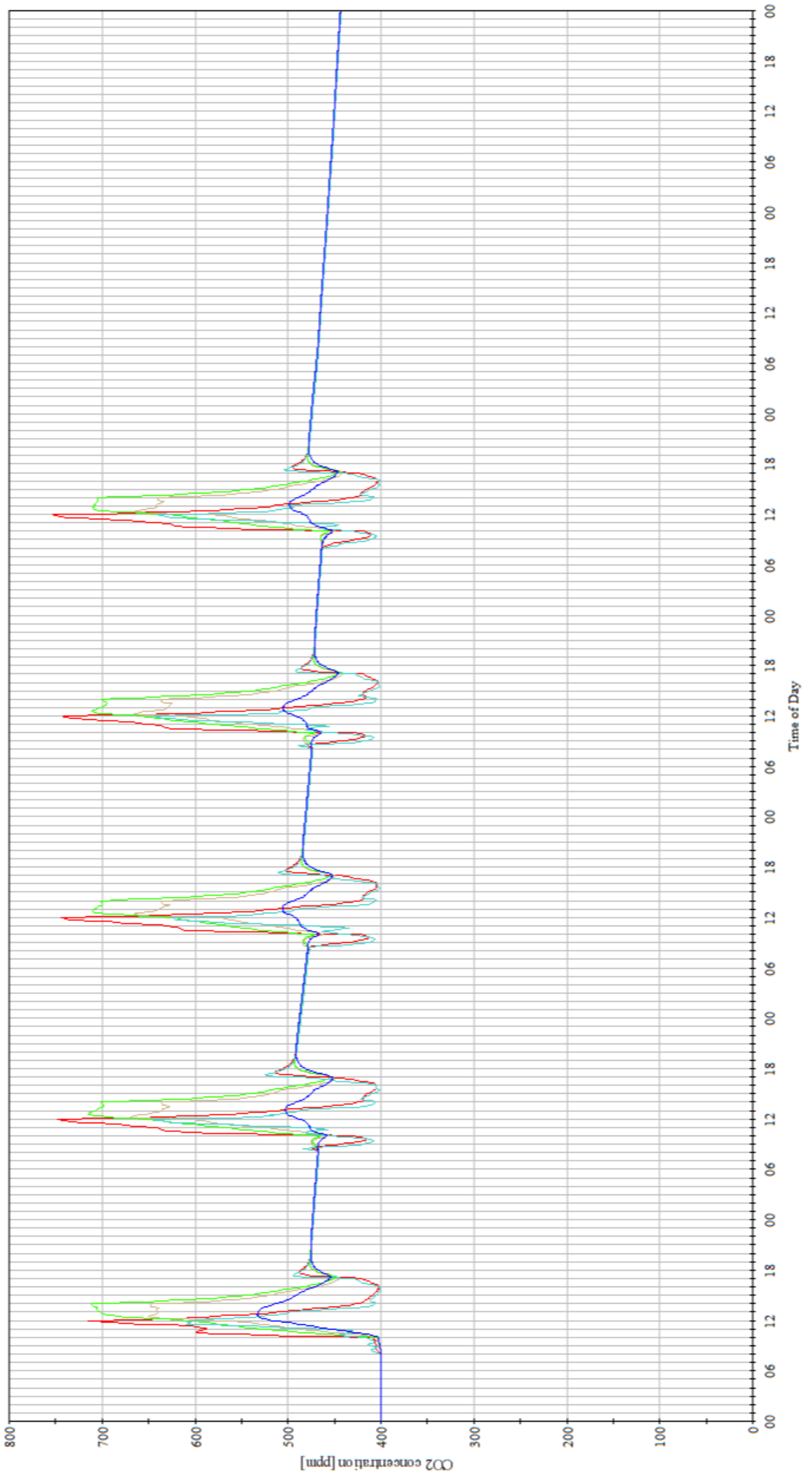


Fig.: G.6 Resulting CO_2 in the fourth floor when simulating building model A.1 during the winter.

Model A.2

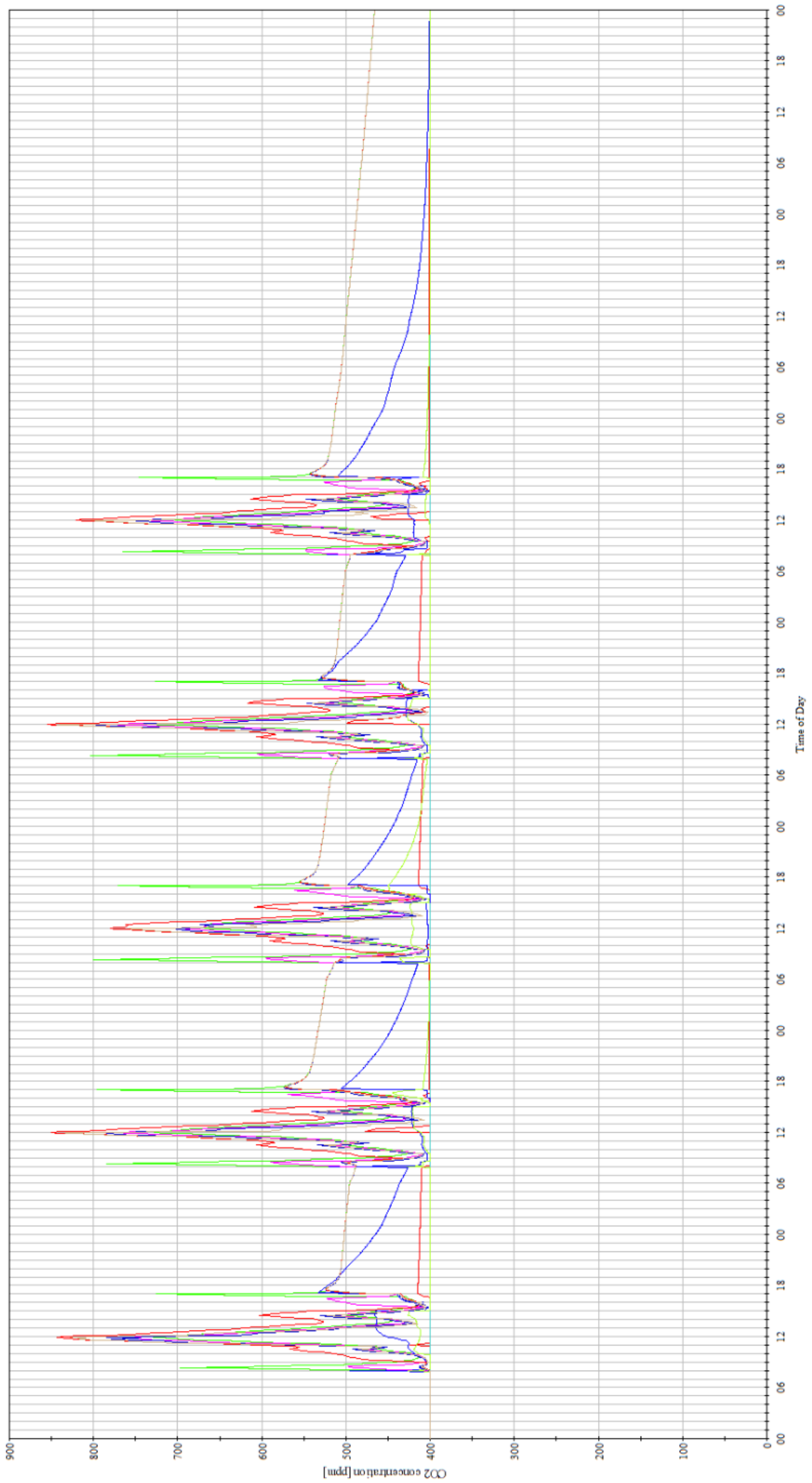


Fig.: G.7 Resulting CO_2 in the first floor when simulating building model A.2 during the winter.

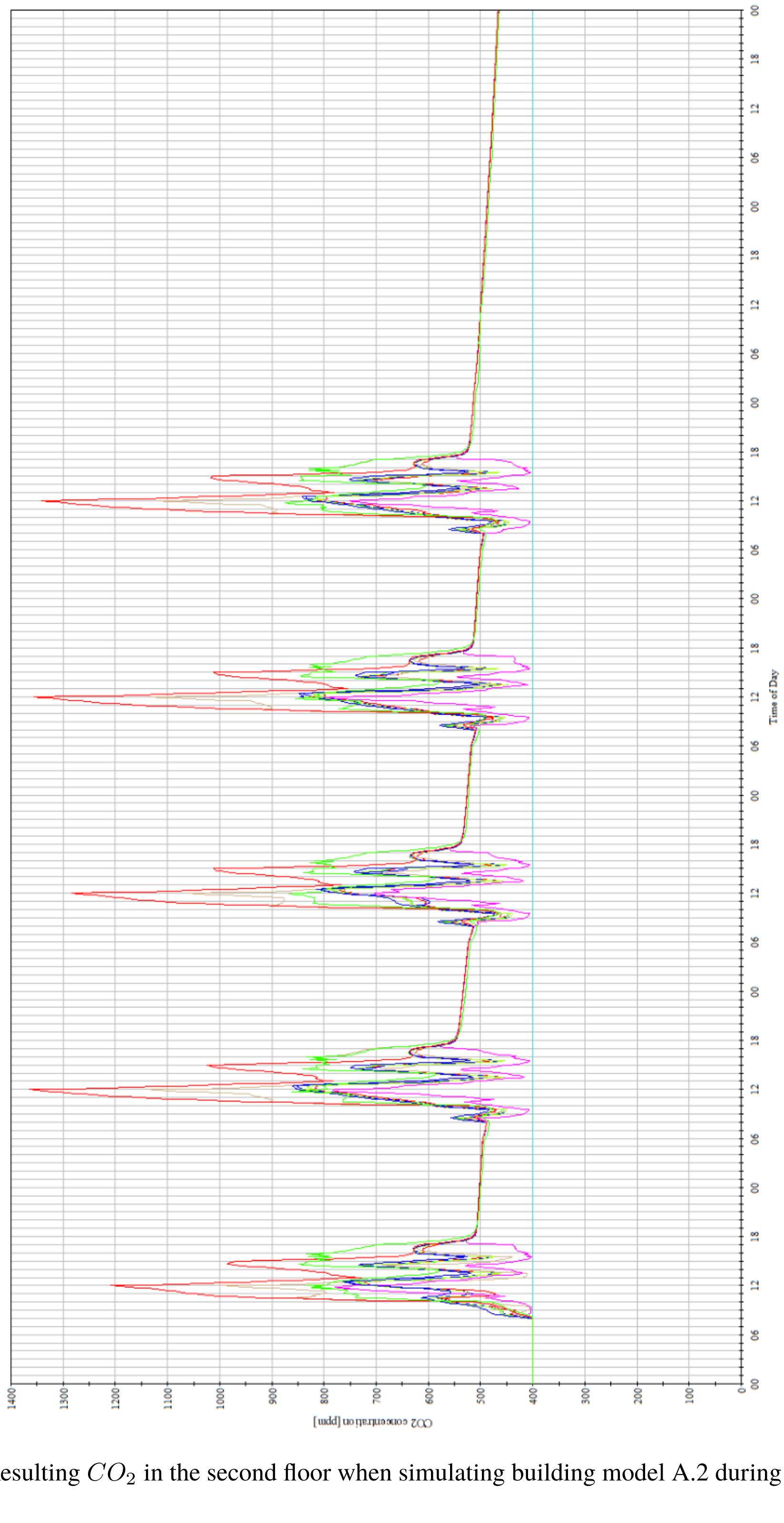


Fig.: G.8 Resulting CO_2 in the second floor when simulating building model A.2 during the winter.

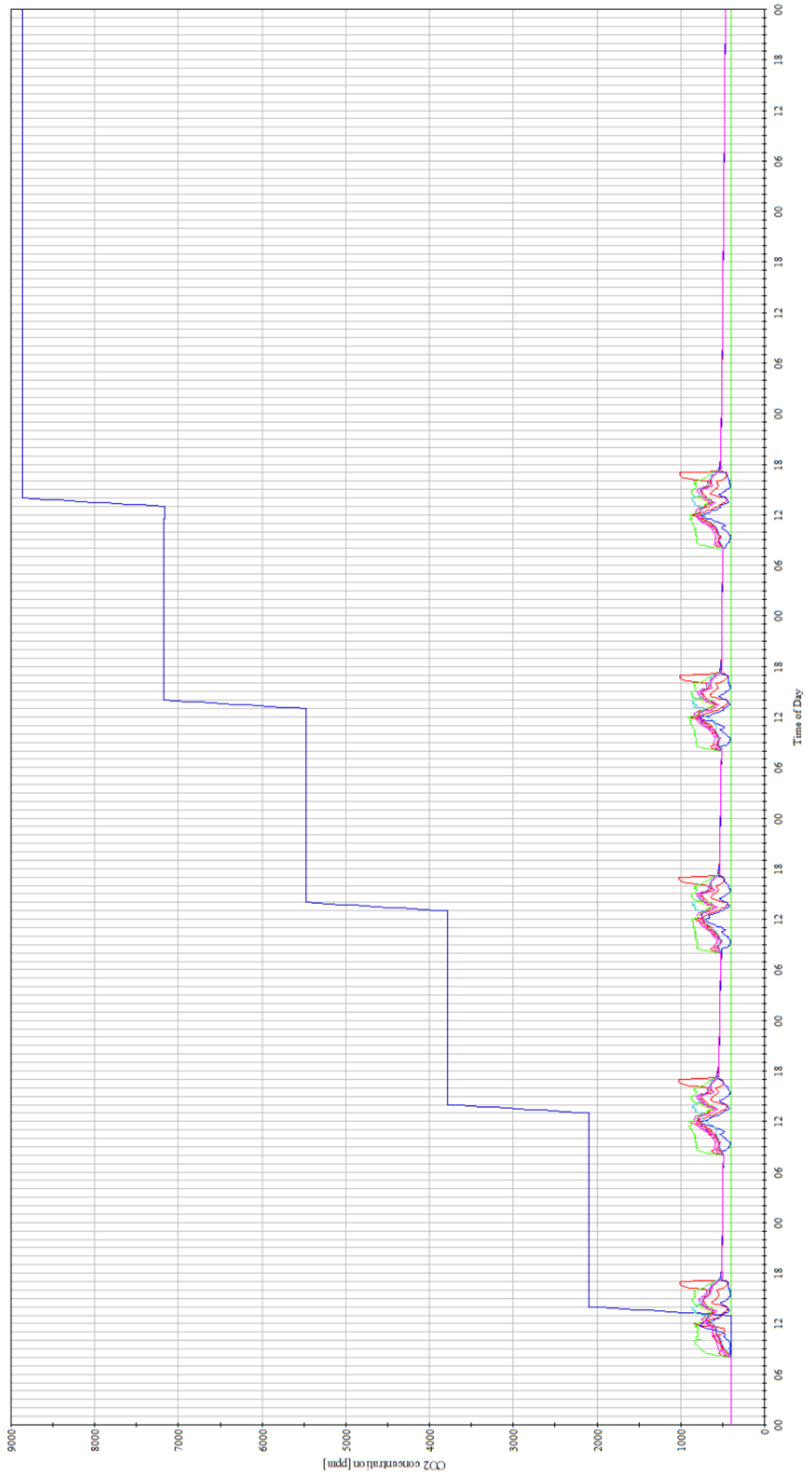


Fig.: G.9 Resulting CO_2 in the third floor when simulating building model A.2 during the winter.

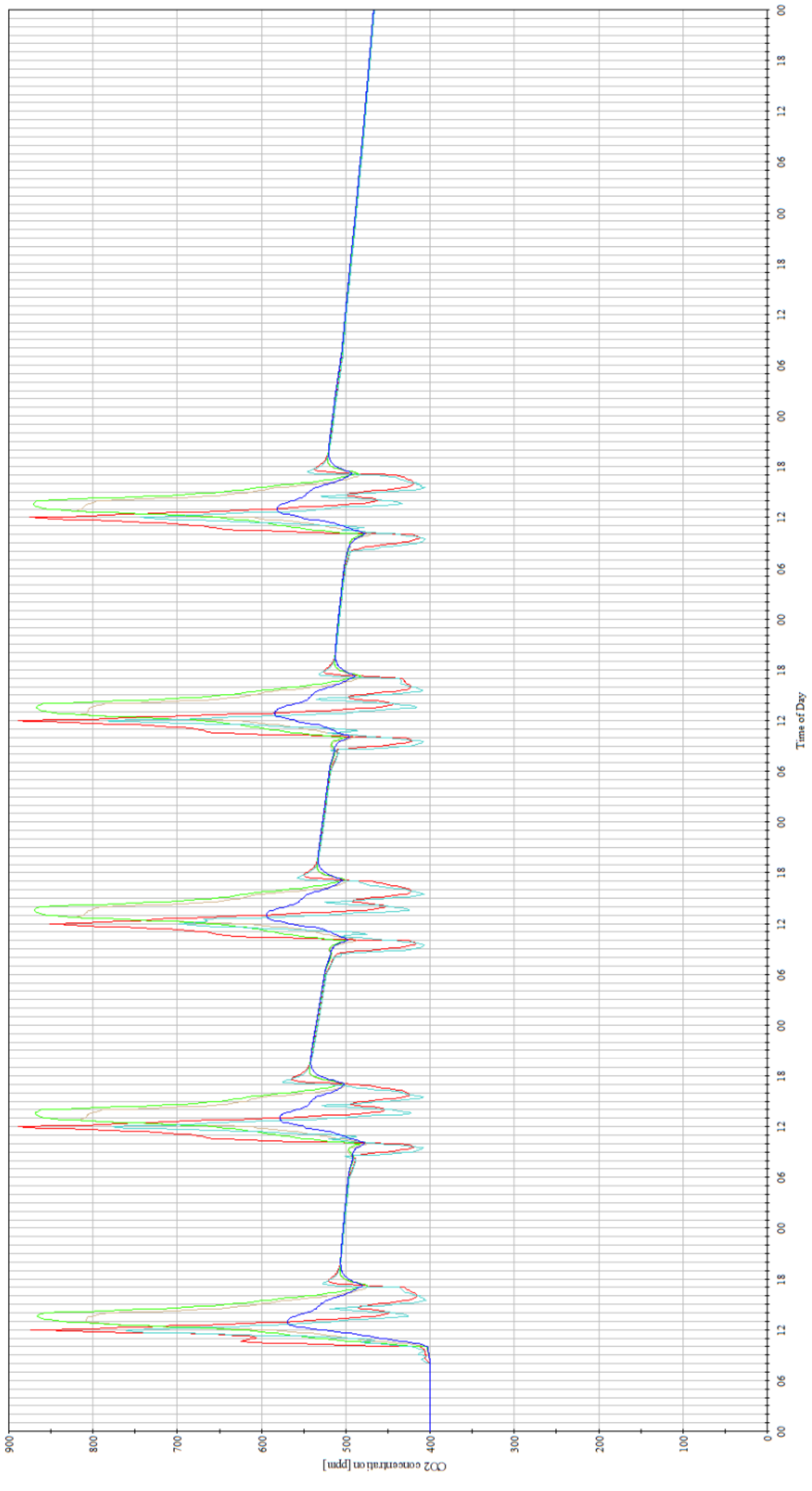


Fig.: G.10 Resulting CO_2 in the fourth floor when simulating building model A.2 during the winter.

Model B.1

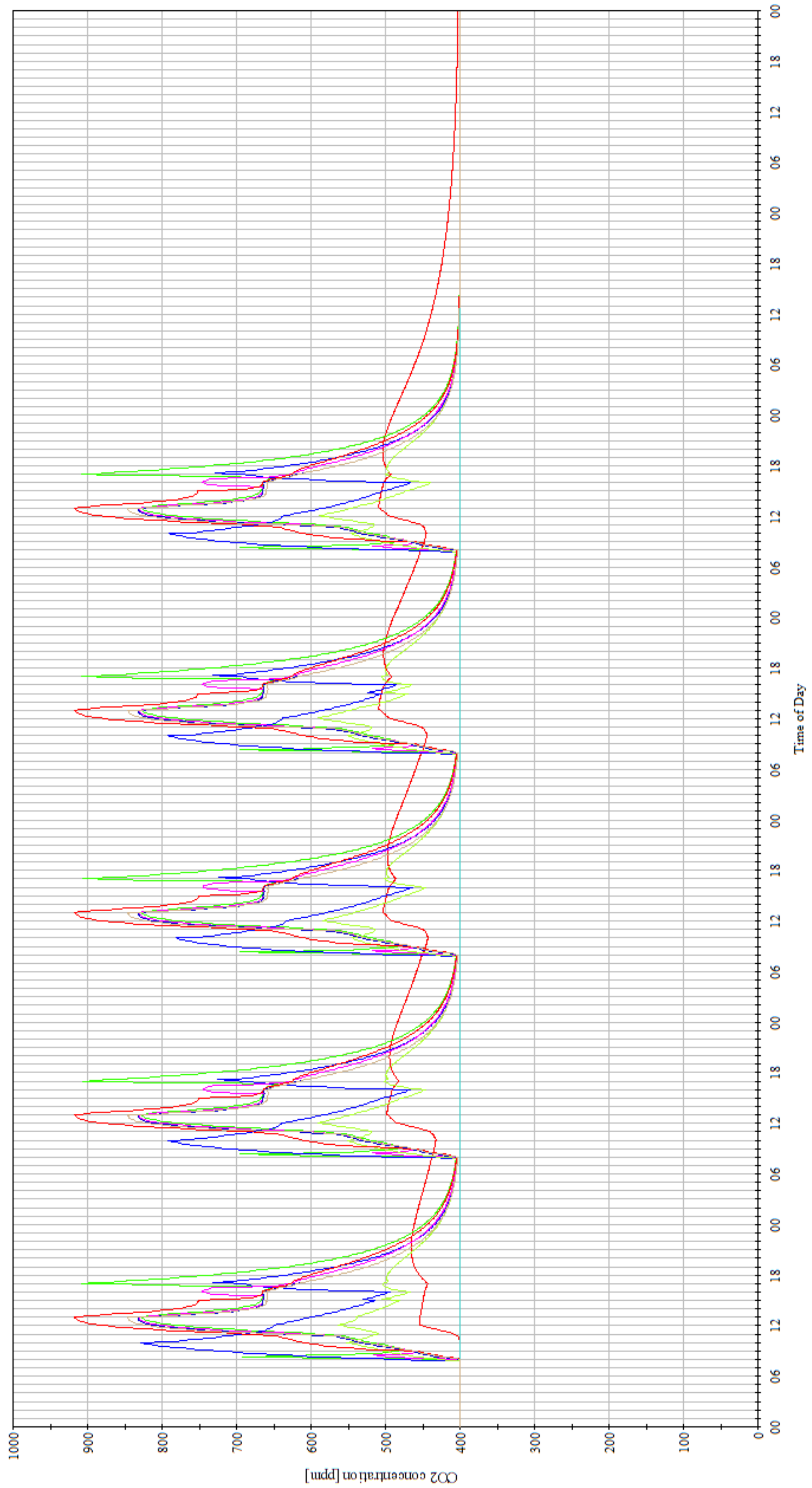


Fig.: G.11 Resulting CO_2 in the first floor when simulating building model B1 during the winter.

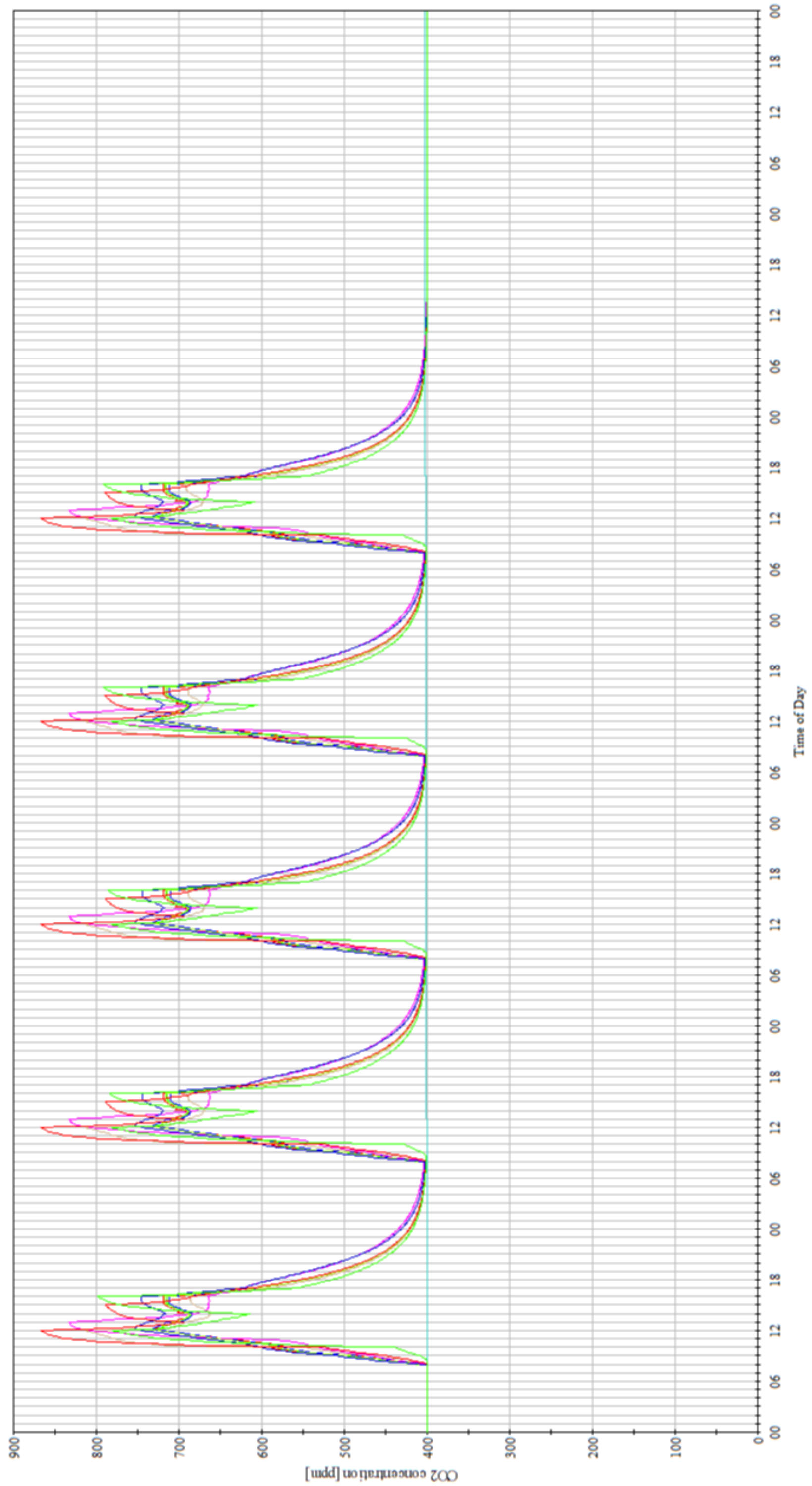


Fig.: G.12 Resulting CO_2 in the second floor when simulating building model B.1 during the winter.

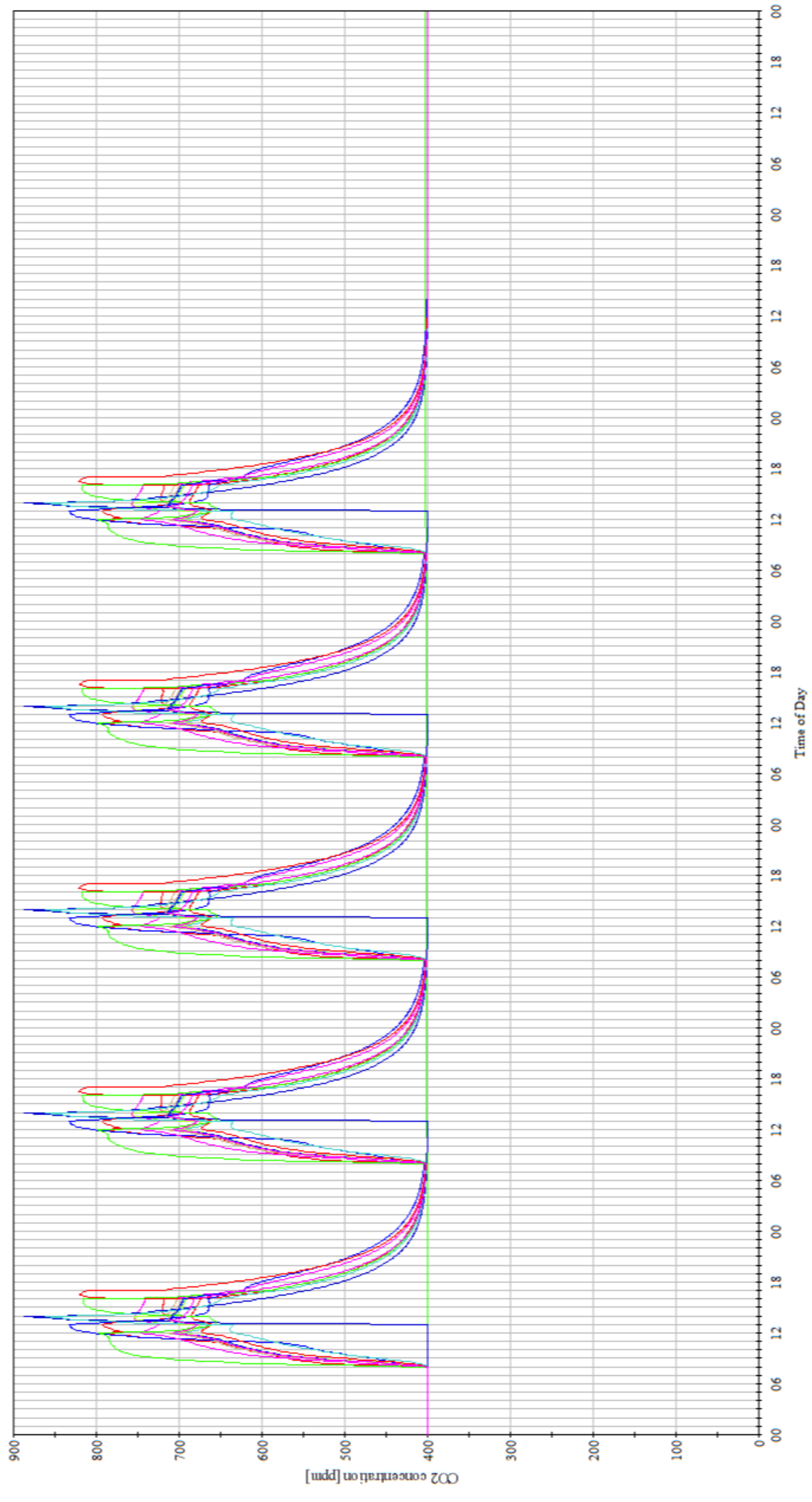


Fig.: G.13 Resulting CO_2 in the third floor when simulating building model B.1 during the winter.

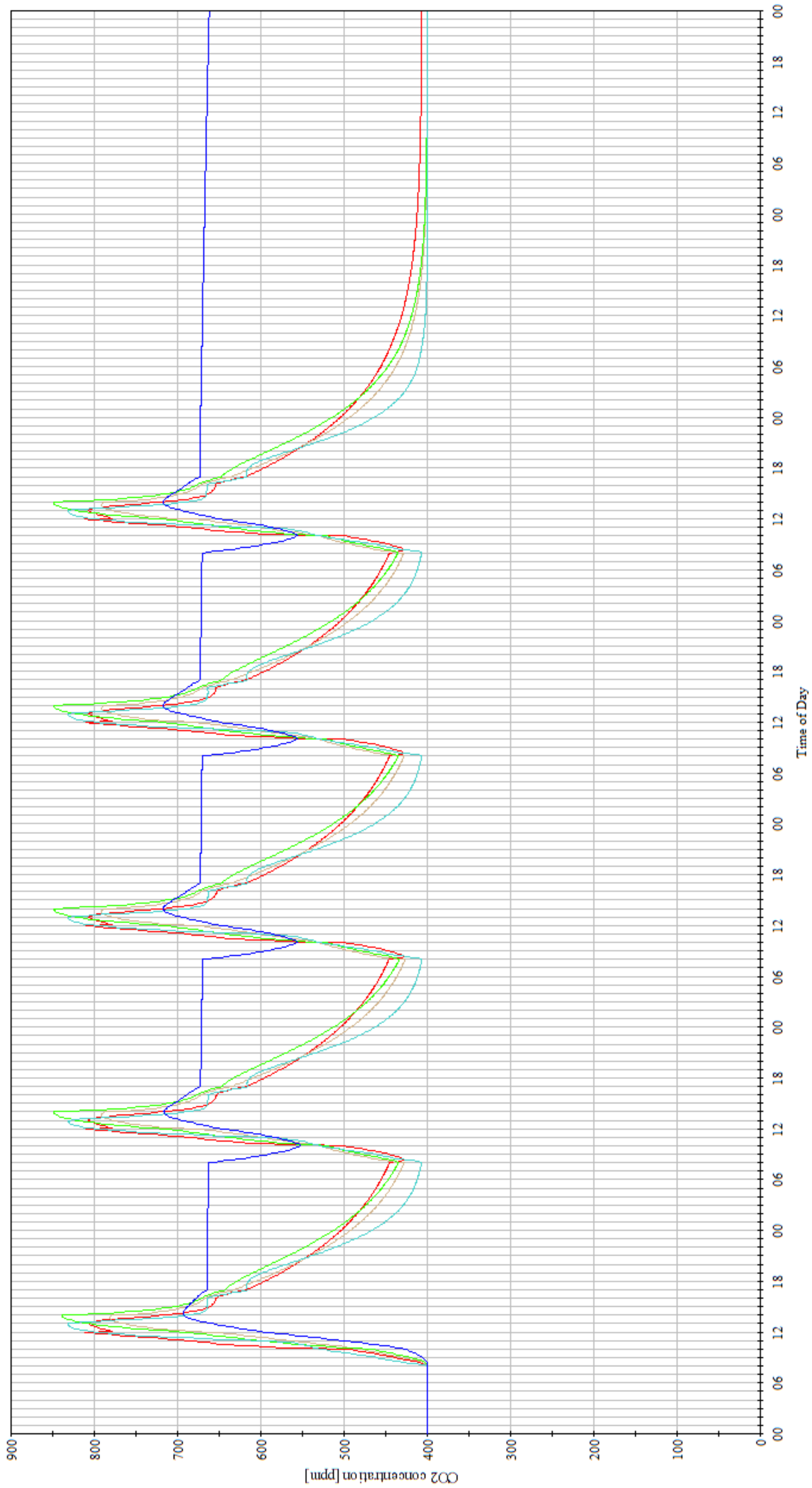


Fig.: G.14 Resulting CO_2 in the fourth floor when simulating building model B.1 during the winter.

Model B.2

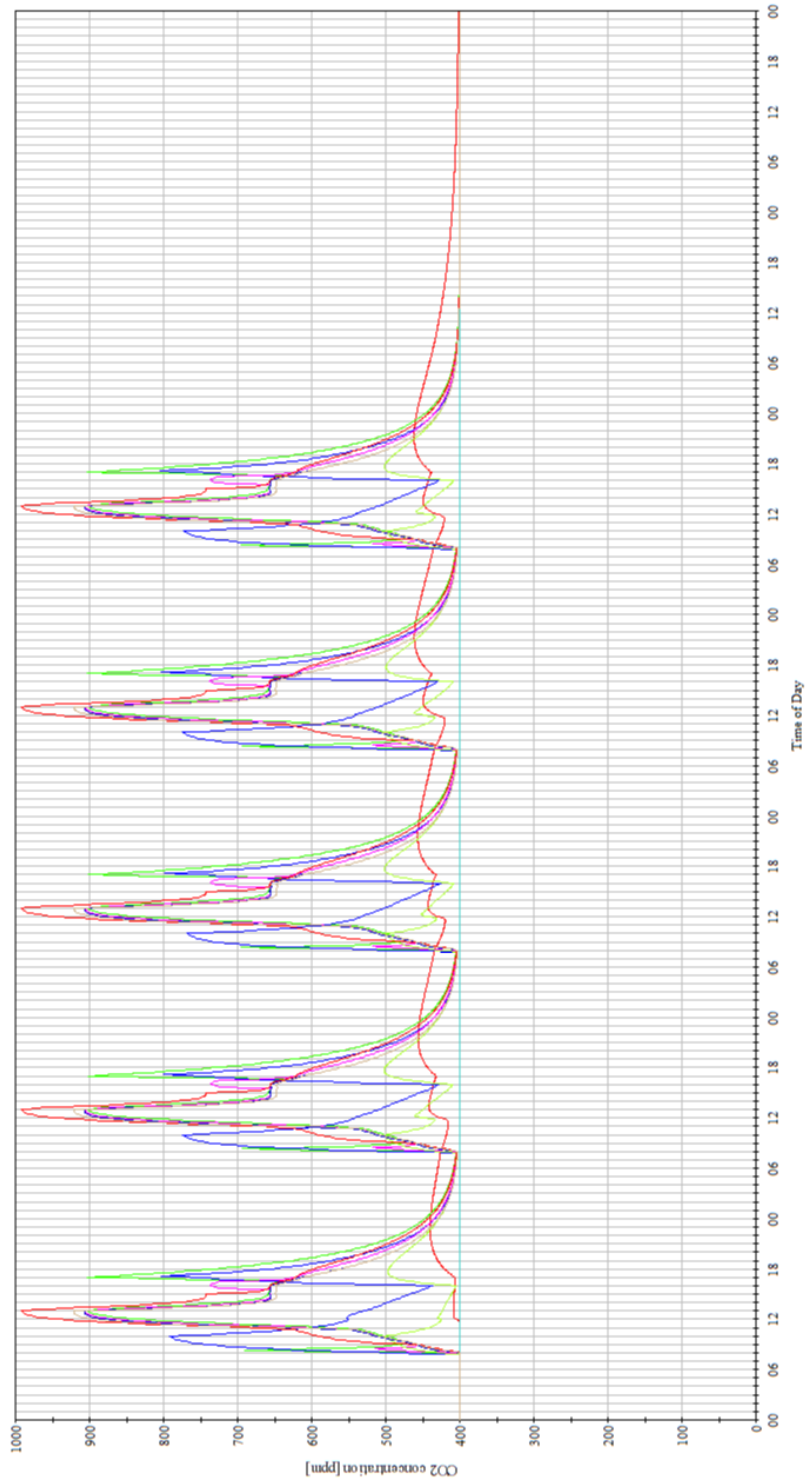


Fig.: G.15 Resulting CO_2 in the first floor when simulating building model B.2 during the winter.

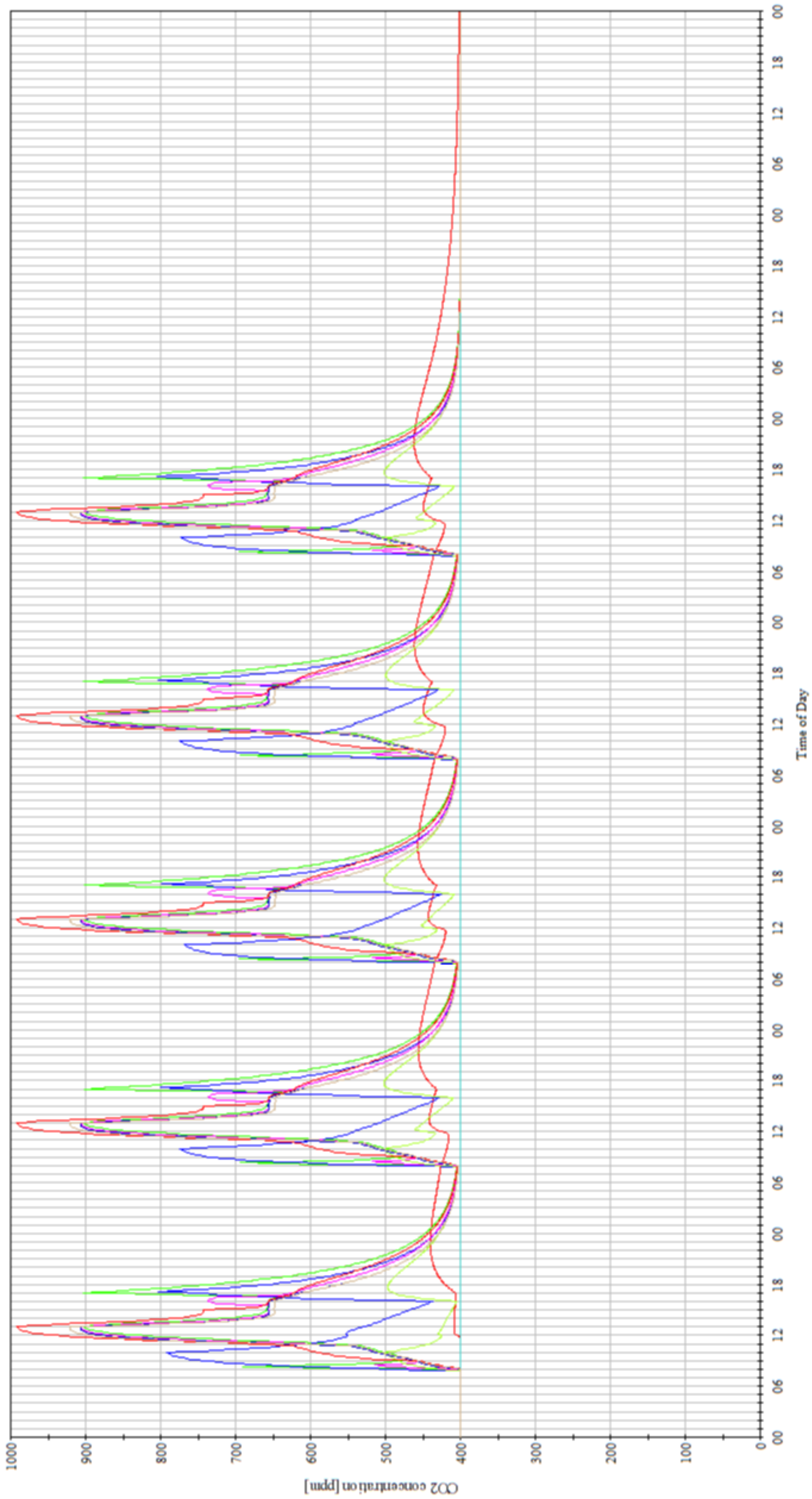


Fig.: G.16 Resulting CO_2 in the second floor when simulating building model B.2 during the winter.

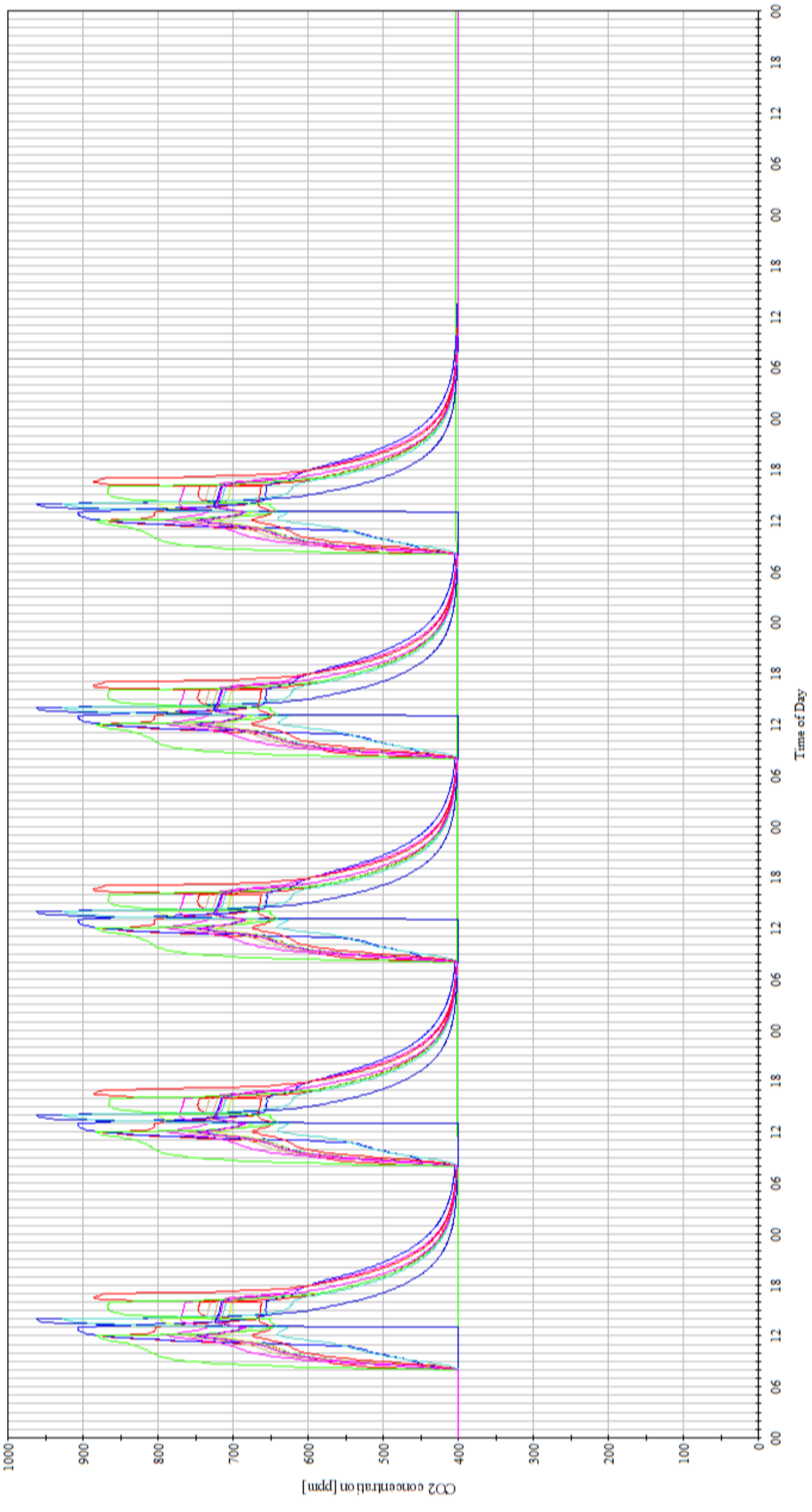


Fig.: G.17 Resulting CO_2 in the third floor when simulating building model B.2 during the winter.

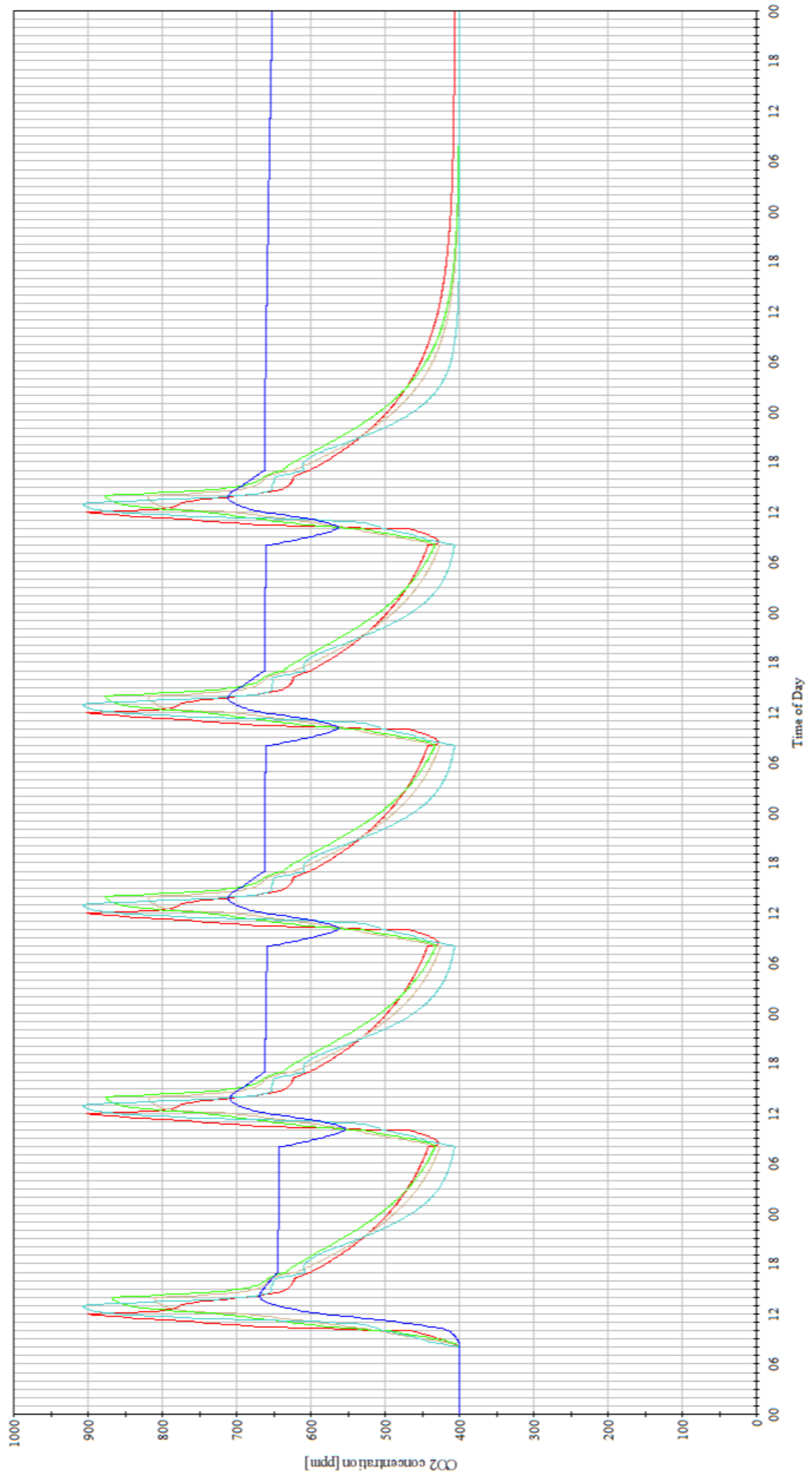


Fig.: G.18 Resulting CO_2 in the fourth floor when simulating building model B.2 during the winter.

Model A.1+B.1

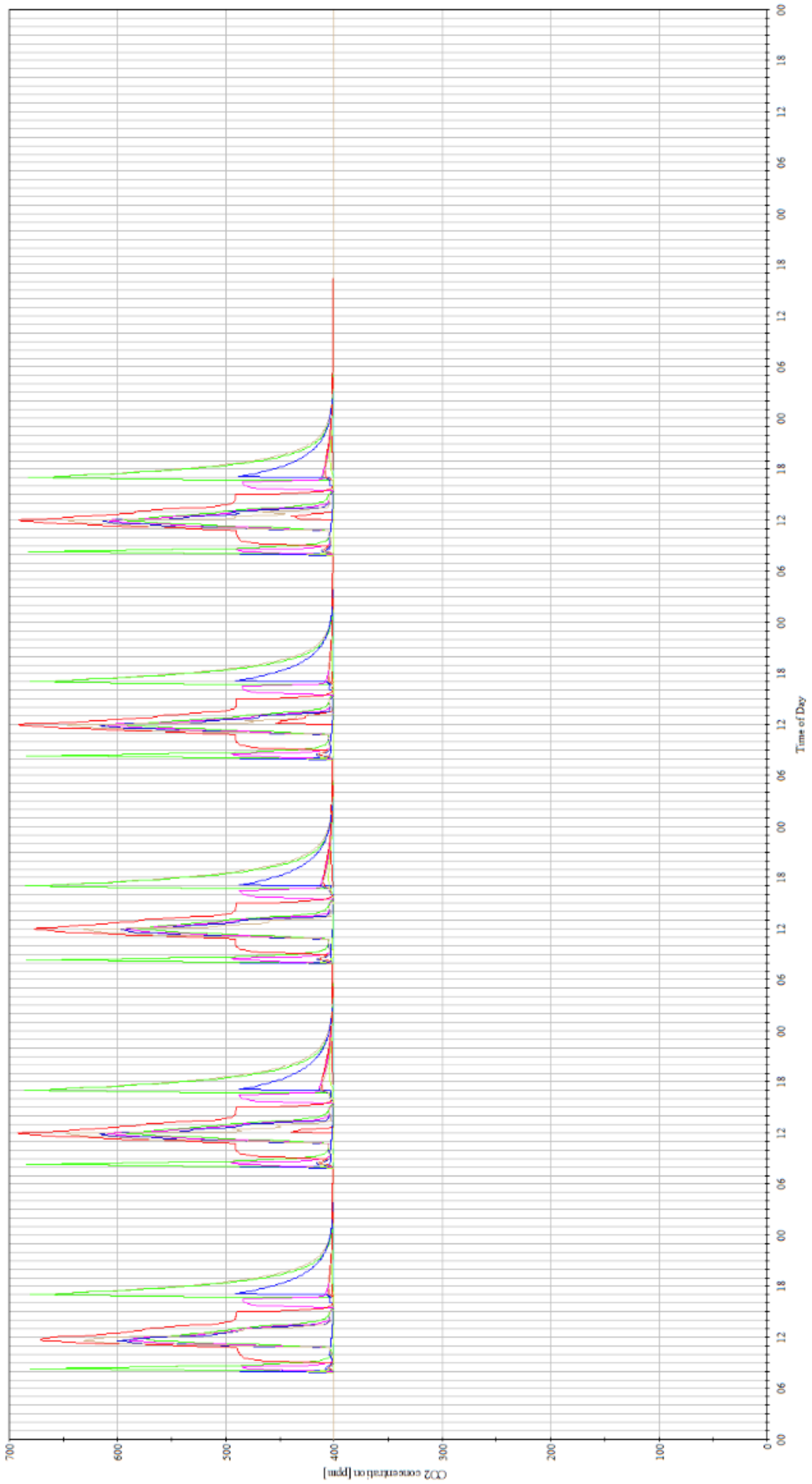


Fig.: G.19 Resulting CO_2 in the first floor when simulating building model A.1+B.1 during the winter.

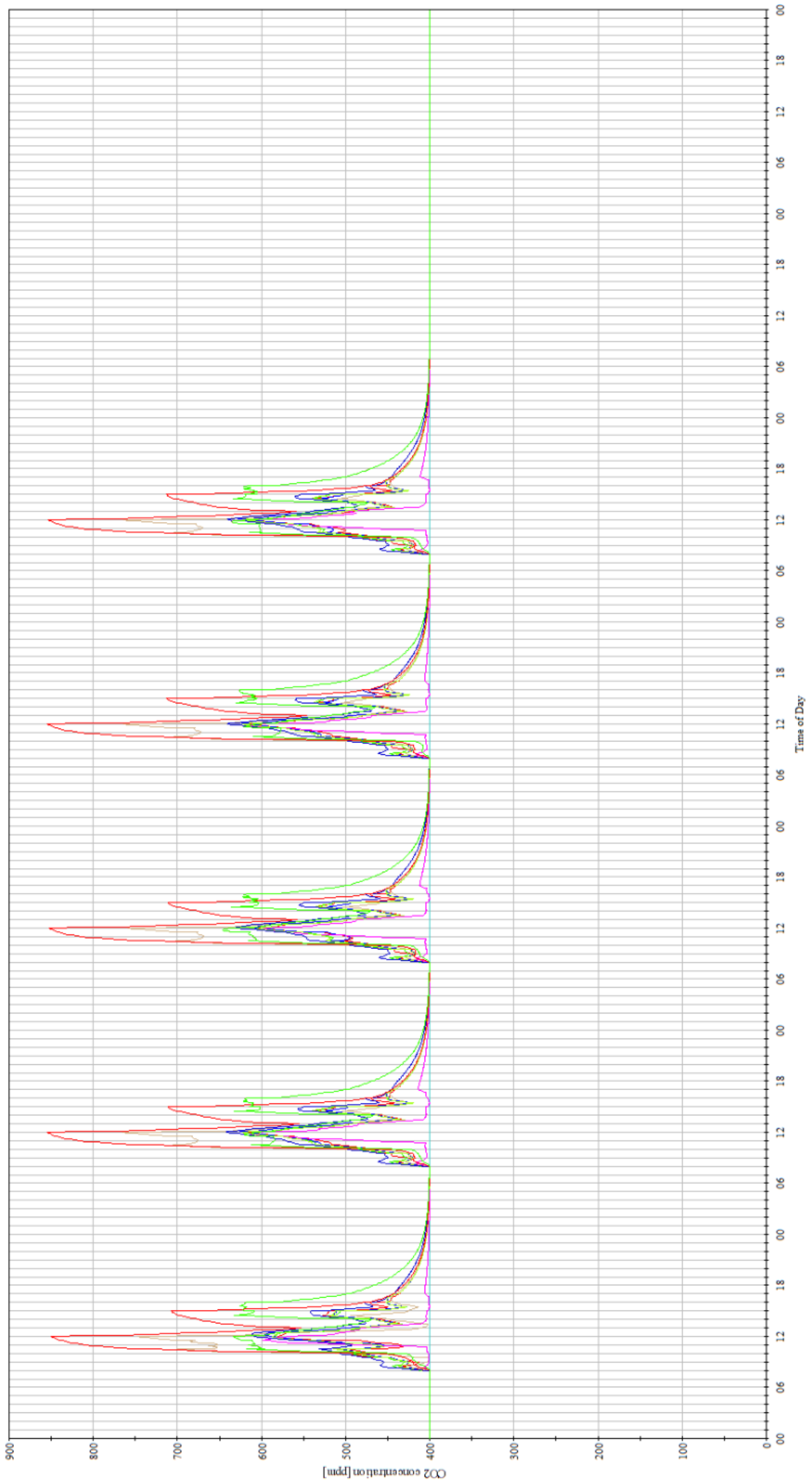


Fig.: G.20 Resulting CO_2 in the second floor when simulating building model A.1+B.1 during the winter.

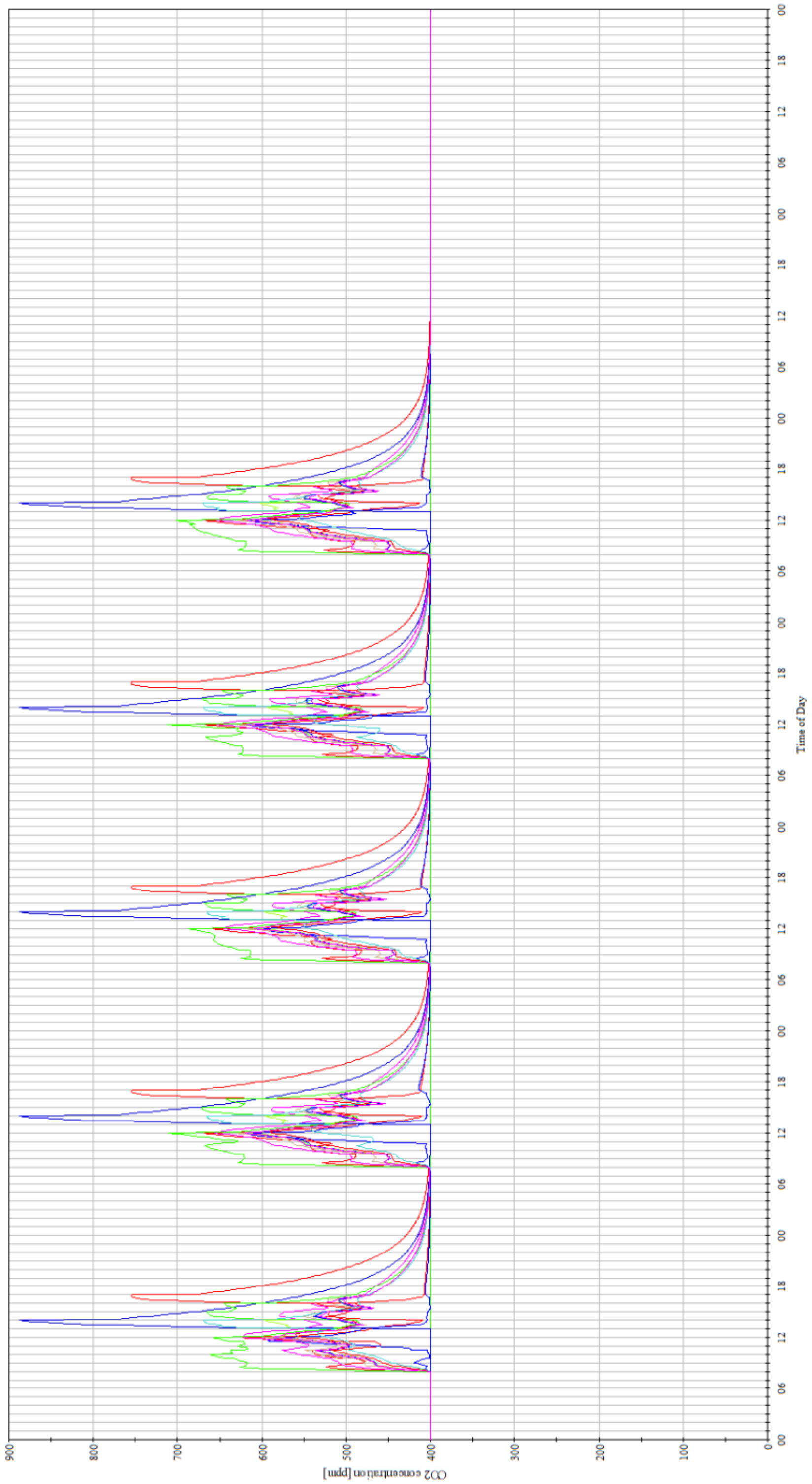


Fig.: G.21 Resulting CO_2 in the third floor when simulating building model A.1+B.1 during the winter.

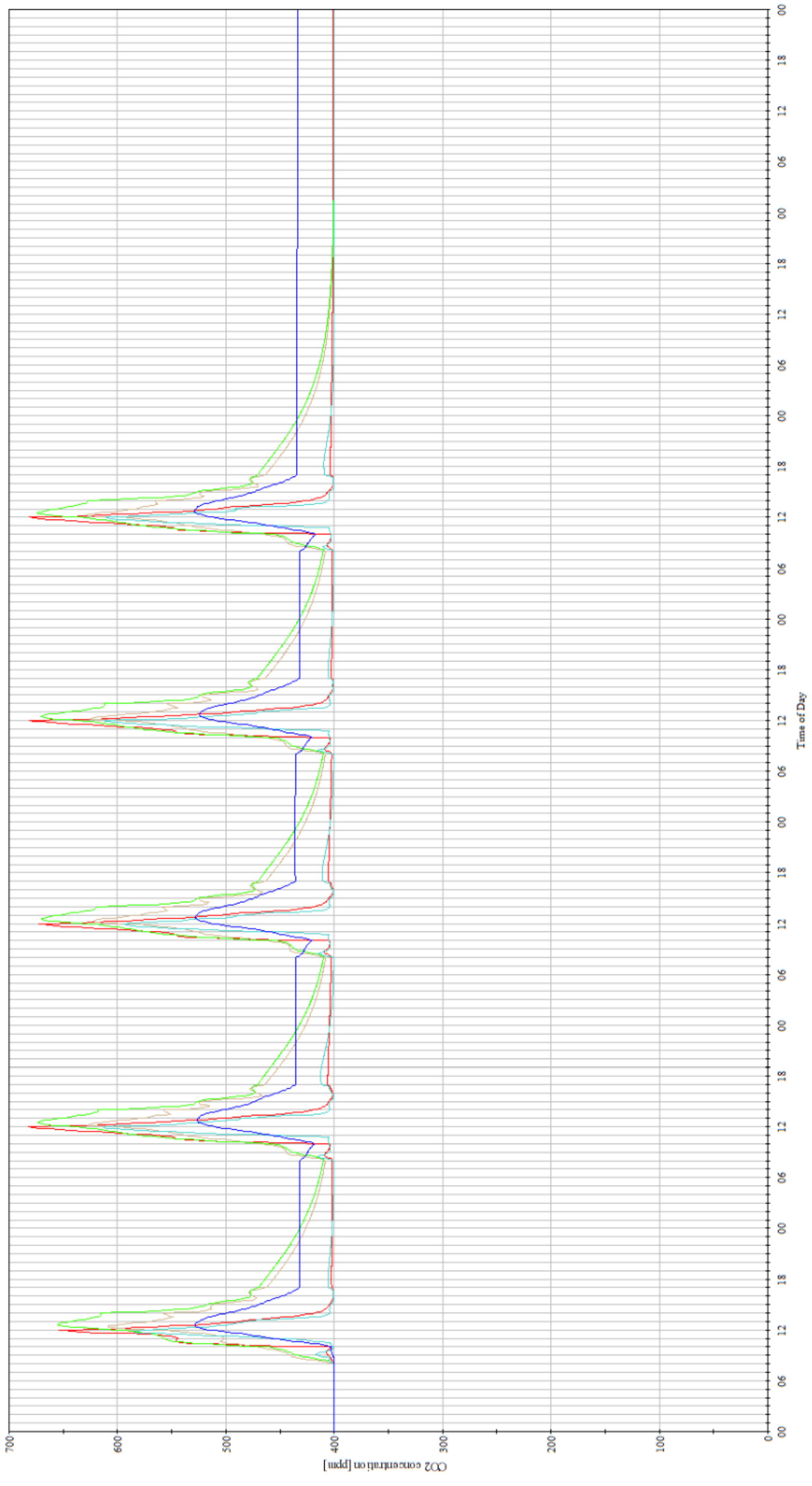


Fig.: G.22 Resulting CO_2 in the fourth floor when simulating building model A.1+B.1 during the winter.

Model A.1+B.2

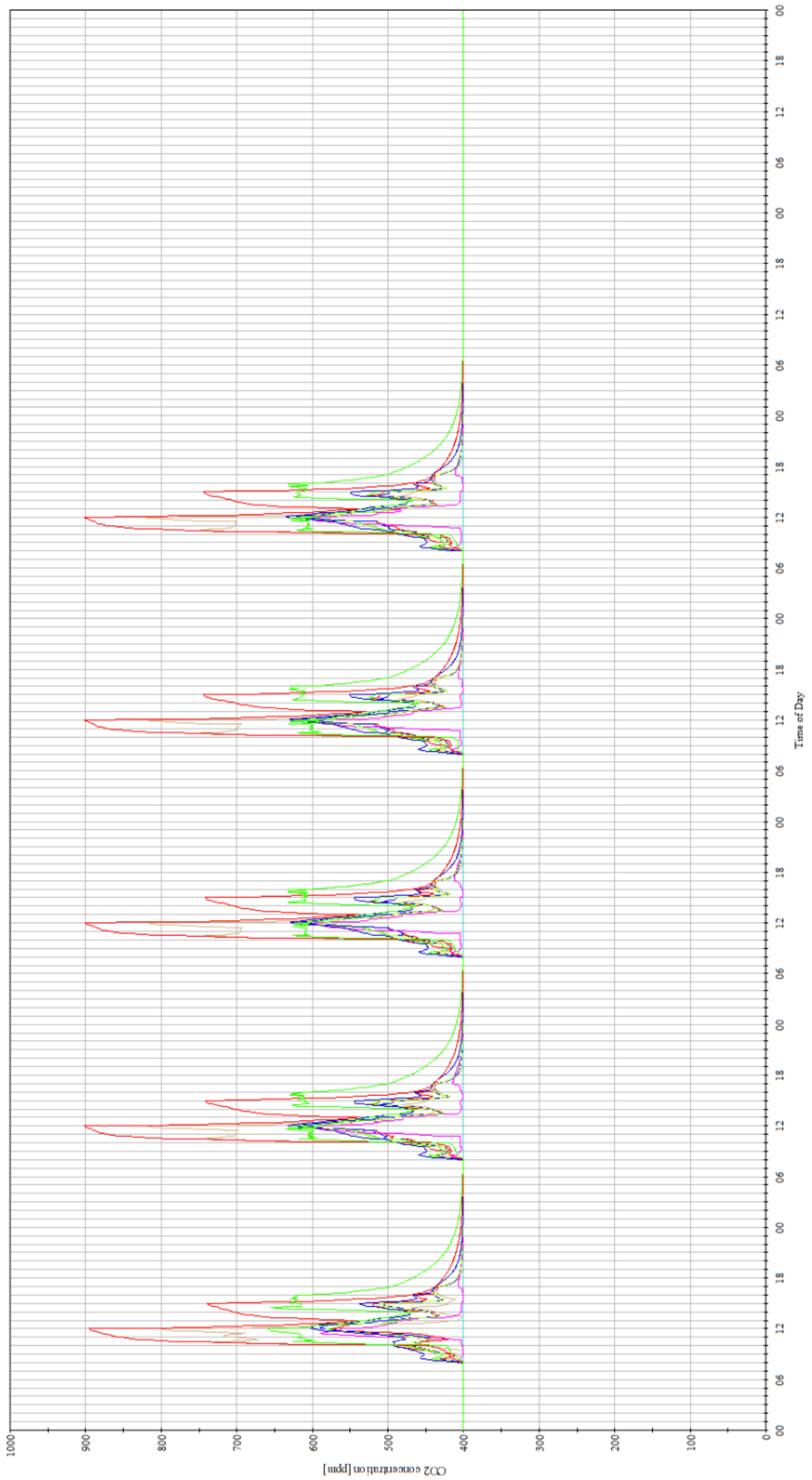


Fig.: G.23 Resulting CO_2 in the first floor when simulating building model A.1+B.2 during the winter.

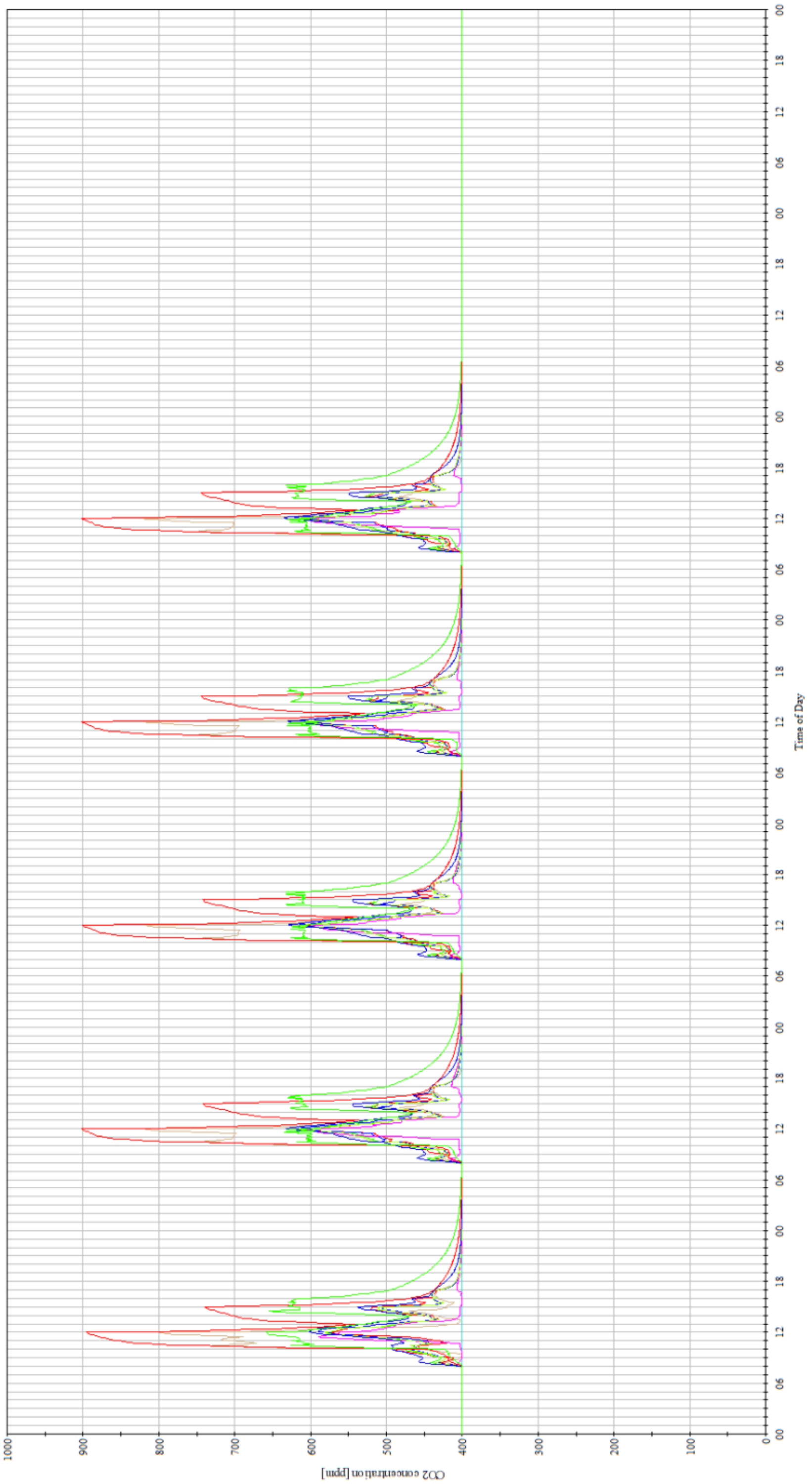


Fig.: G.24 Resulting CO_2 in the second floor when simulating building model A.1+B.2 during the winter.

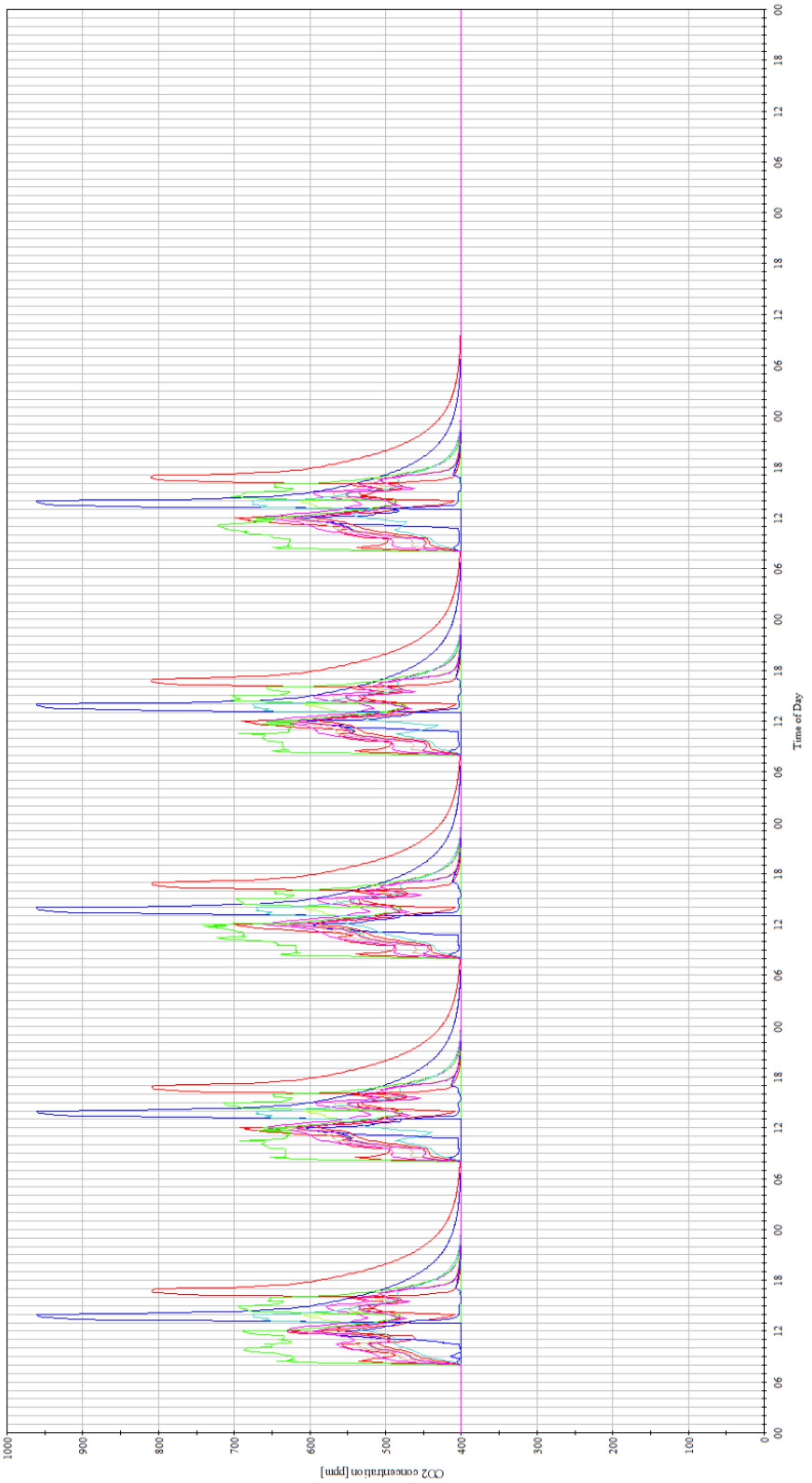


Fig.: G.25 Resulting CO_2 in the third floor when simulating building model A.1+B.2 during the winter.

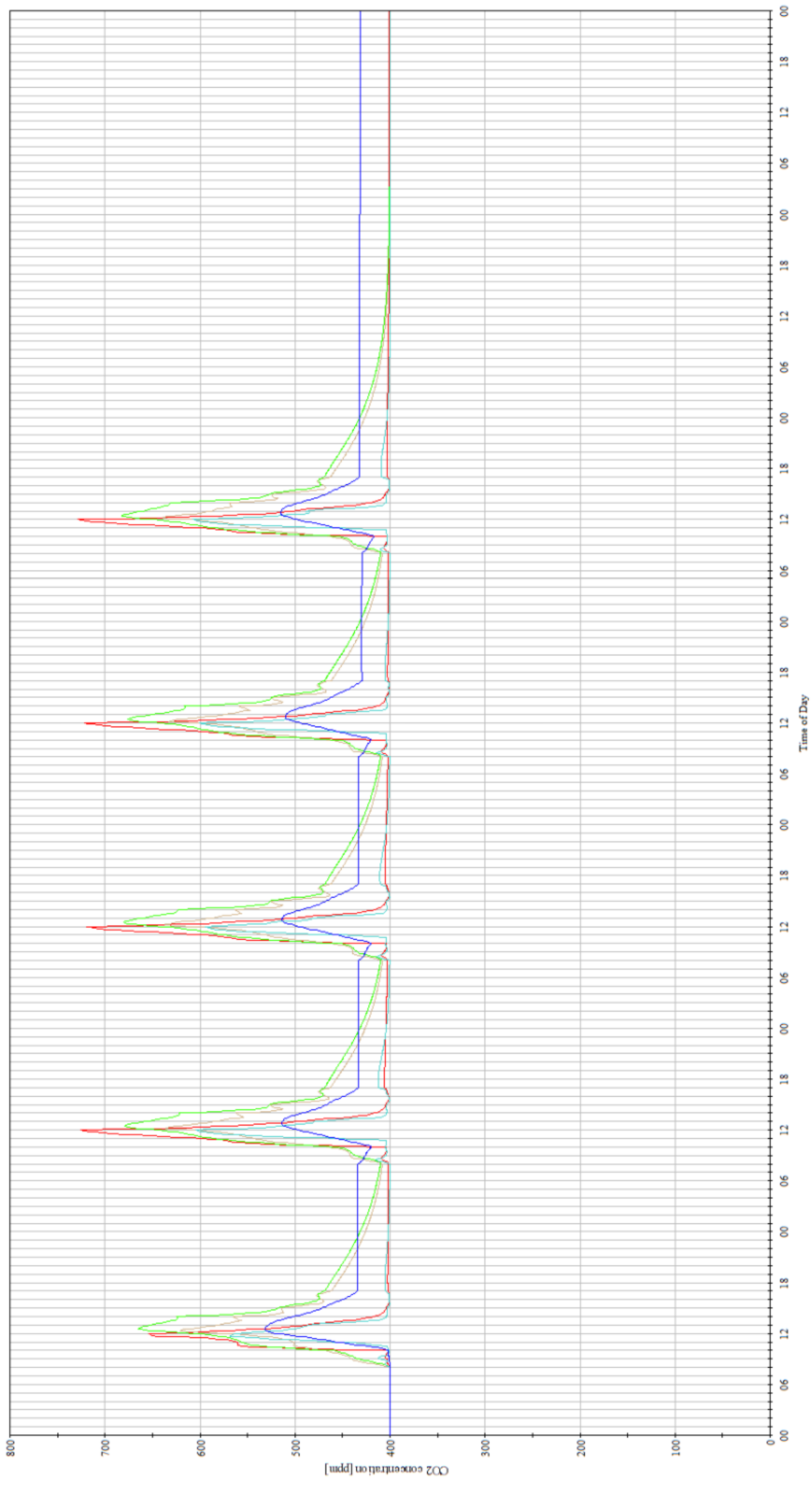


Fig.: G.26 Resulting CO_2 in the fourth floor when simulating building model A.1+B.2 during the winter.

Model A.1+B.2

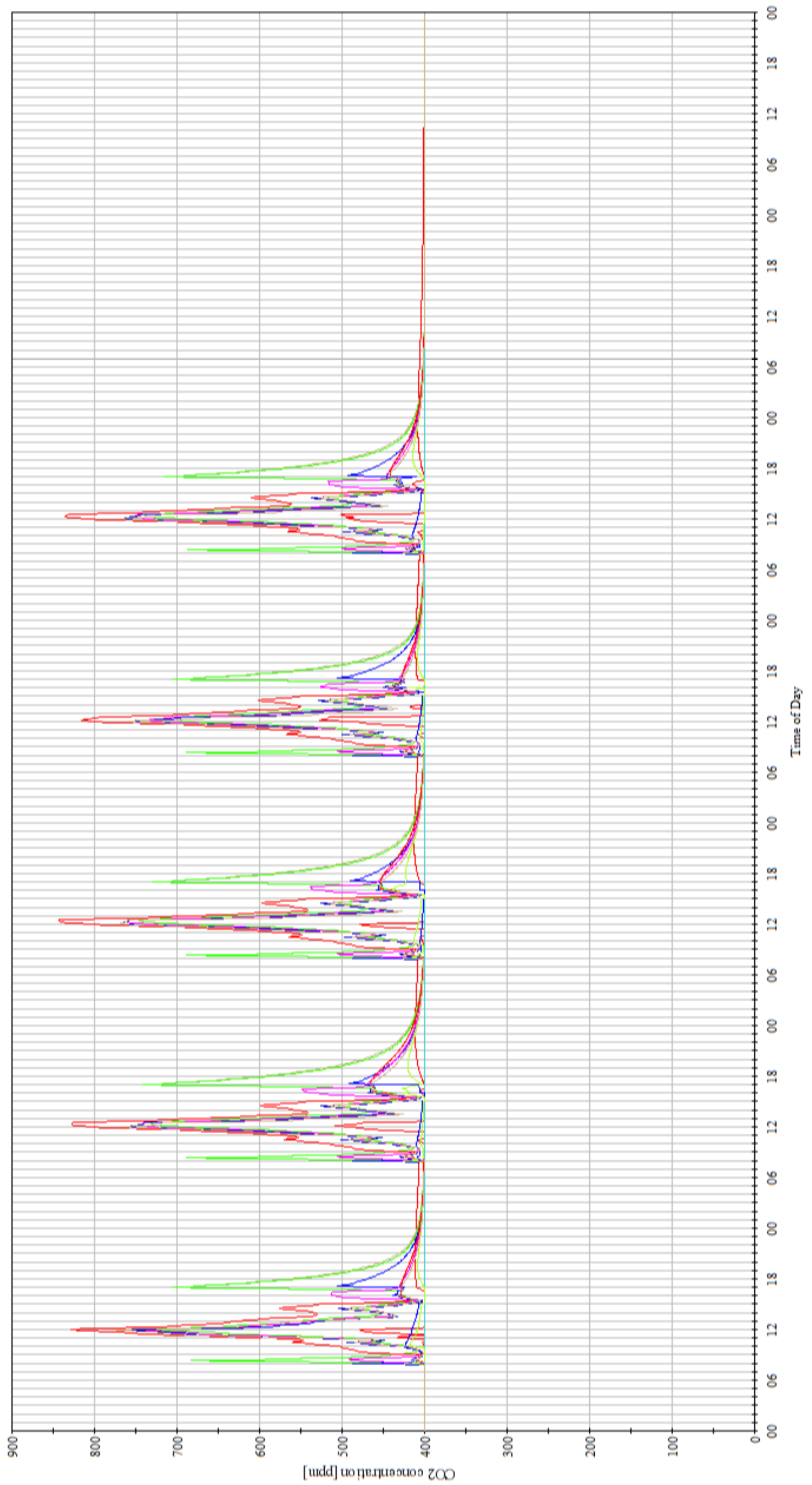


Fig.: G.27 Resulting CO_2 in the first floor when simulating building model A.2+B.1 during the winter.

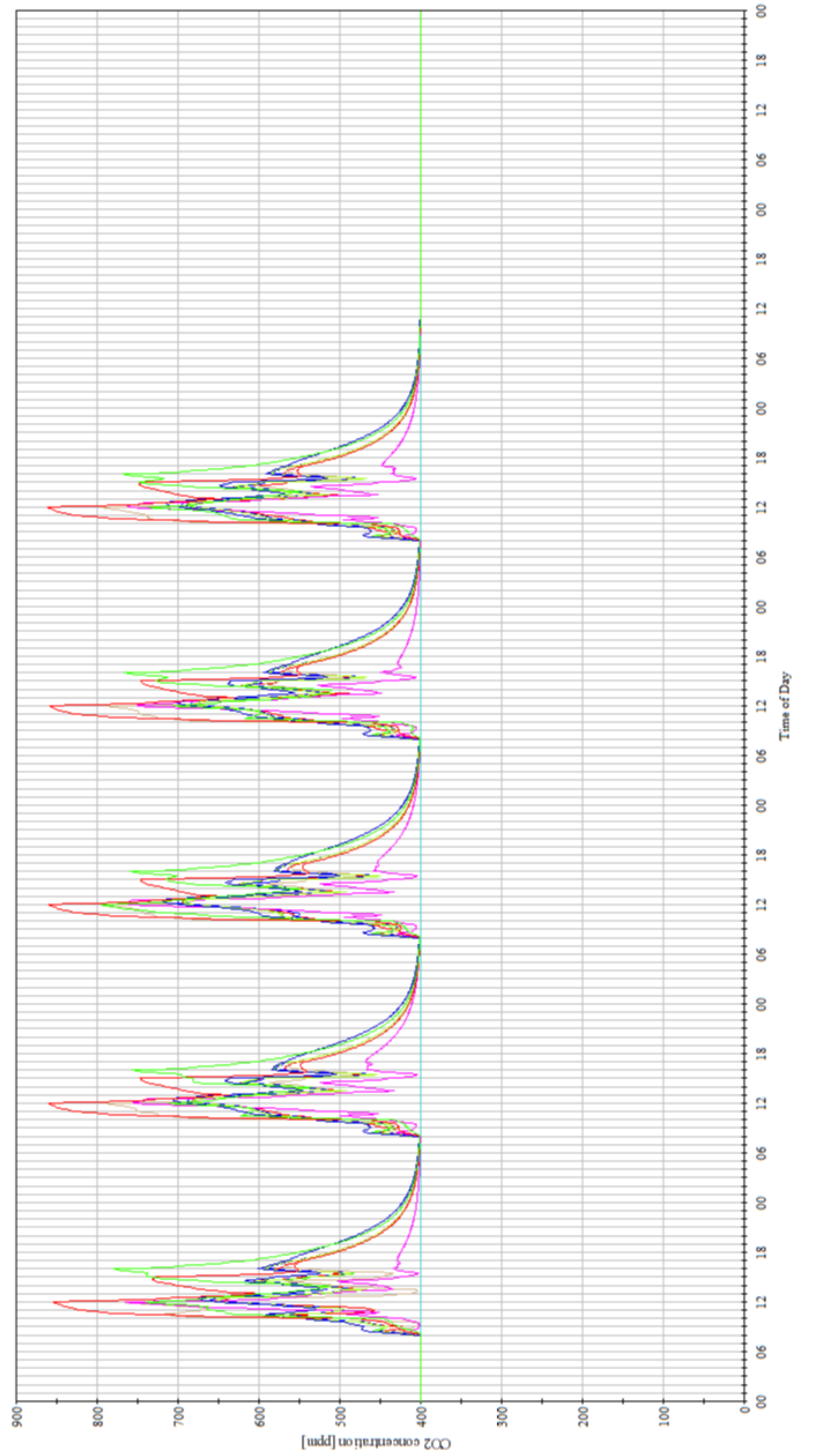


Fig.: G.28 Resulting CO_2 in the second floor when simulating building model A.2+B.1 during the winter.

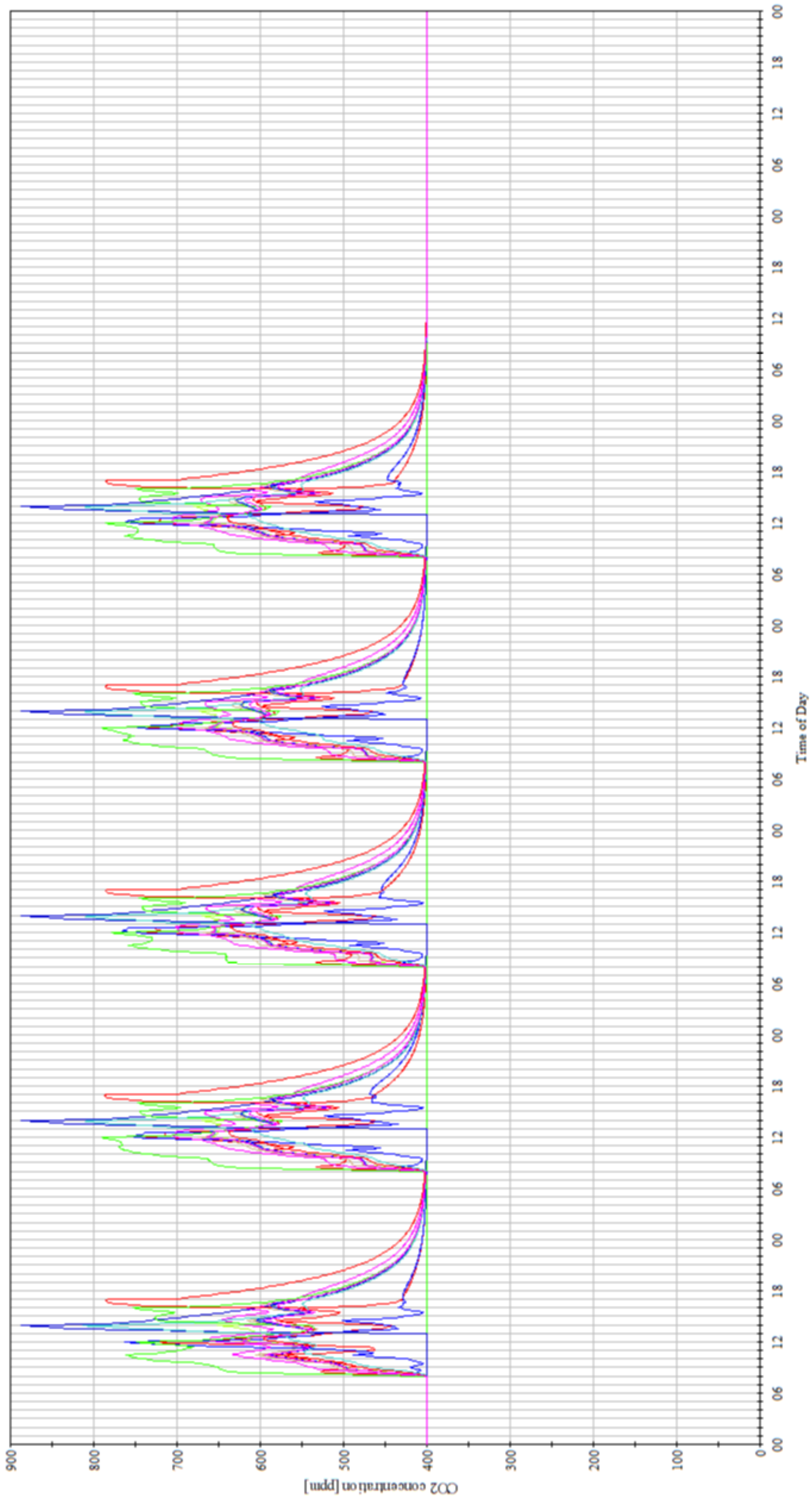


Fig.: G.29 Resulting CO_2 in the third floor when simulating building model A.2+B.1 during the winter.

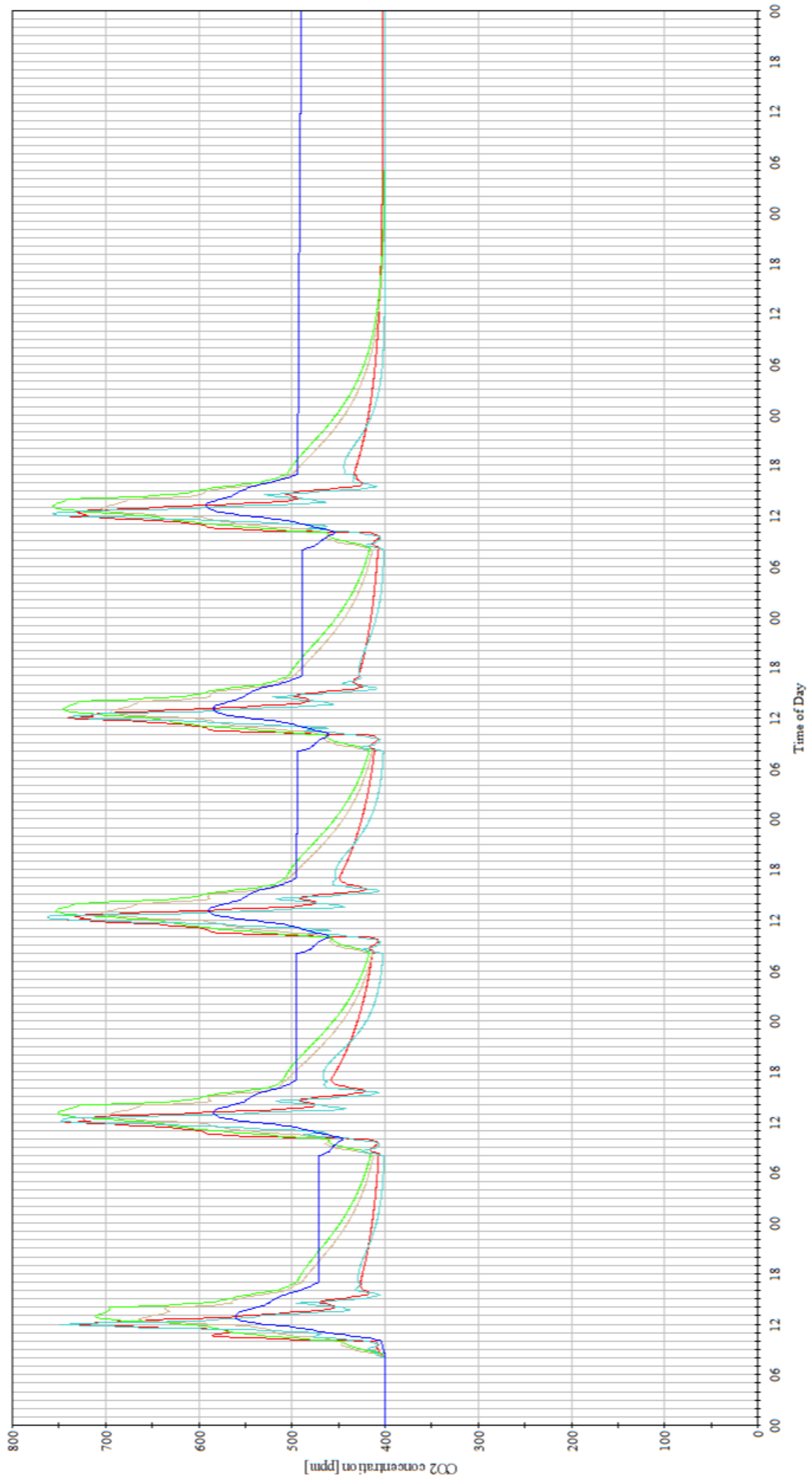


Fig.: G.30 Resulting CO_2 in the fourth floor when simulating building model A.2+B.1 during the winter.

Model A.2+B.2

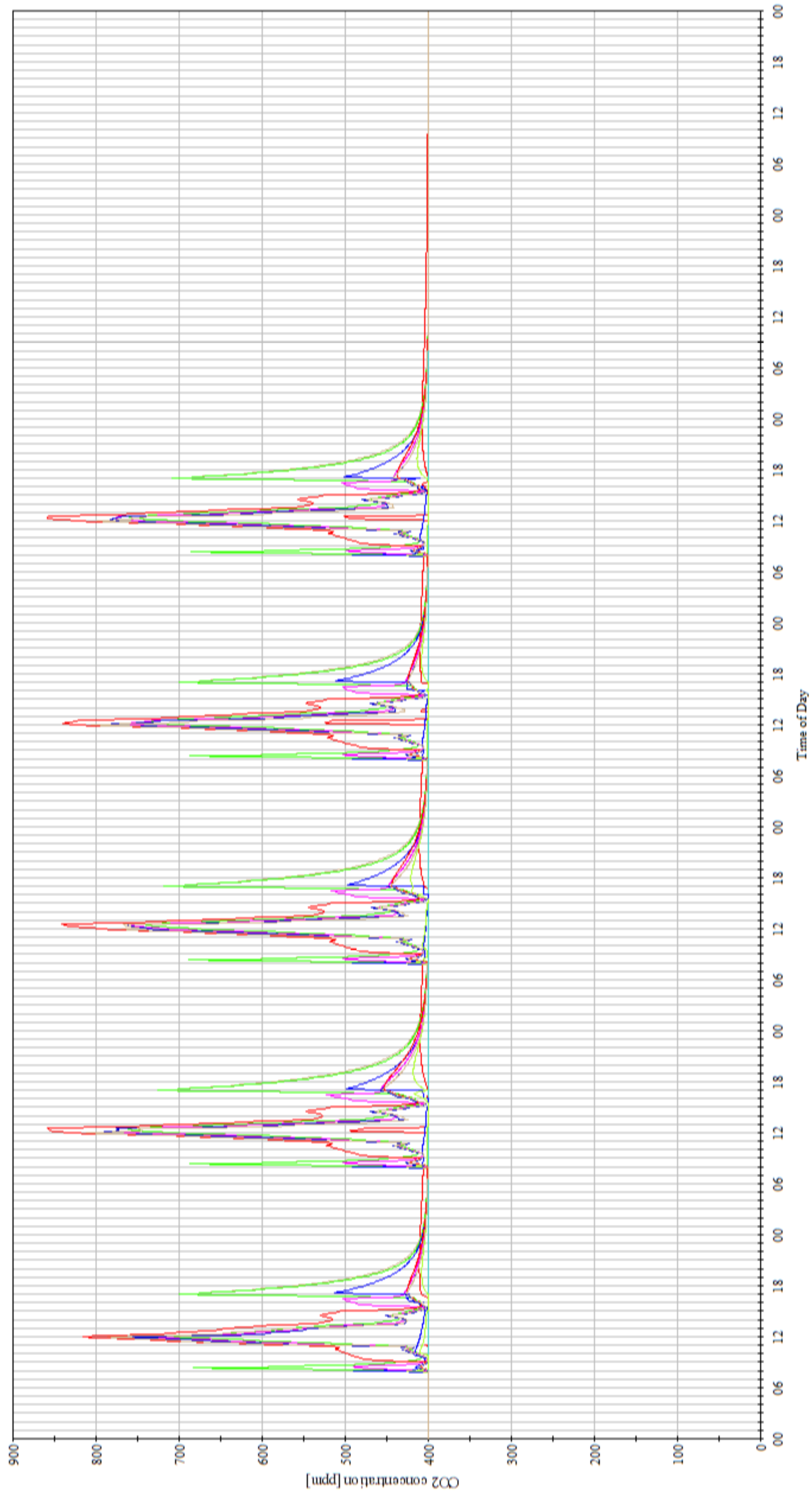


Fig.: G.31 Resulting CO_2 in the first floor when simulating building model A.2+B.2 during the winter.

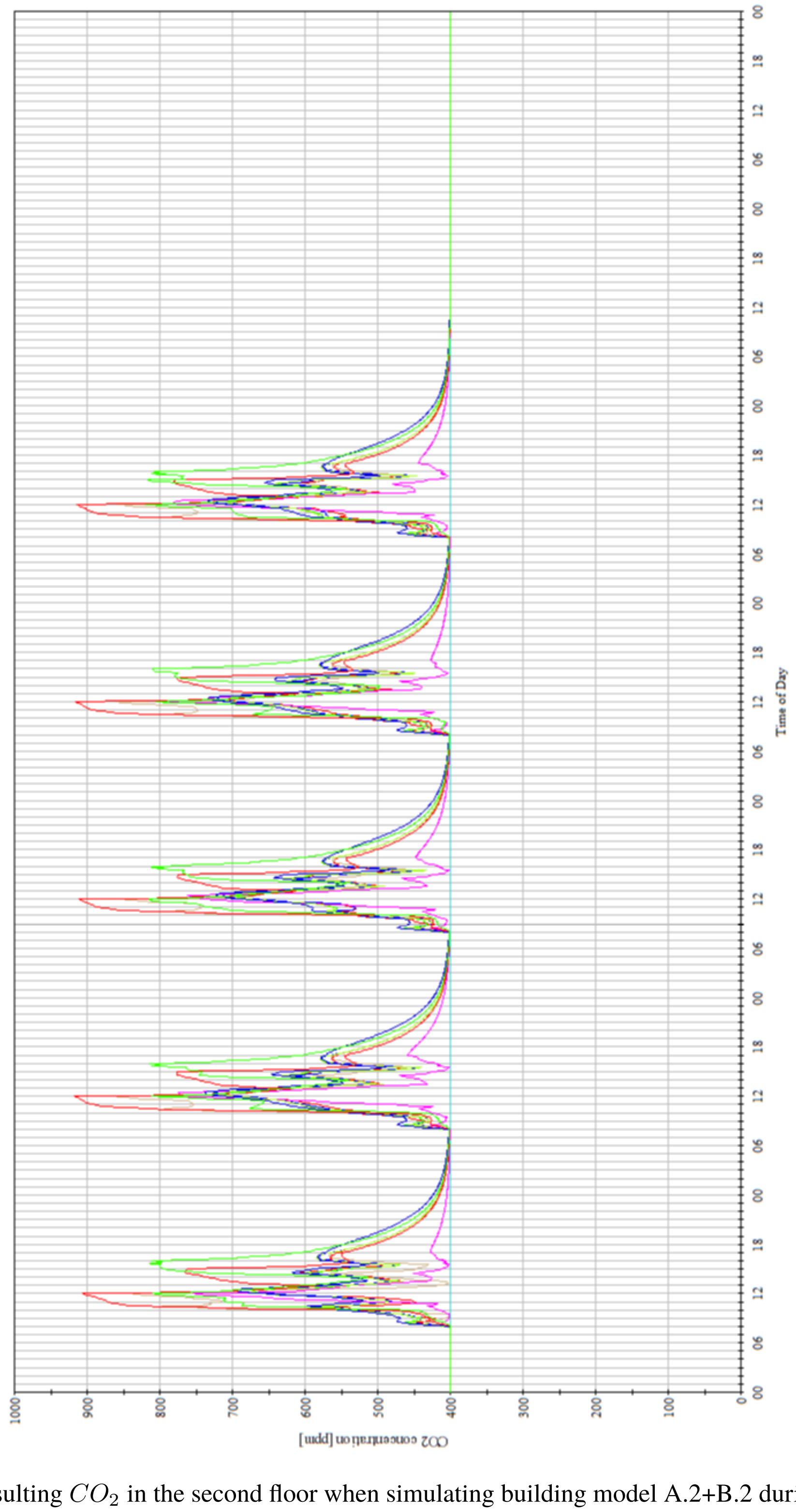


Fig.: G.32 Resulting CO_2 in the second floor when simulating building model A.2+B.2 during the winter.

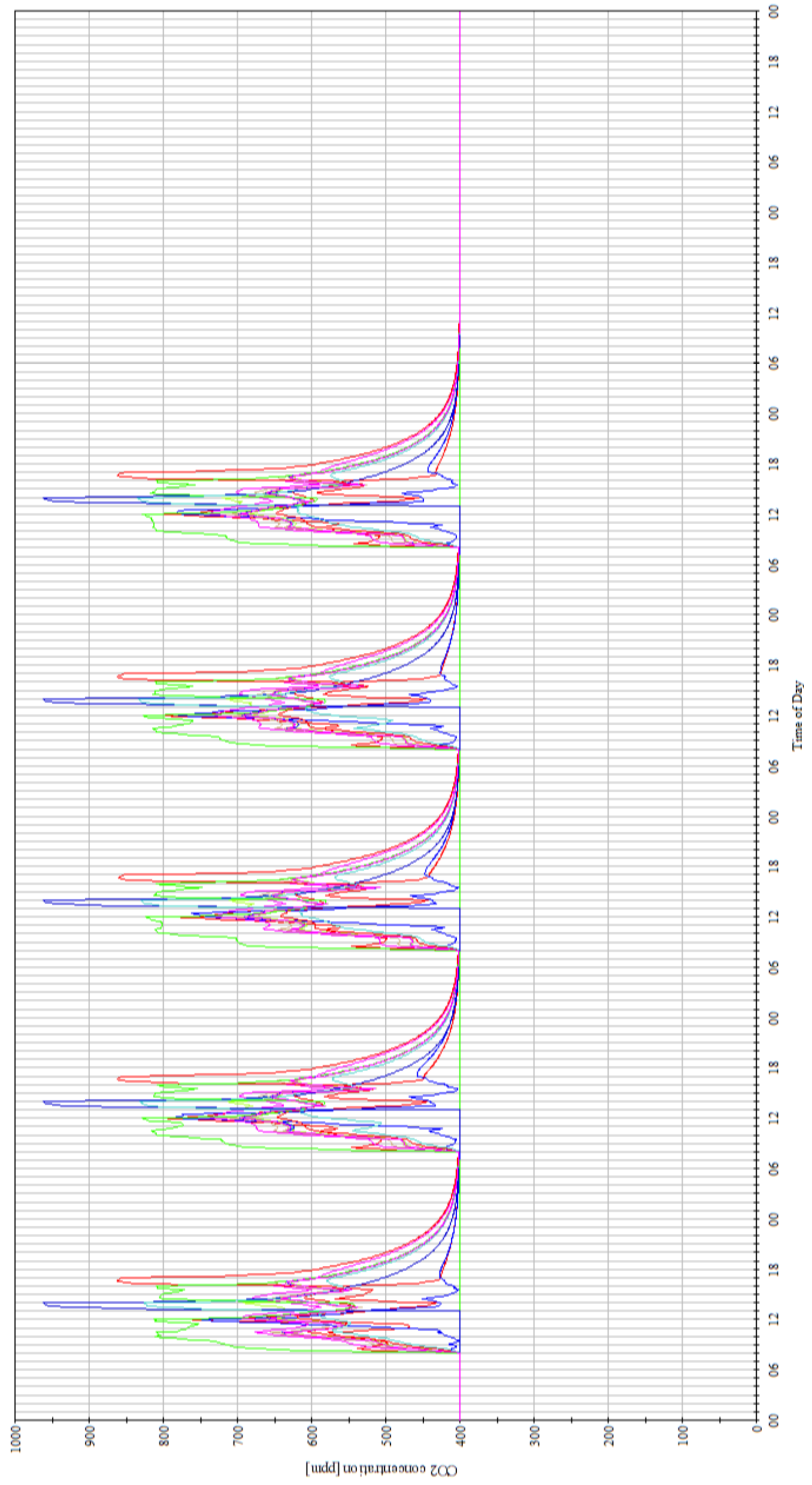


Fig.: G.33 Resulting CO_2 in the third floor when simulating building model A.2+B.2 during the winter.

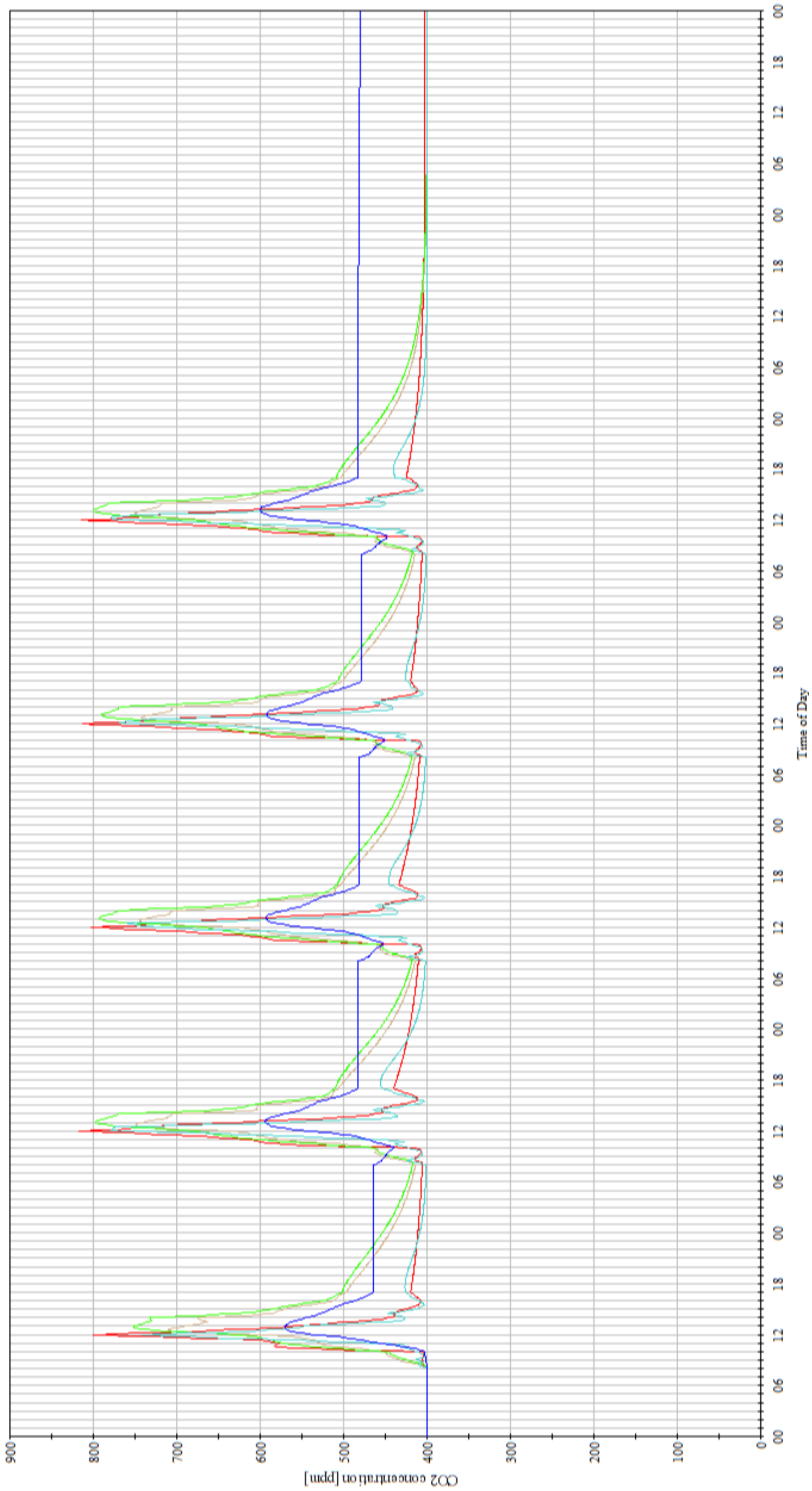


Fig.: G.34 Resulting CO_2 in the fourth floor when simulating building model A.2+B.2 during the winter.

Appendix H

Transition week results

H.1 Resulting air change rate from simulations

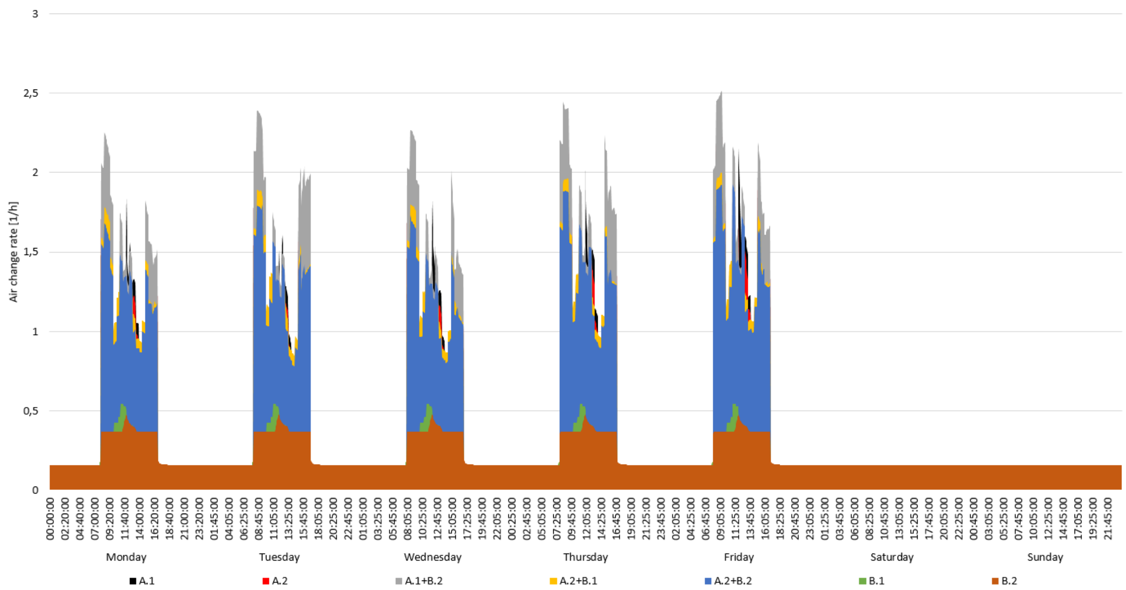
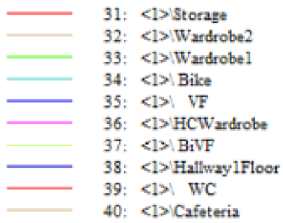
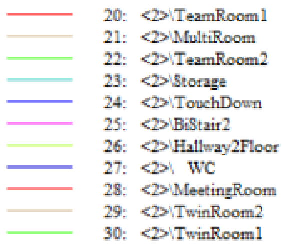


Fig.: H.1 The resulting air changes rates of different corrected building models simulated during the transition season season.

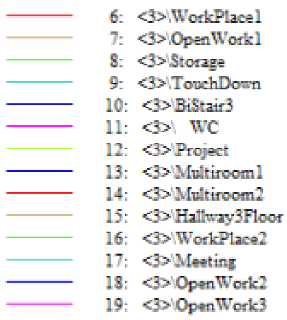
H.2 Resulting CO_2 levels from the simulations



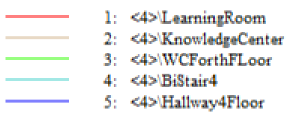
(a) First floor labels.



(b) Second floor labels.



(c) Third floor labels.



(d) Fourth floor labels.

Fig.: H.2 Labels describing the resulting CO_2 levels from the simulations.

Model A.1

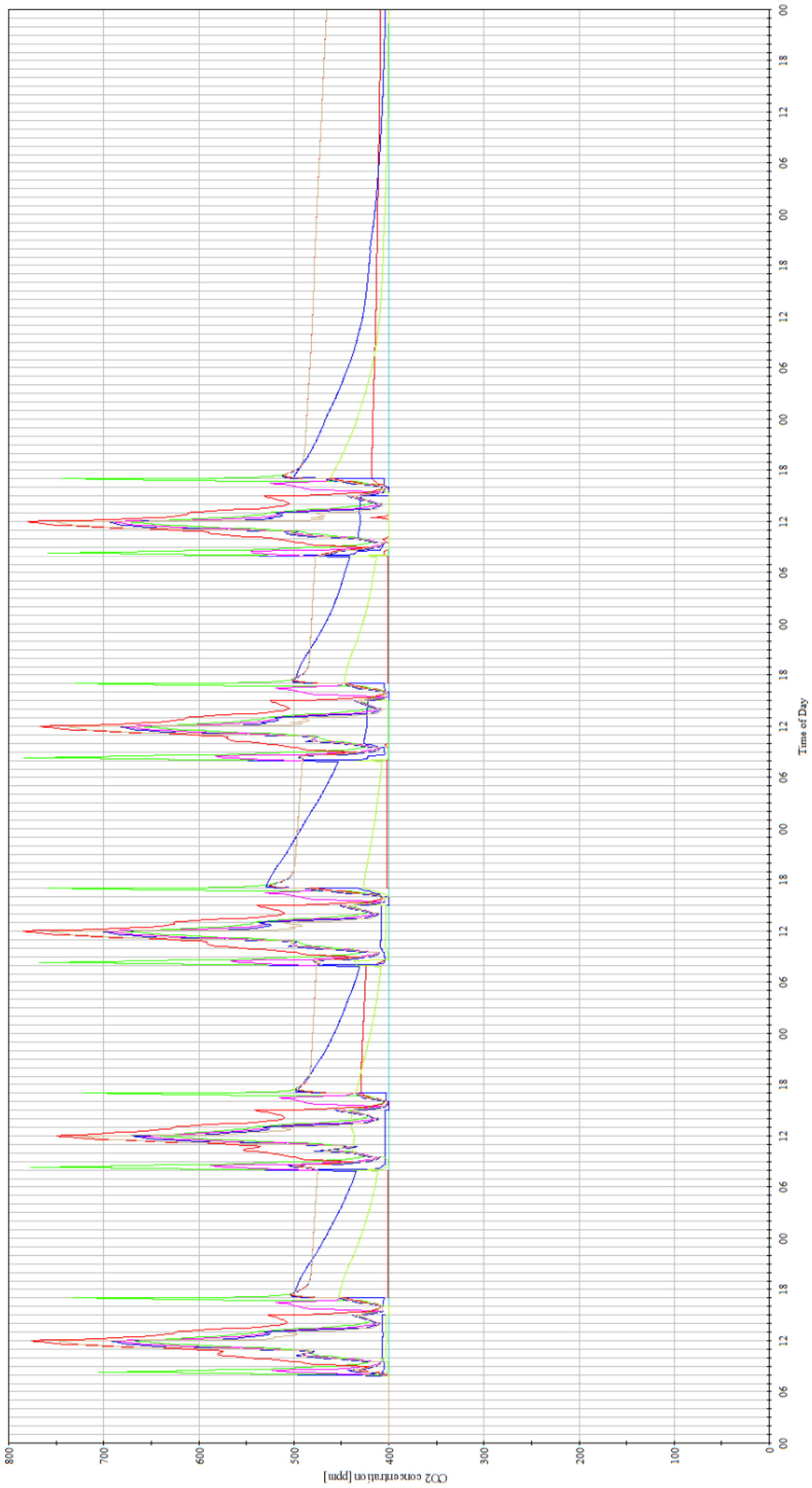


Fig.: H.3 Resulting CO_2 in the first floor when simulating building model A.1 during the transition.

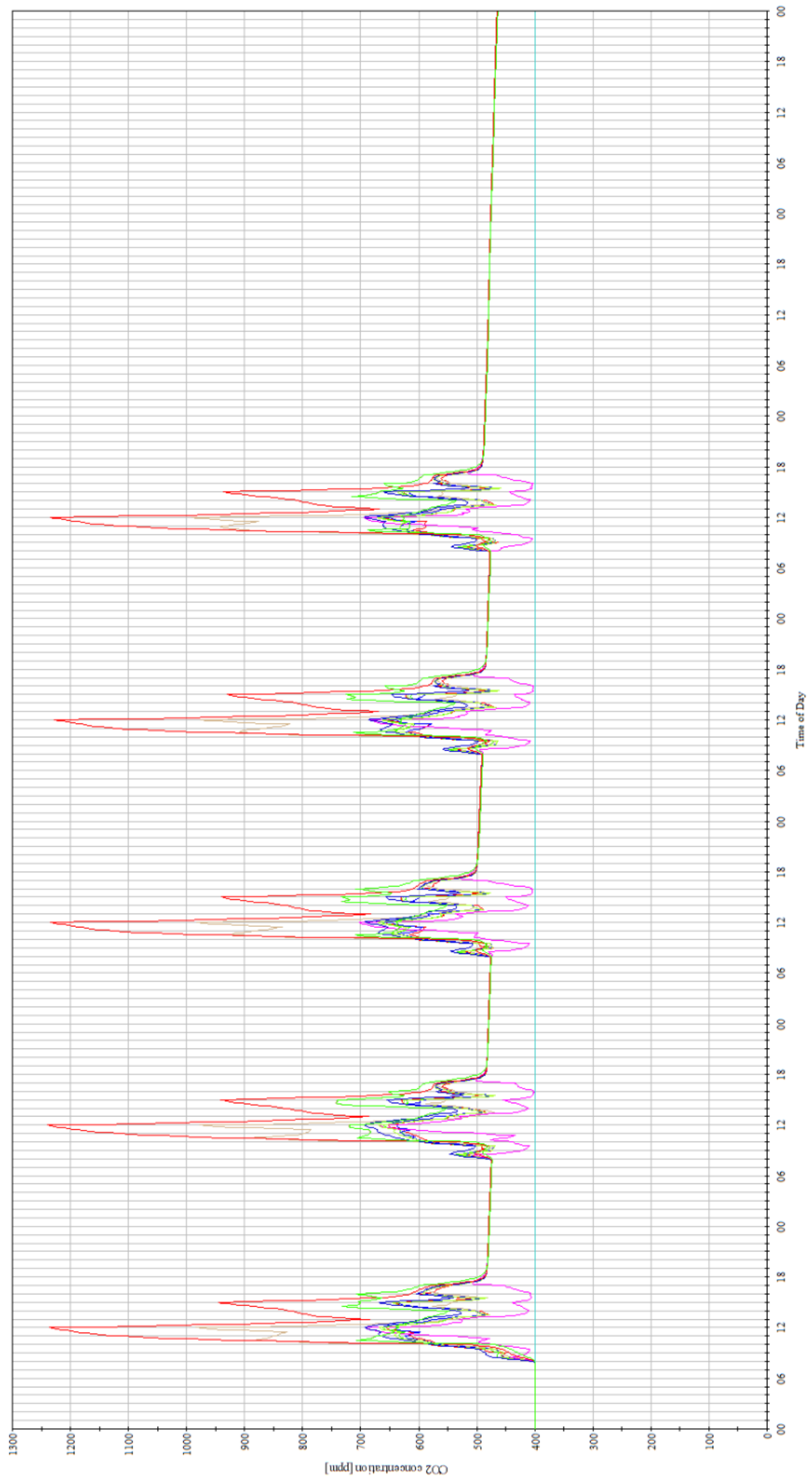


Fig.: H.4 Resulting CO_2 in the second floor when simulating building model A.1 during the transition.

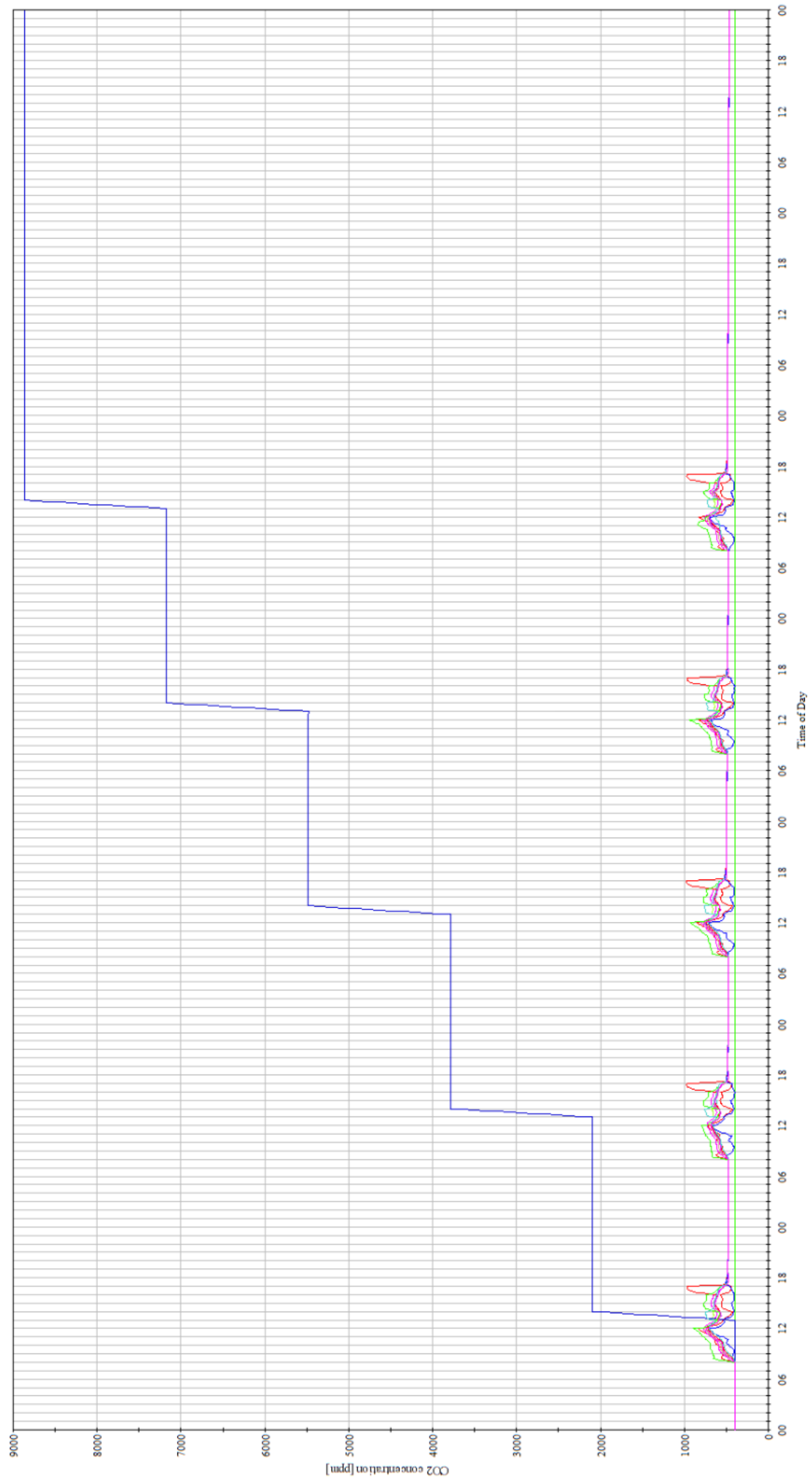


Fig.: H.5 Resulting CO_2 in the third floor when simulating building model A.1 during the transition.

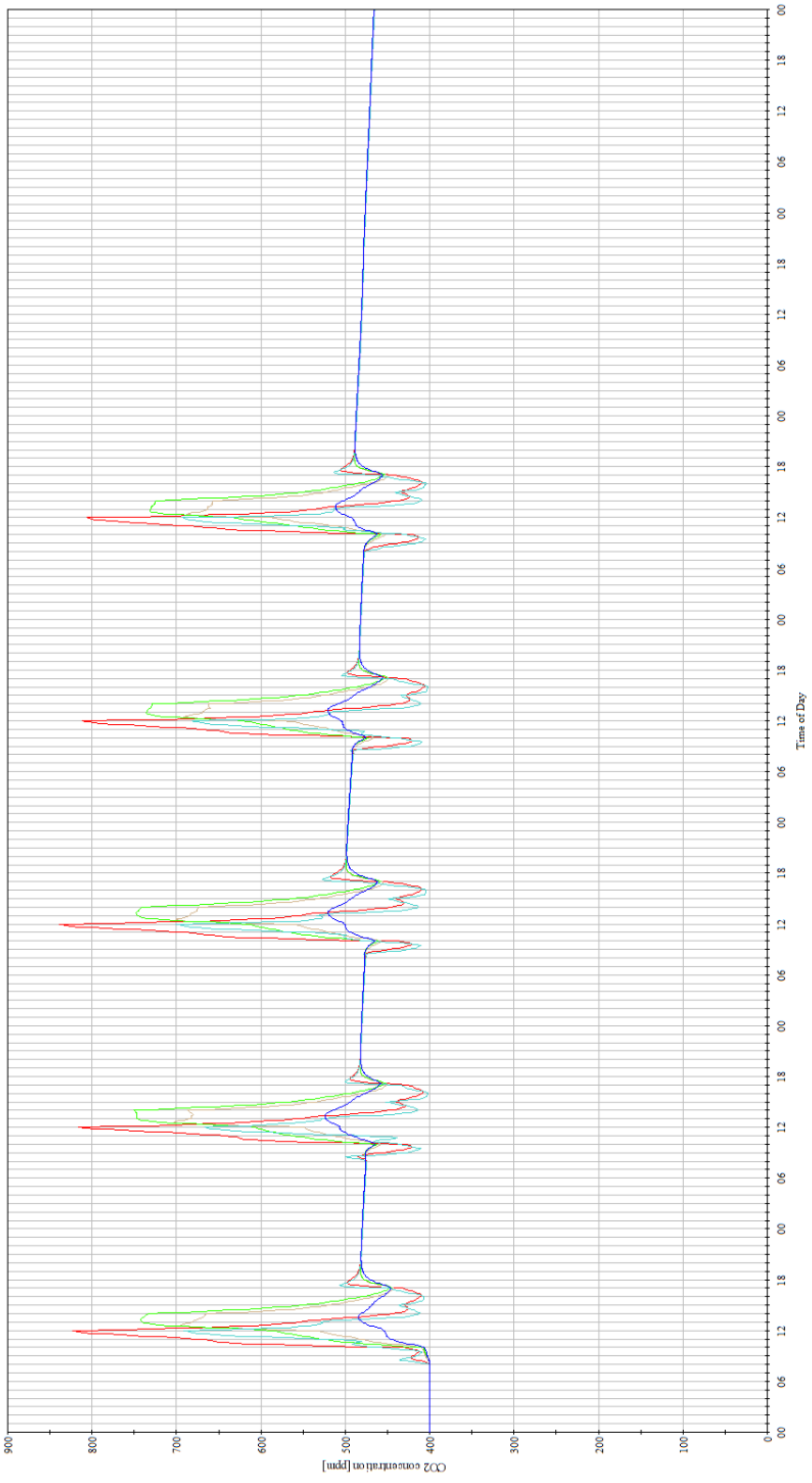


Fig.: H.6 Resulting CO_2 in the fourth floor when simulating building model A.1 during the transition

Model A.2

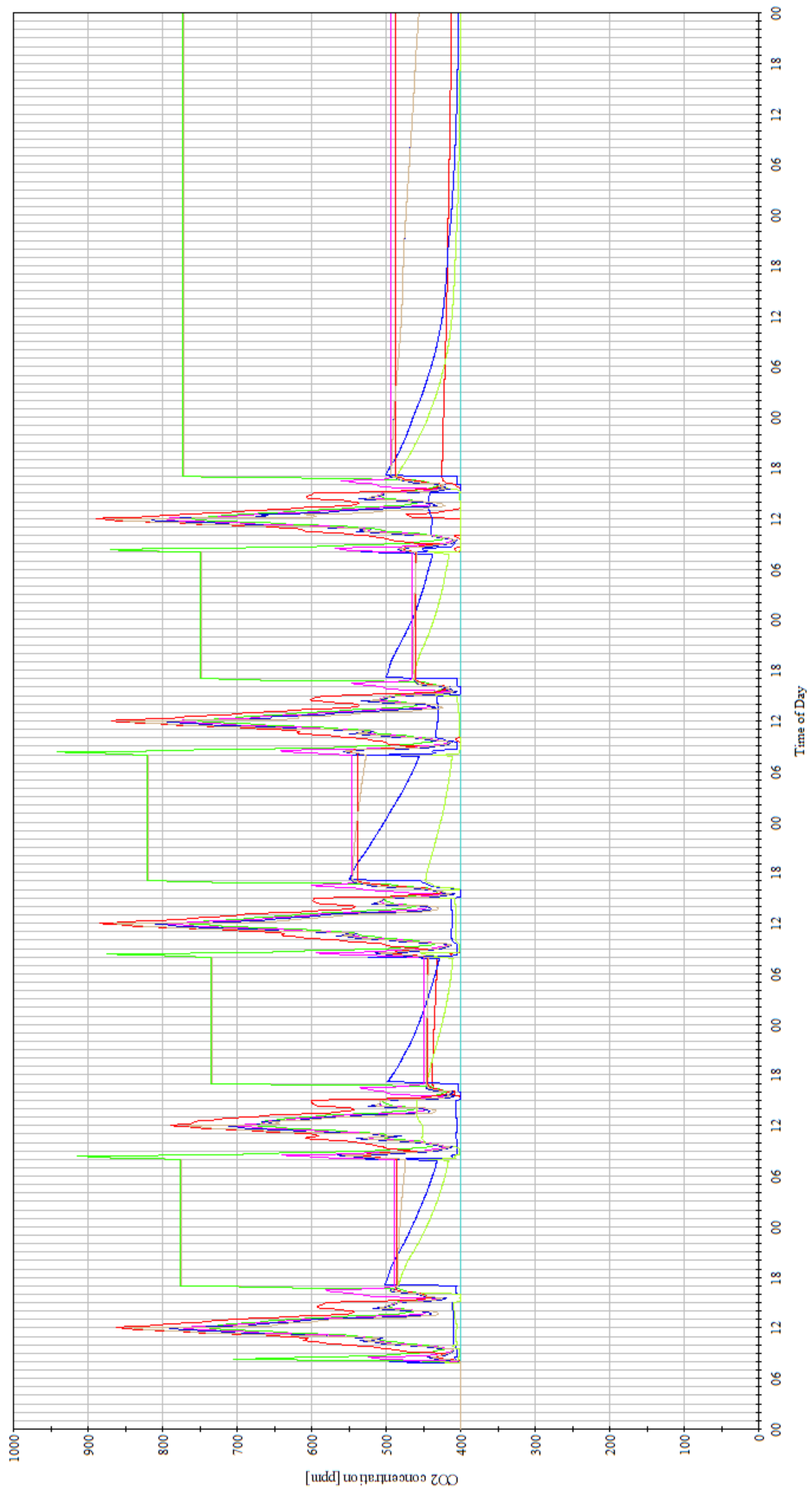


Fig.: H.7 Resulting CO_2 in the first floor when simulating building model A.2 during the transition.

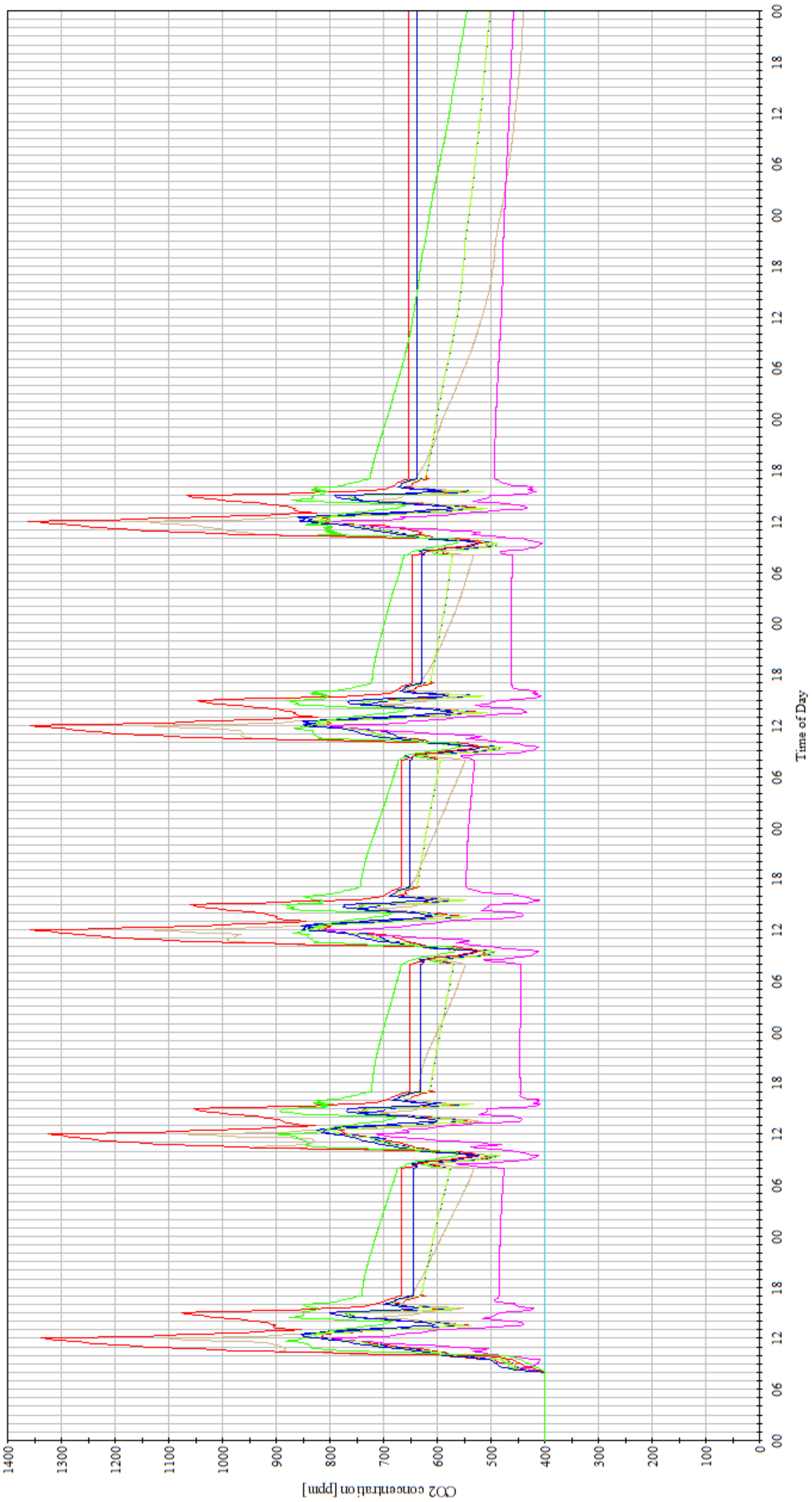


Fig.: H.8 Resulting CO_2 in the second floor when simulating building model A.2 during the transition.

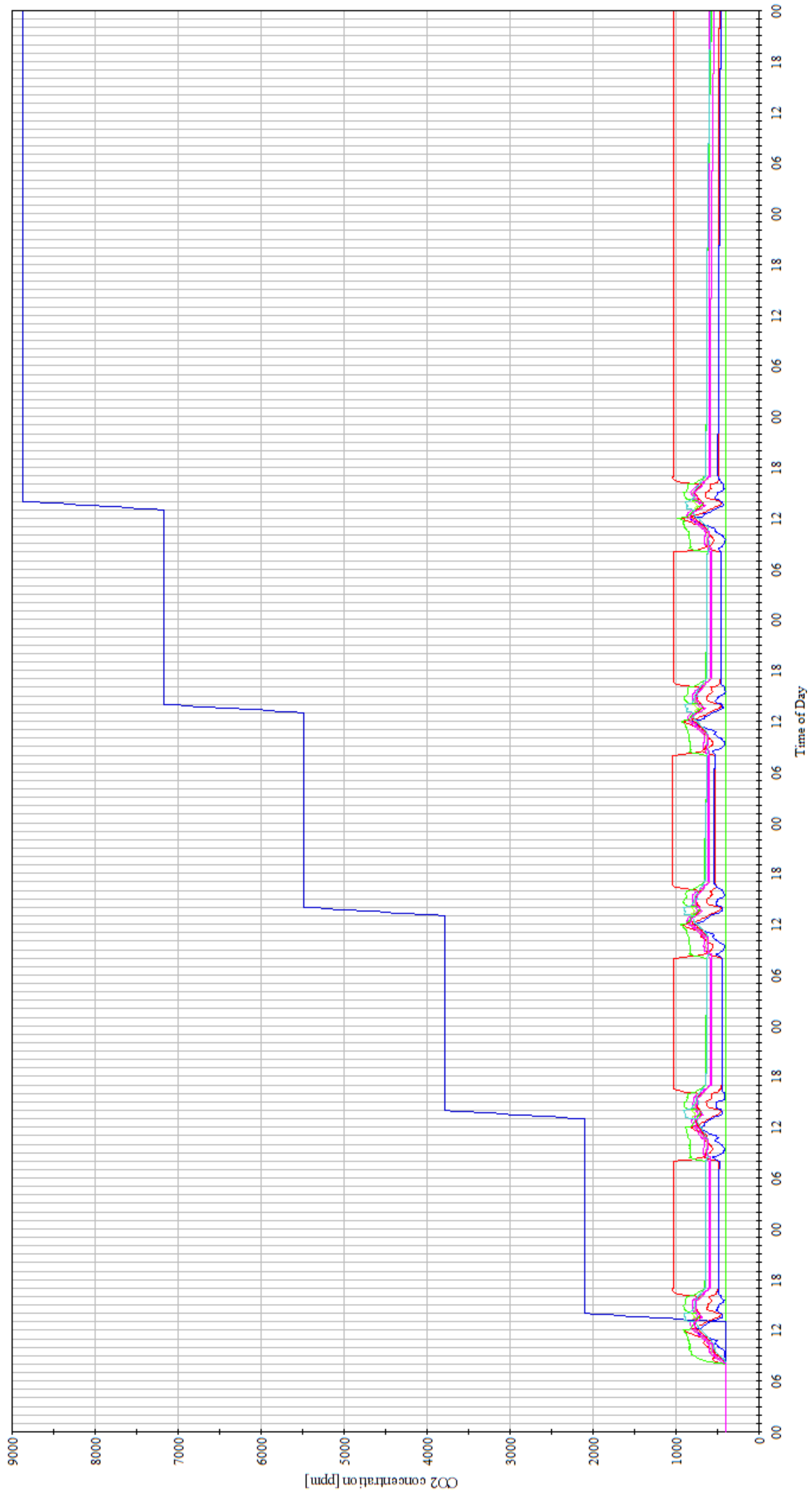


Fig.: H.9 Resulting CO_2 in the third floor when simulating building model A.2 during the transition.

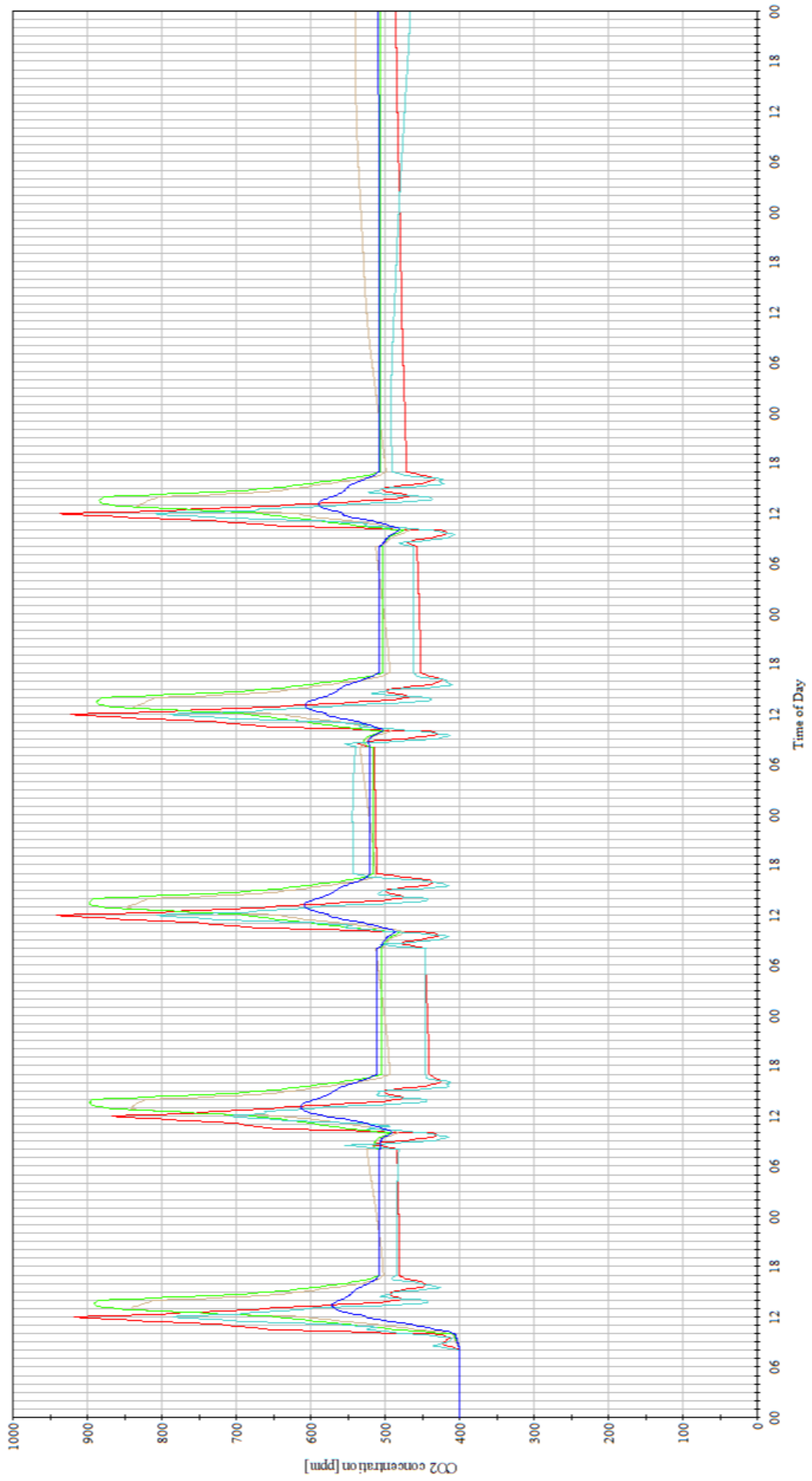


Fig.: H.10 Resulting CO_2 in the fourth floor when simulating building model A.2 during the transition

Model B.1

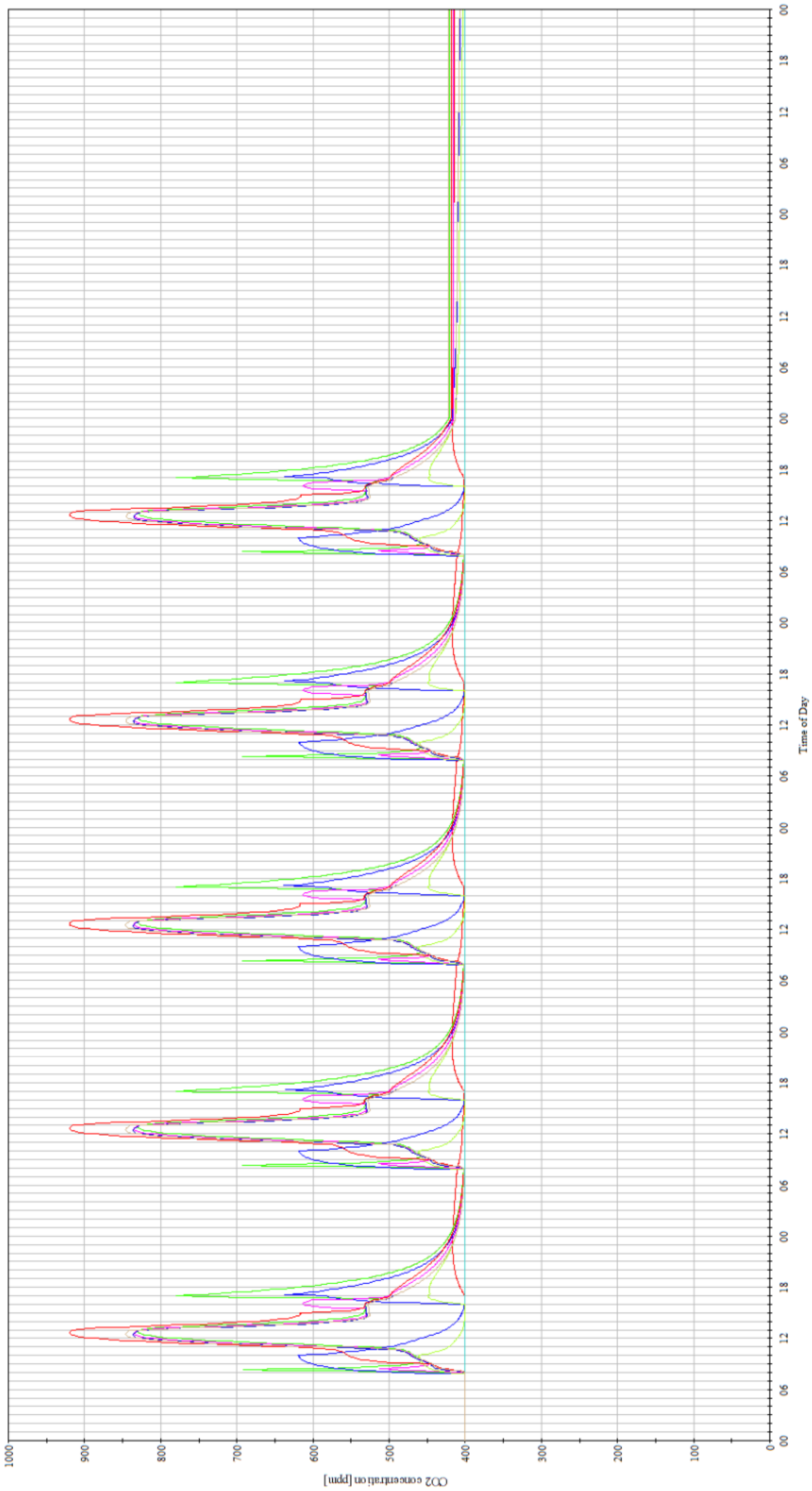


Fig.: H.11 Resulting CO_2 in the first floor when simulating building model B.1 during the transition.

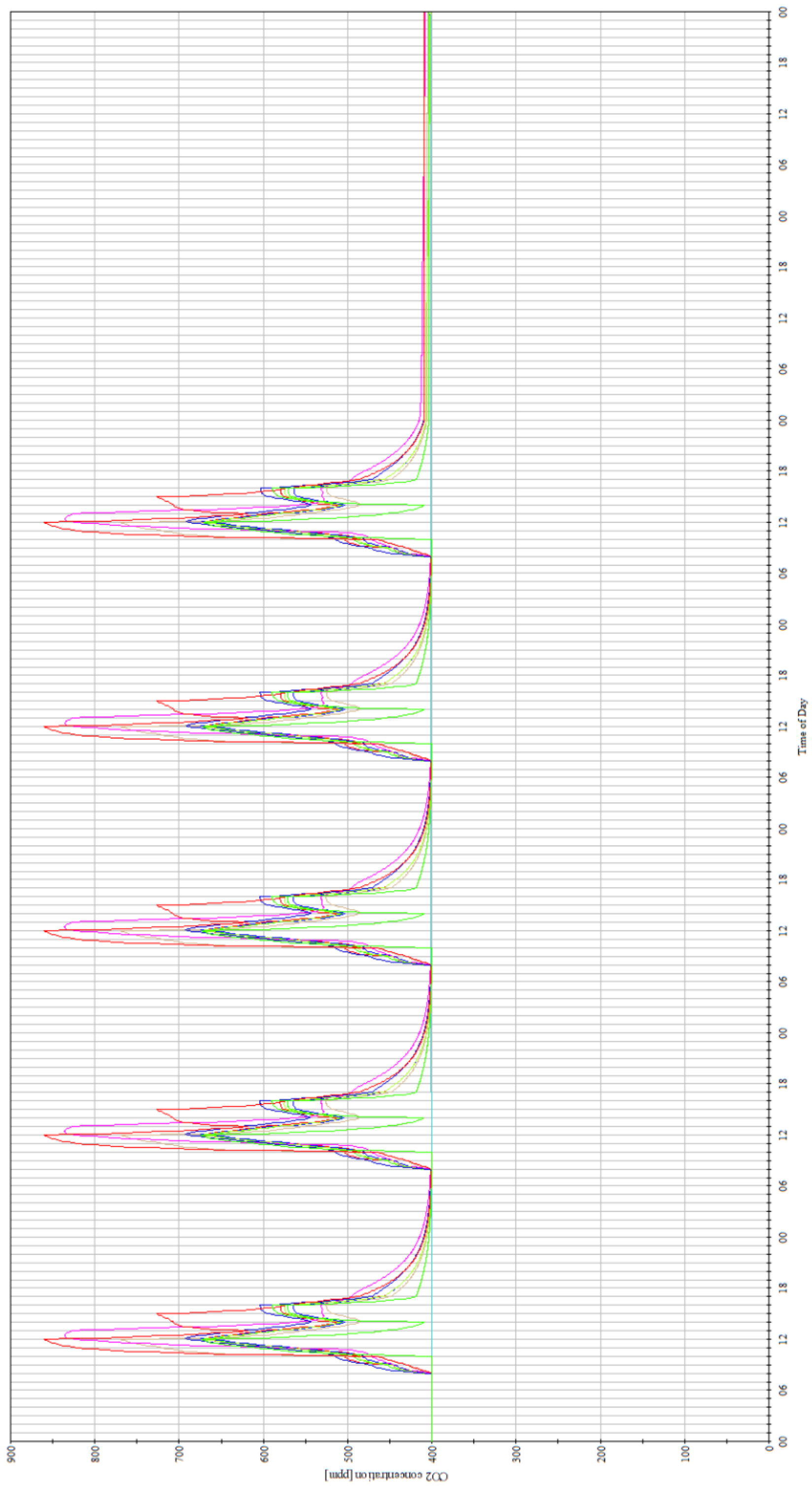


Fig.: H.12 Resulting CO_2 in the second floor when simulating building model B.1 during the transition.

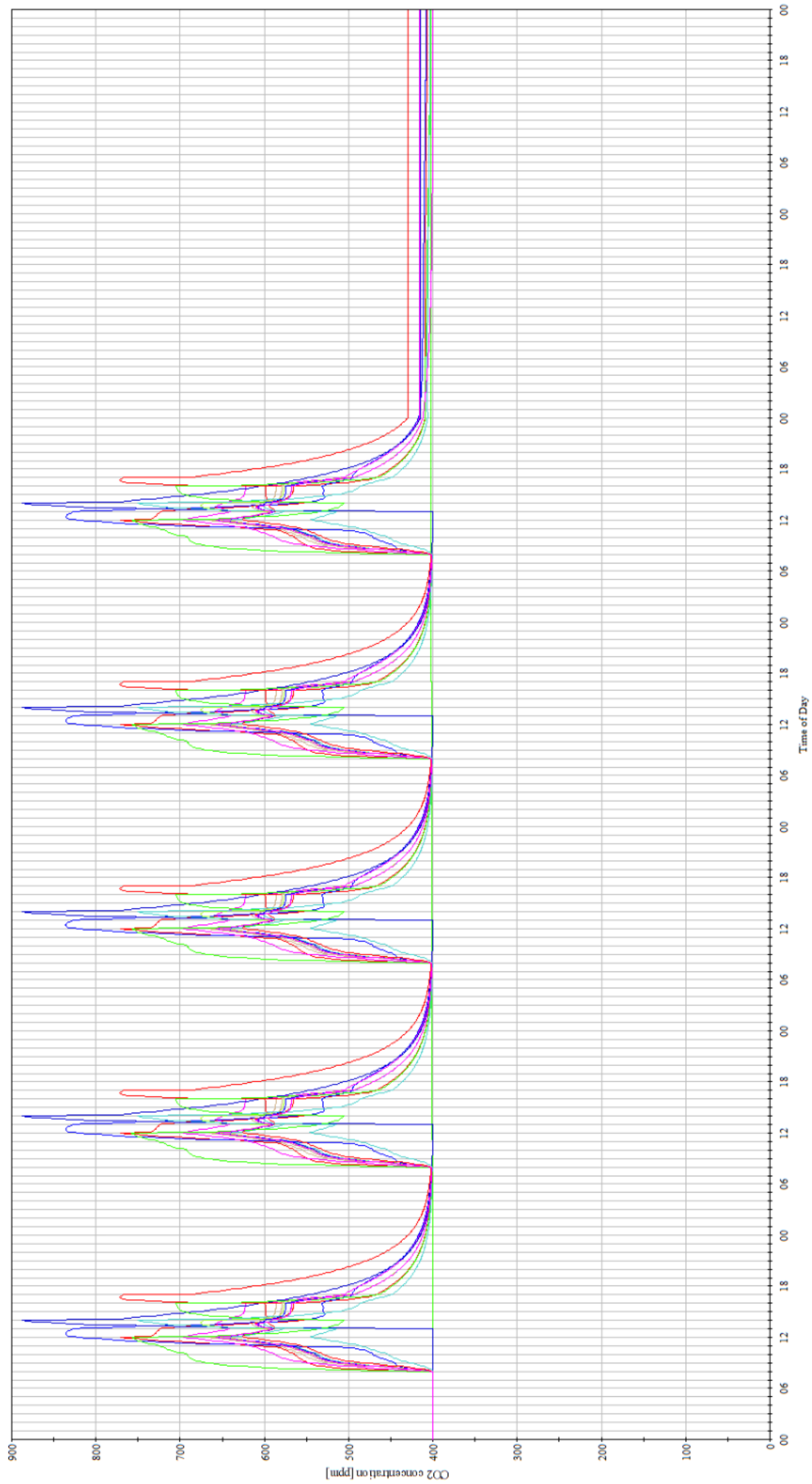


Fig.: H.13 Resulting CO_2 in the third floor when simulating building model B.1 during the transition.

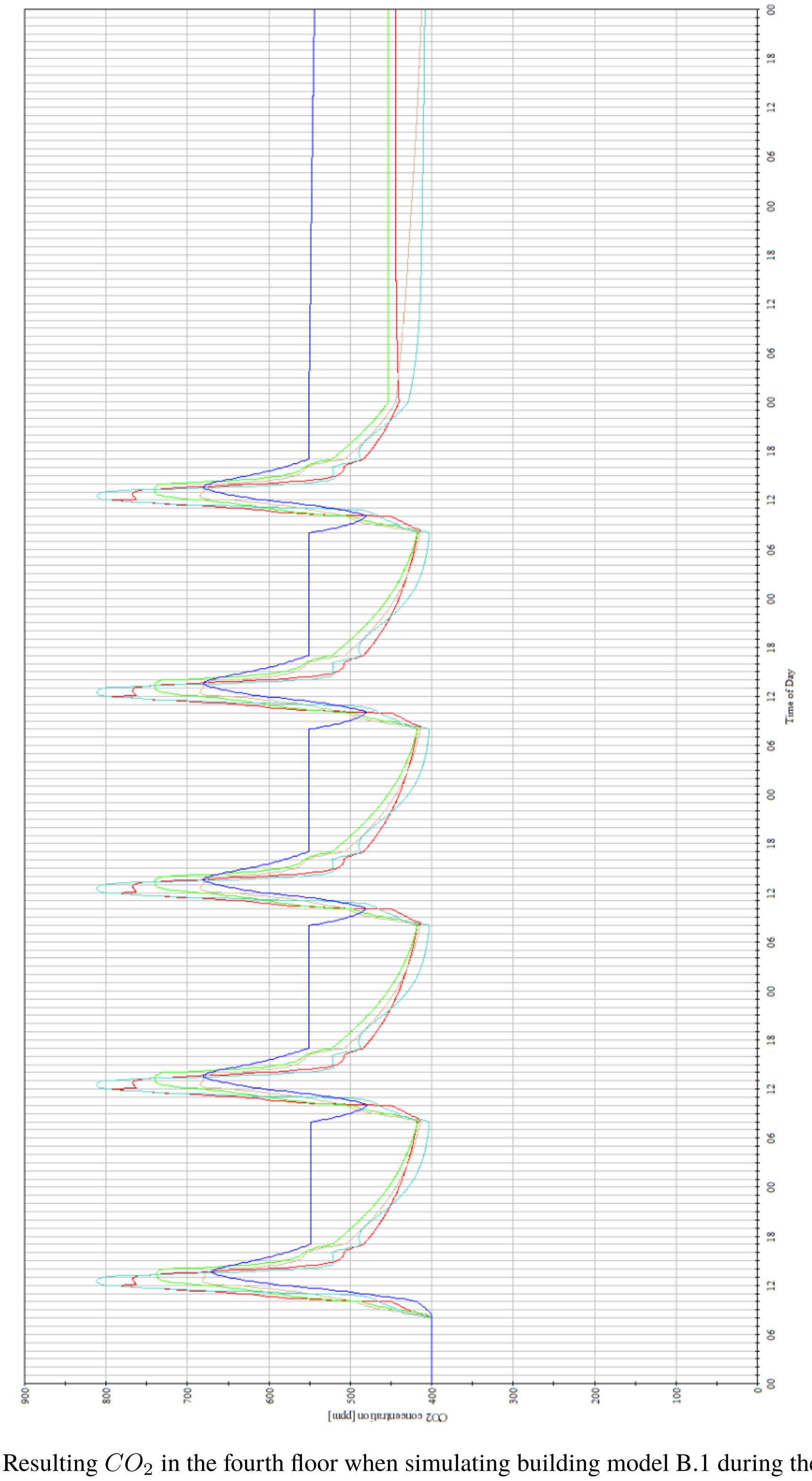


Fig.: H.14 Resulting CO_2 in the fourth floor when simulating building model B.1 during the transition

Model B.2

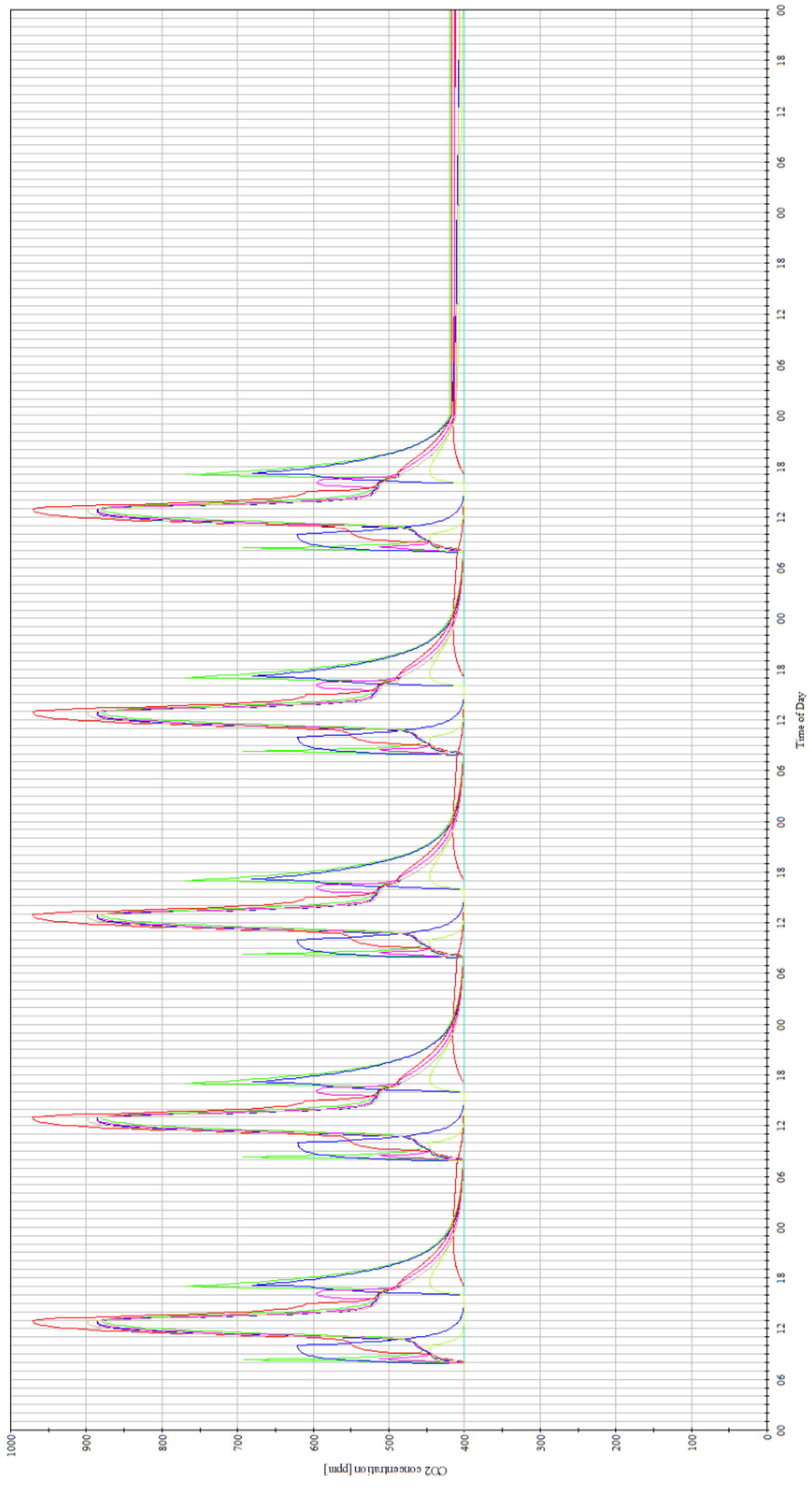


Fig.: H.15 Resulting CO_2 in the first floor when simulating building model B.2 during the transition.

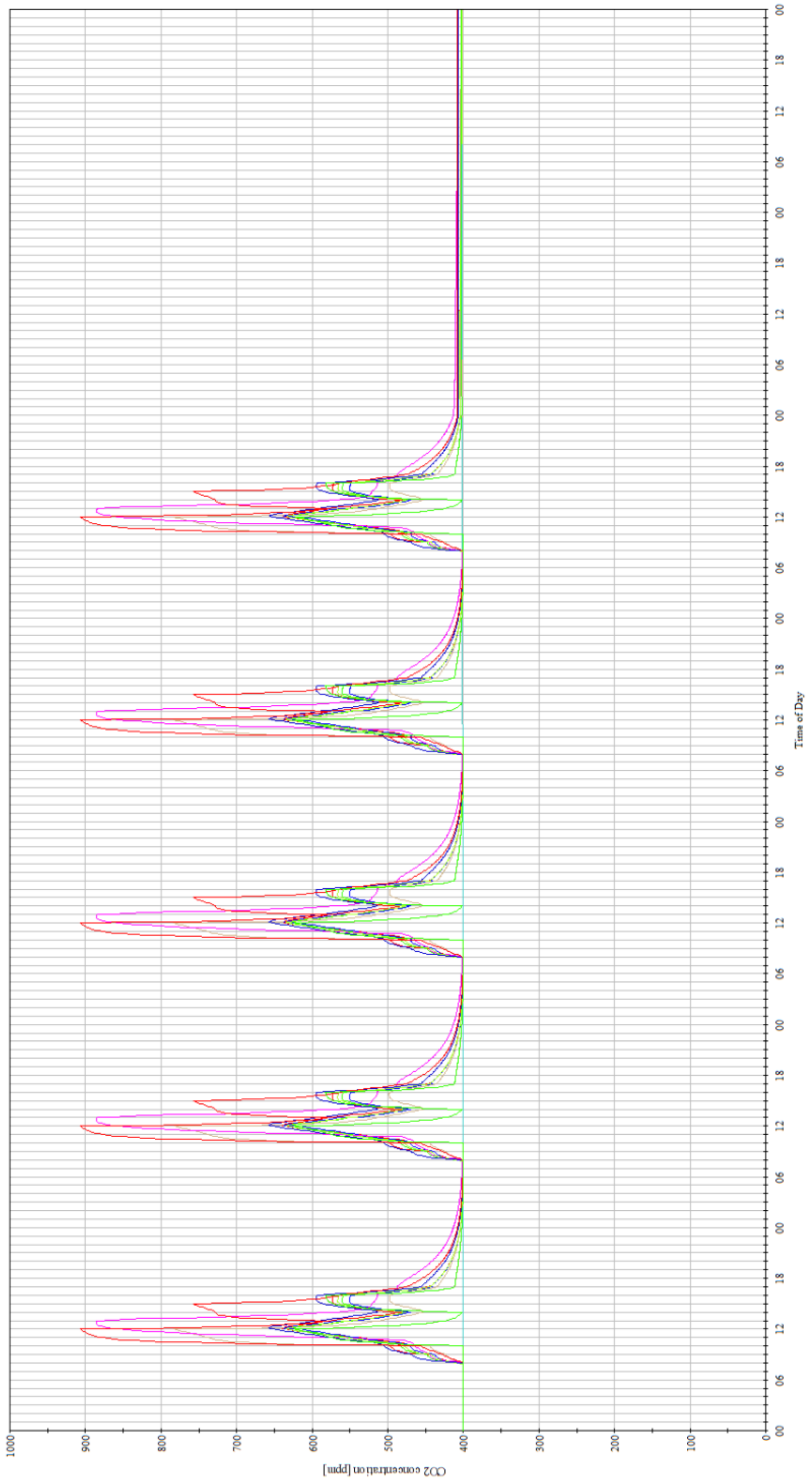


Fig.: H.16 Resulting CO_2 in the second floor when simulating building model B.2 during the transition.

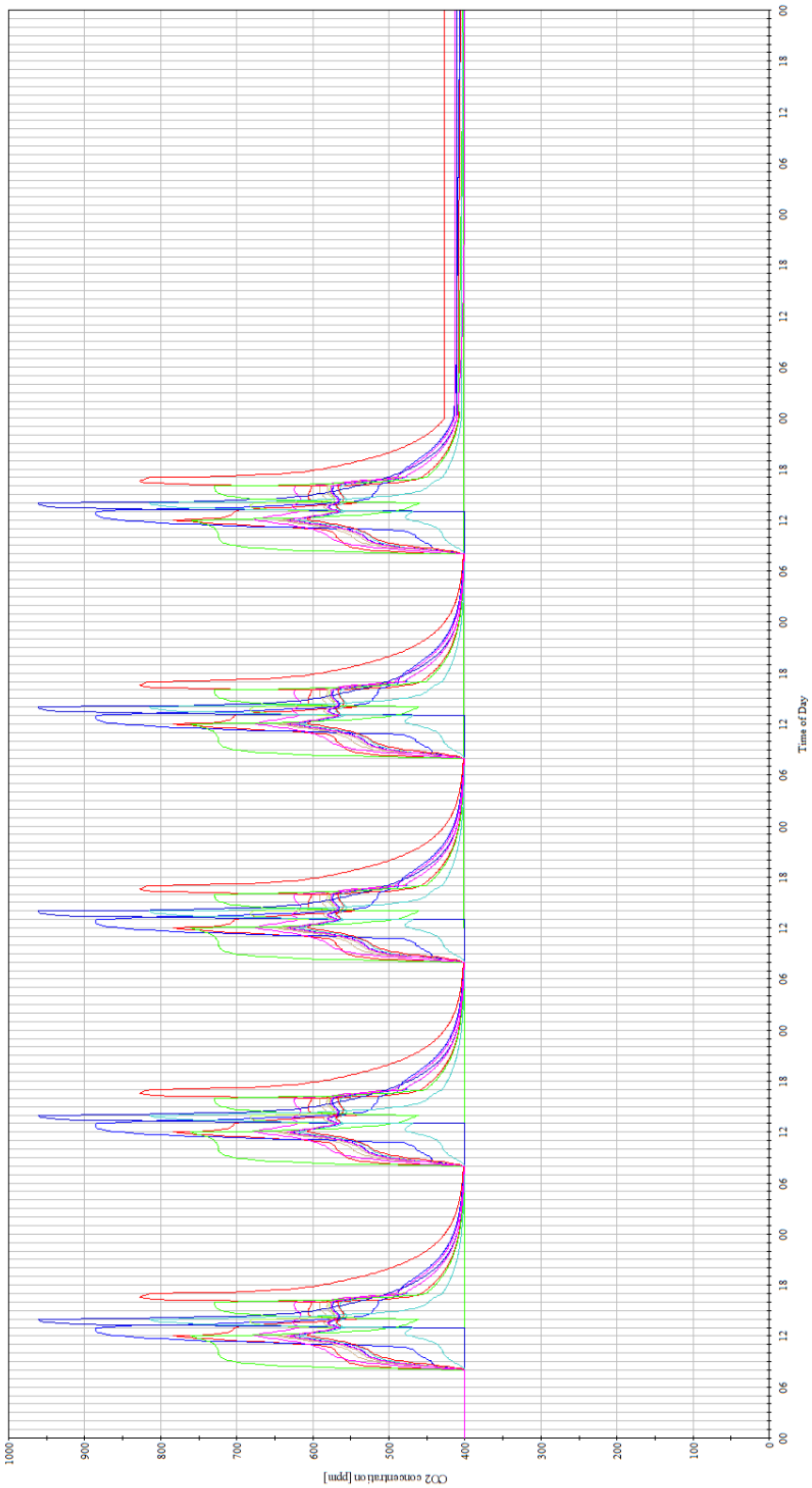


Fig.: H.17 Resulting CO_2 in the third floor when simulating building model B.2 during the transition.

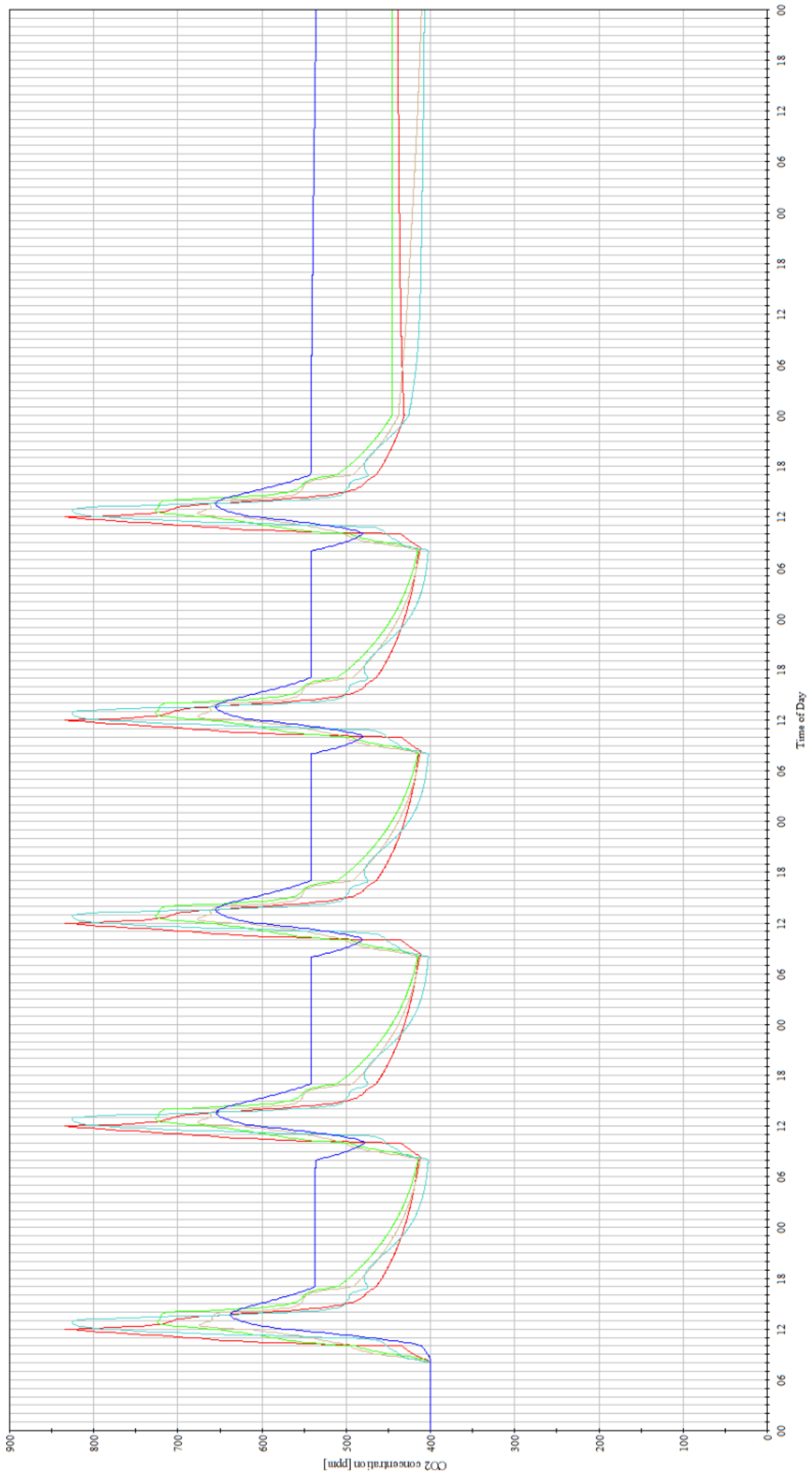


Fig.: H.18 Resulting CO_2 in the fourth floor when simulating building model B.2 during the transition

Model A.1+B.1

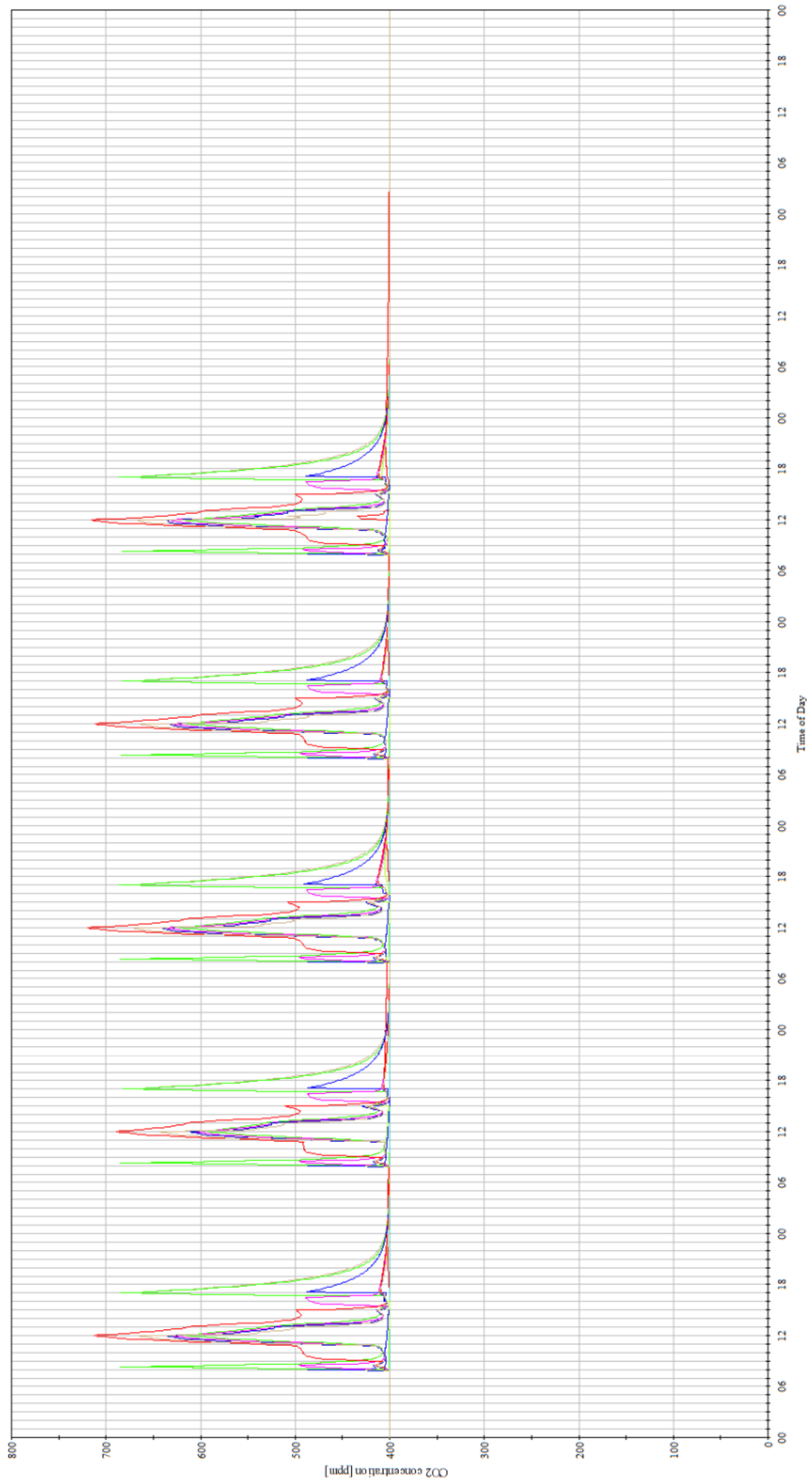


Fig.: H.19 Resulting CO_2 in the first floor when simulating building model A.1+B.1 during the transition.

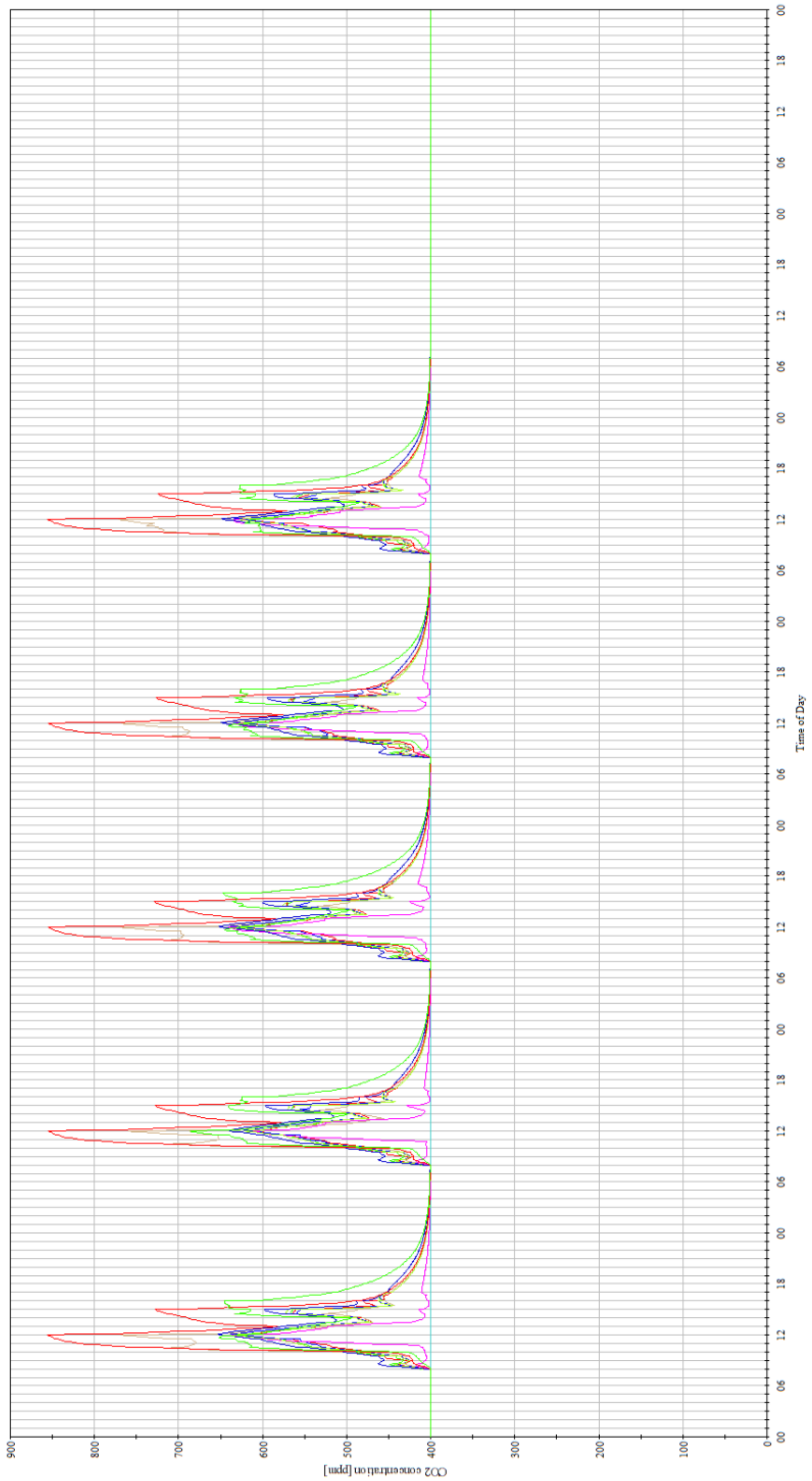


Fig.: H.20 Resulting CO_2 in the second floor when simulating building model A.1+B.1 during the transition.

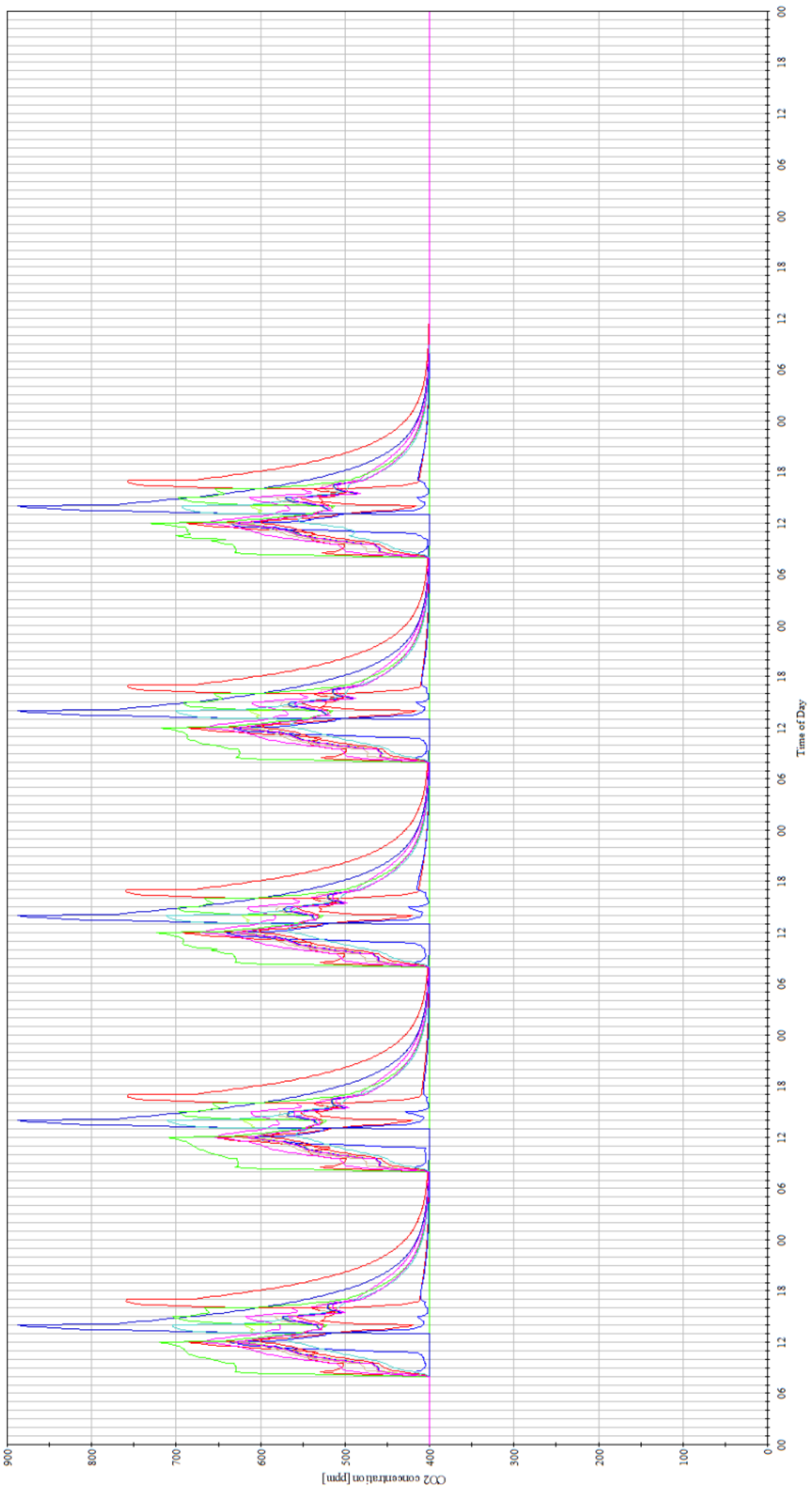


Fig.: H.21 Resulting CO_2 in the third floor when simulating building model A.1+B.1 during the transition.

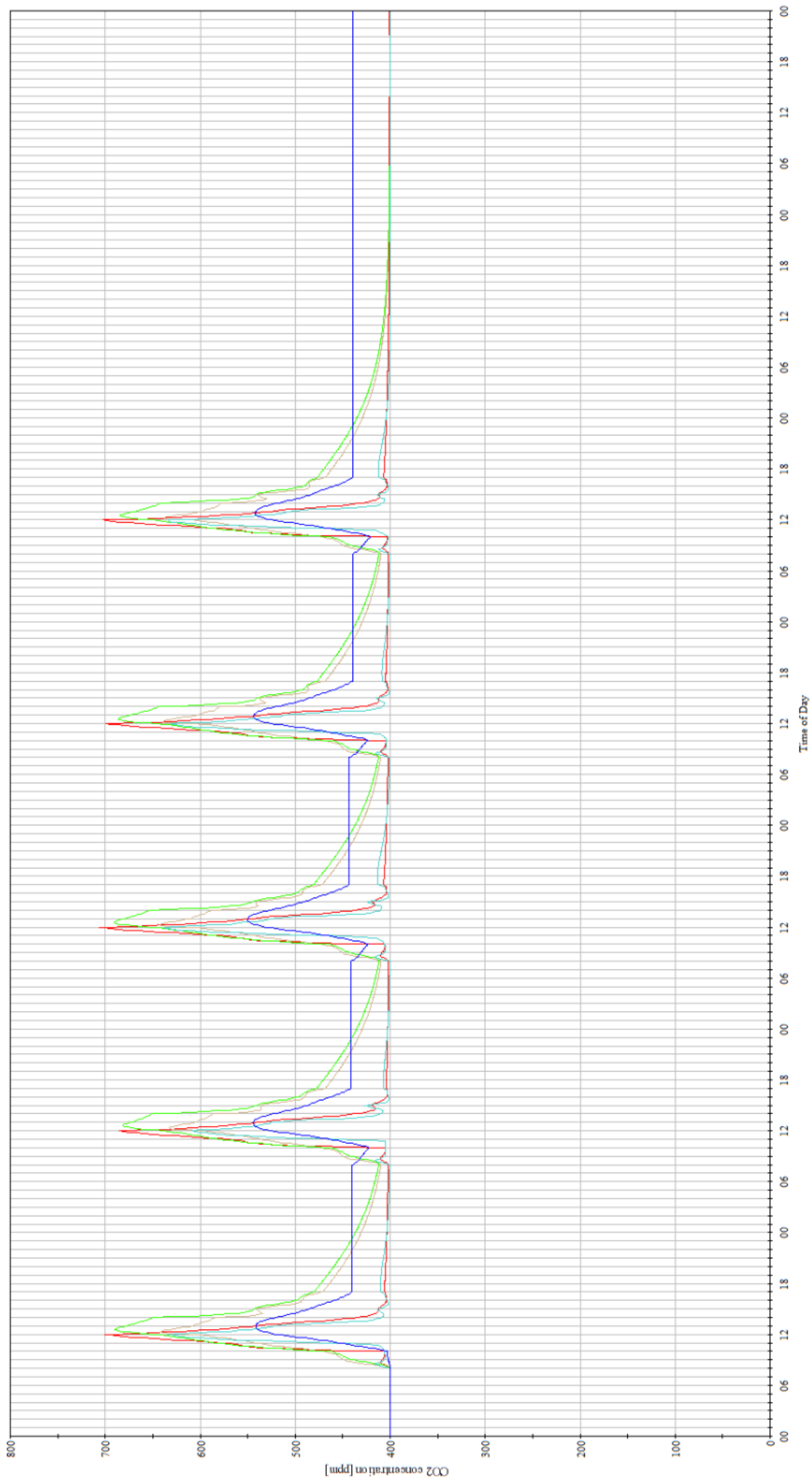


Fig.: H.22 Resulting CO_2 in the fourth floor when simulating building model A.1+B.1 during the transition

Model A.1+B.2

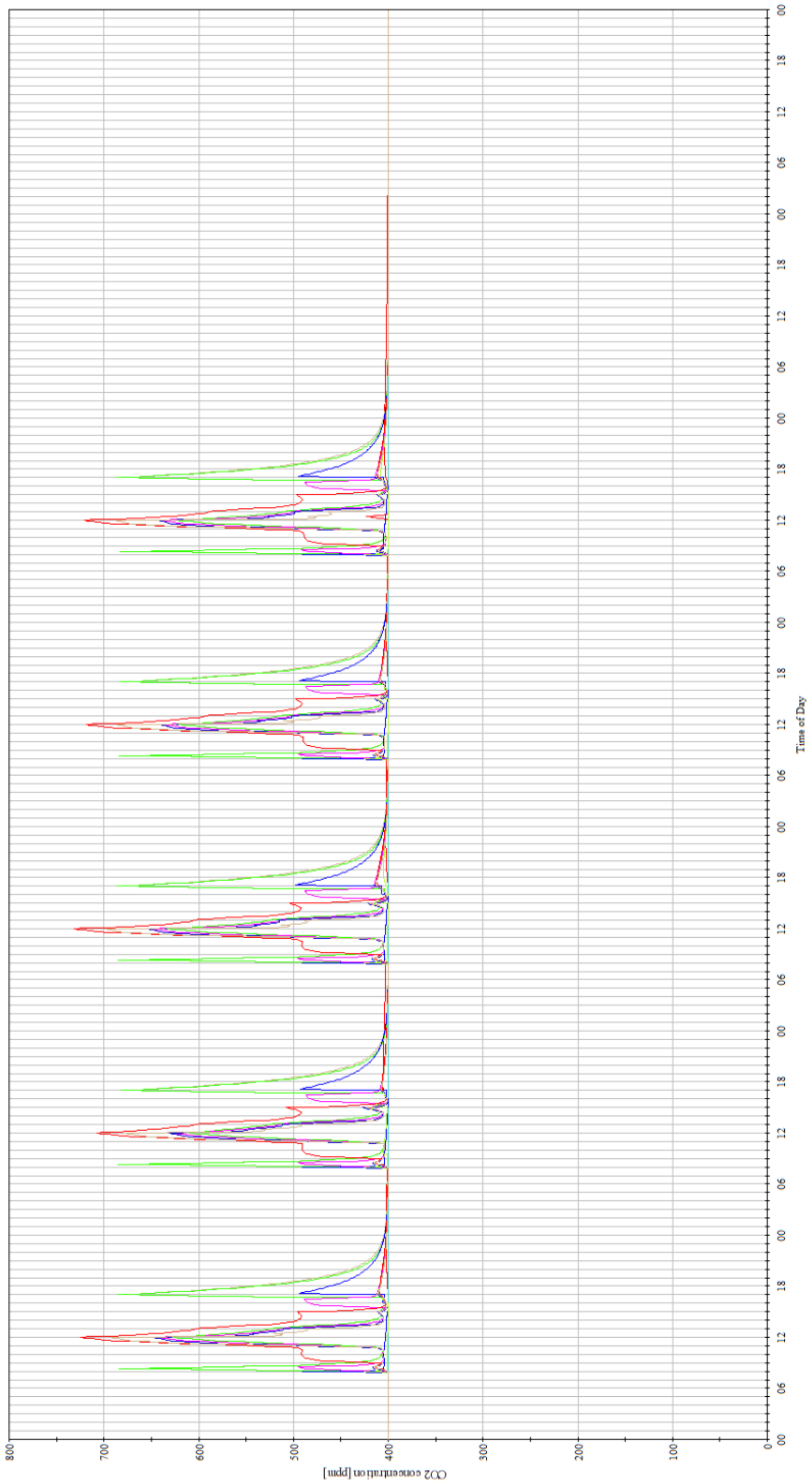


Fig.: H.23 Resulting CO_2 in the first floor when simulating building model A.1+B.2 during the transition.

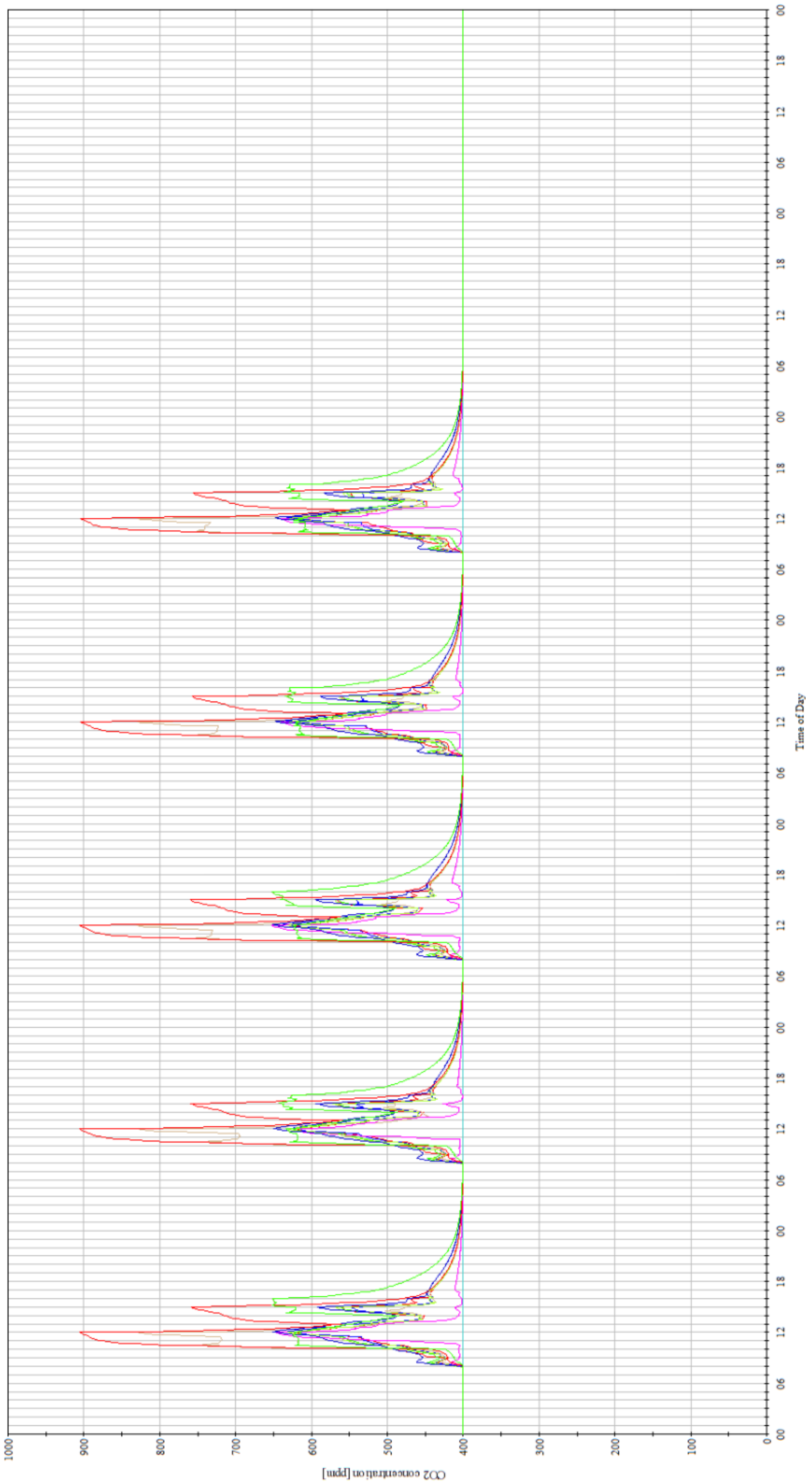


Fig.: H.24 Resulting CO_2 in the second floor when simulating building model A.1+B.2 during the transition.

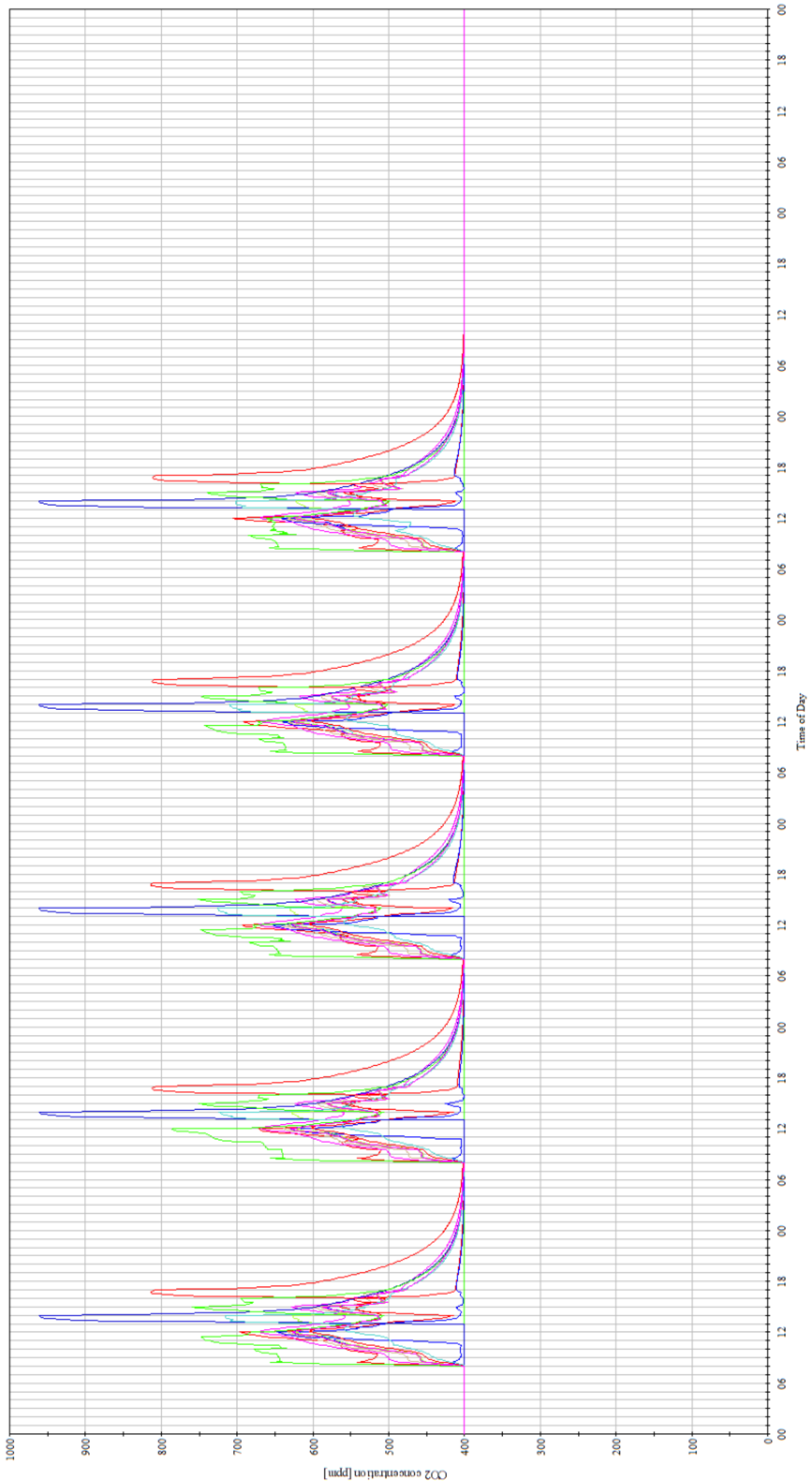


Fig.: H.25 Resulting CO_2 in the third floor when simulating building model A.1+B.2 during the transition.

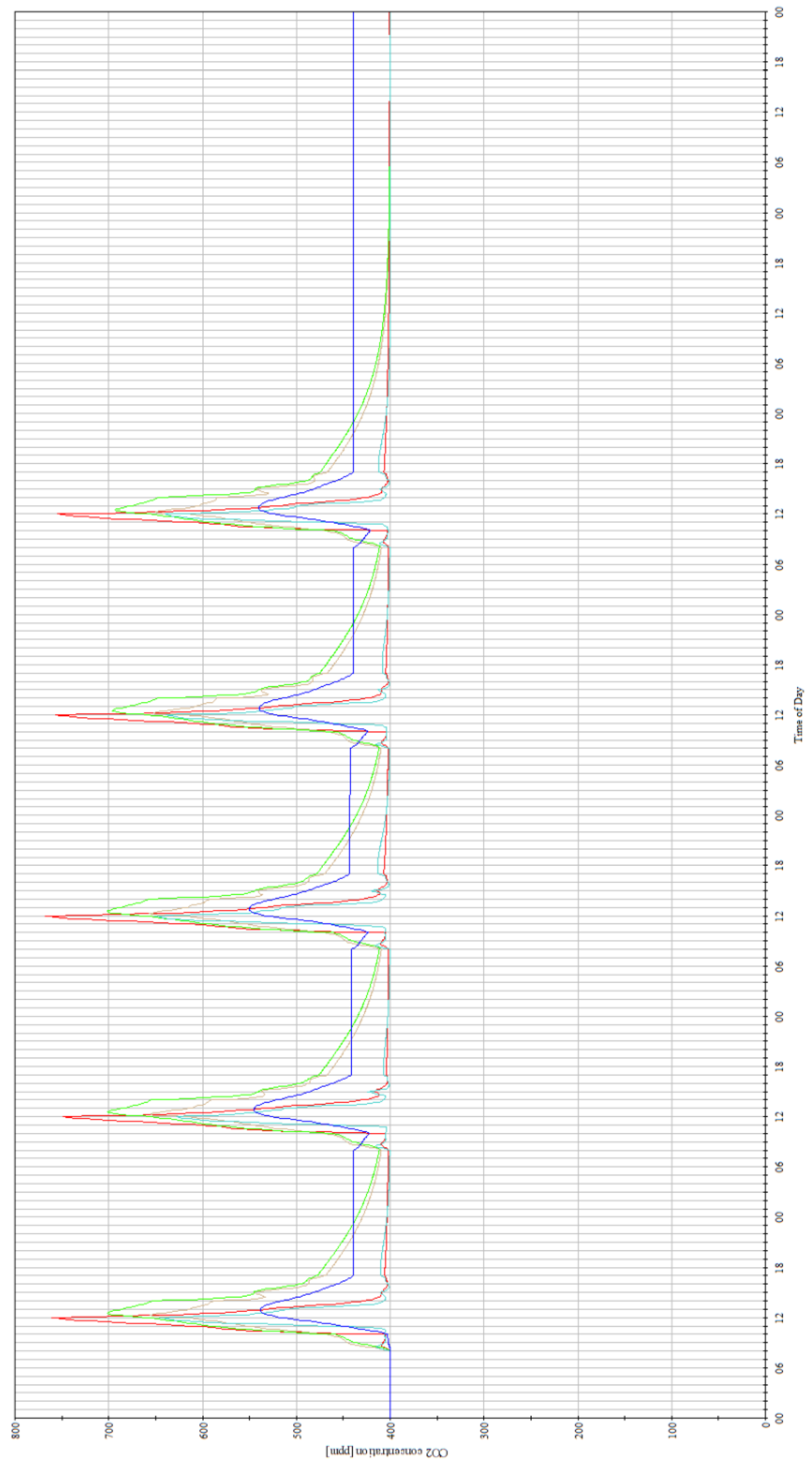


Fig.: H.26 Resulting CO_2 in the fourth floor when simulating building model A.1+B.2 during the transition

Model A.2+B.1

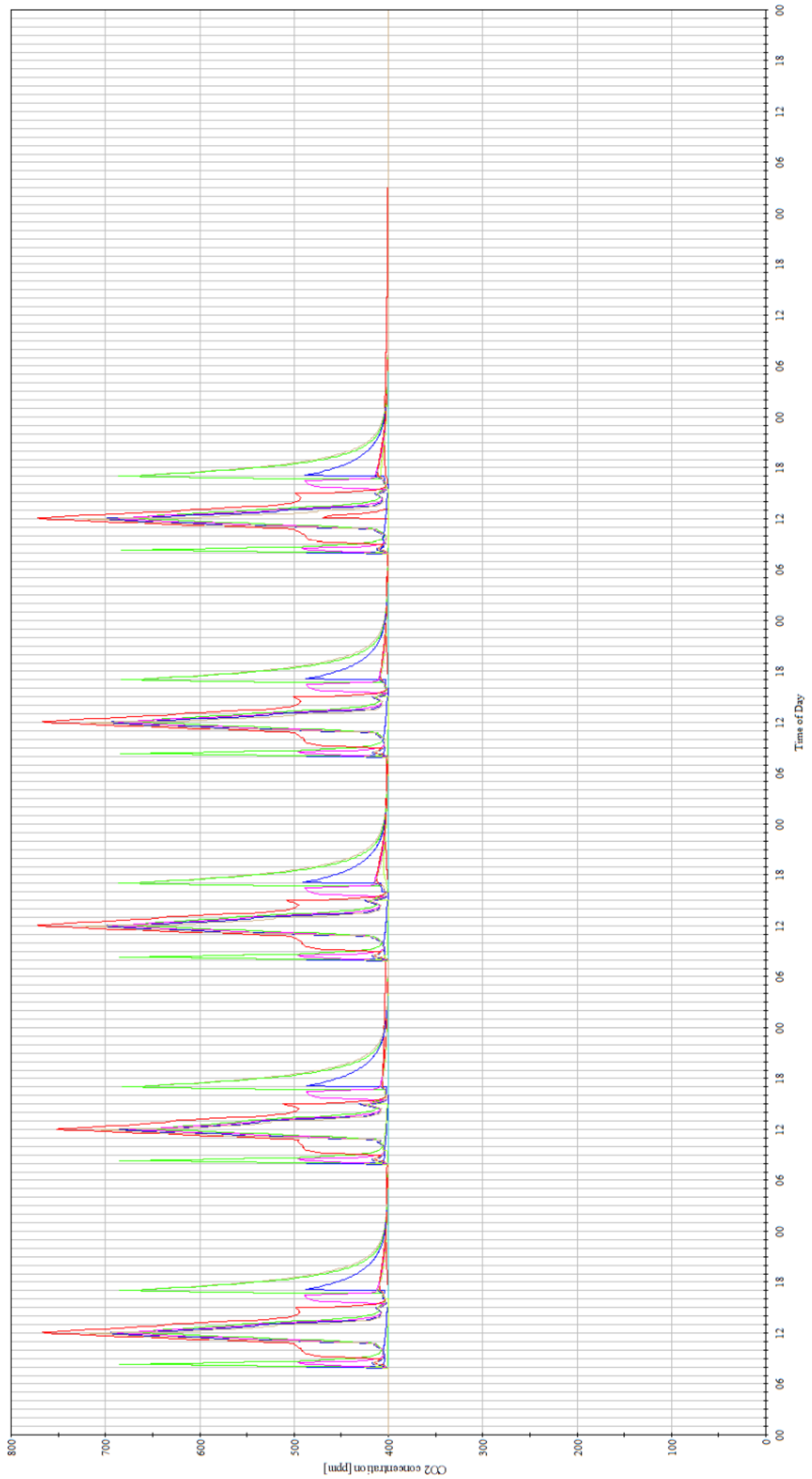


Fig.: H.27 Resulting CO_2 in the first floor when simulating building model A.2+B.1 during the transition.

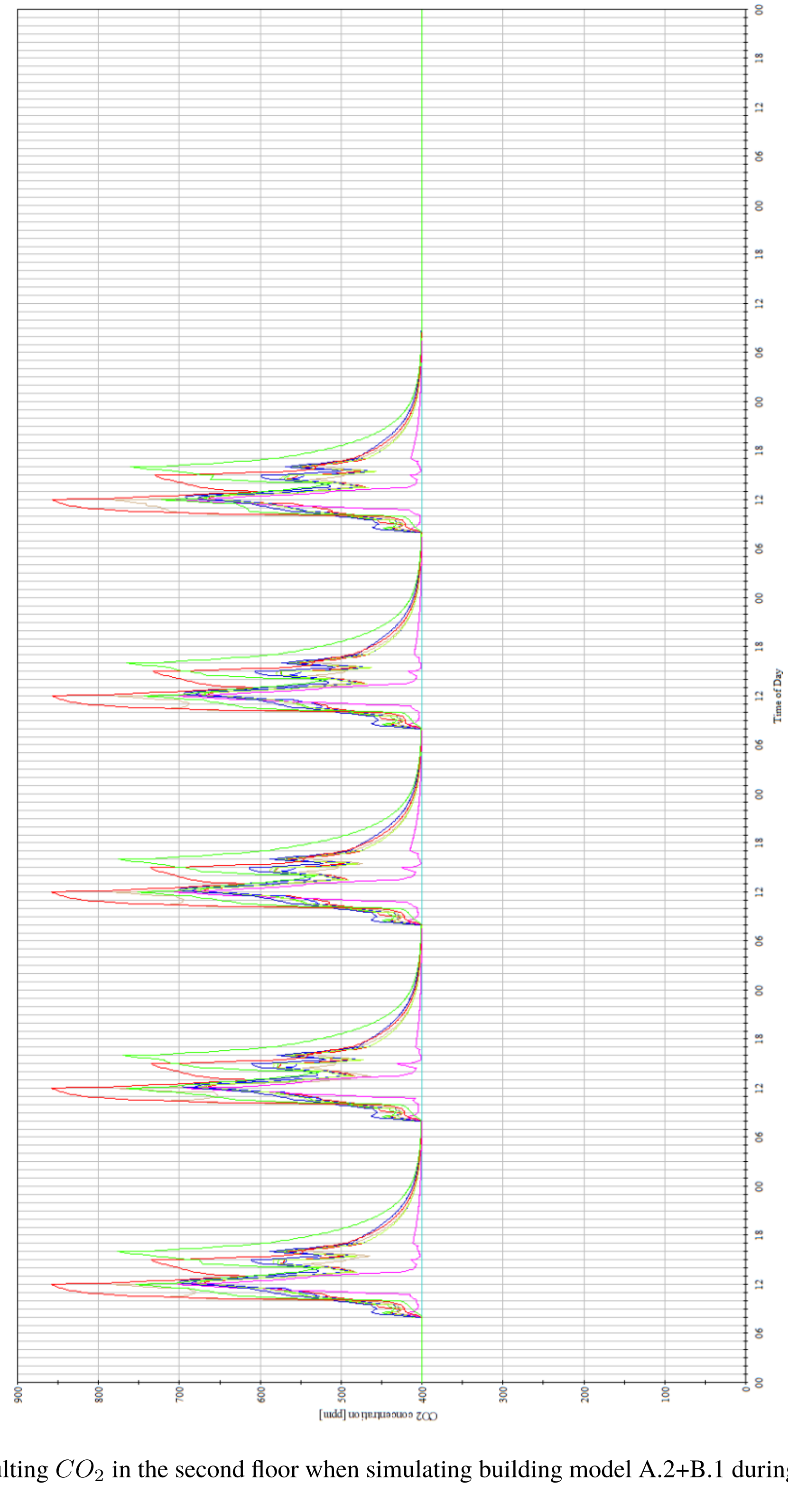


Fig.: H.28 Resulting CO_2 in the second floor when simulating building model A.2+B.1 during the transition.

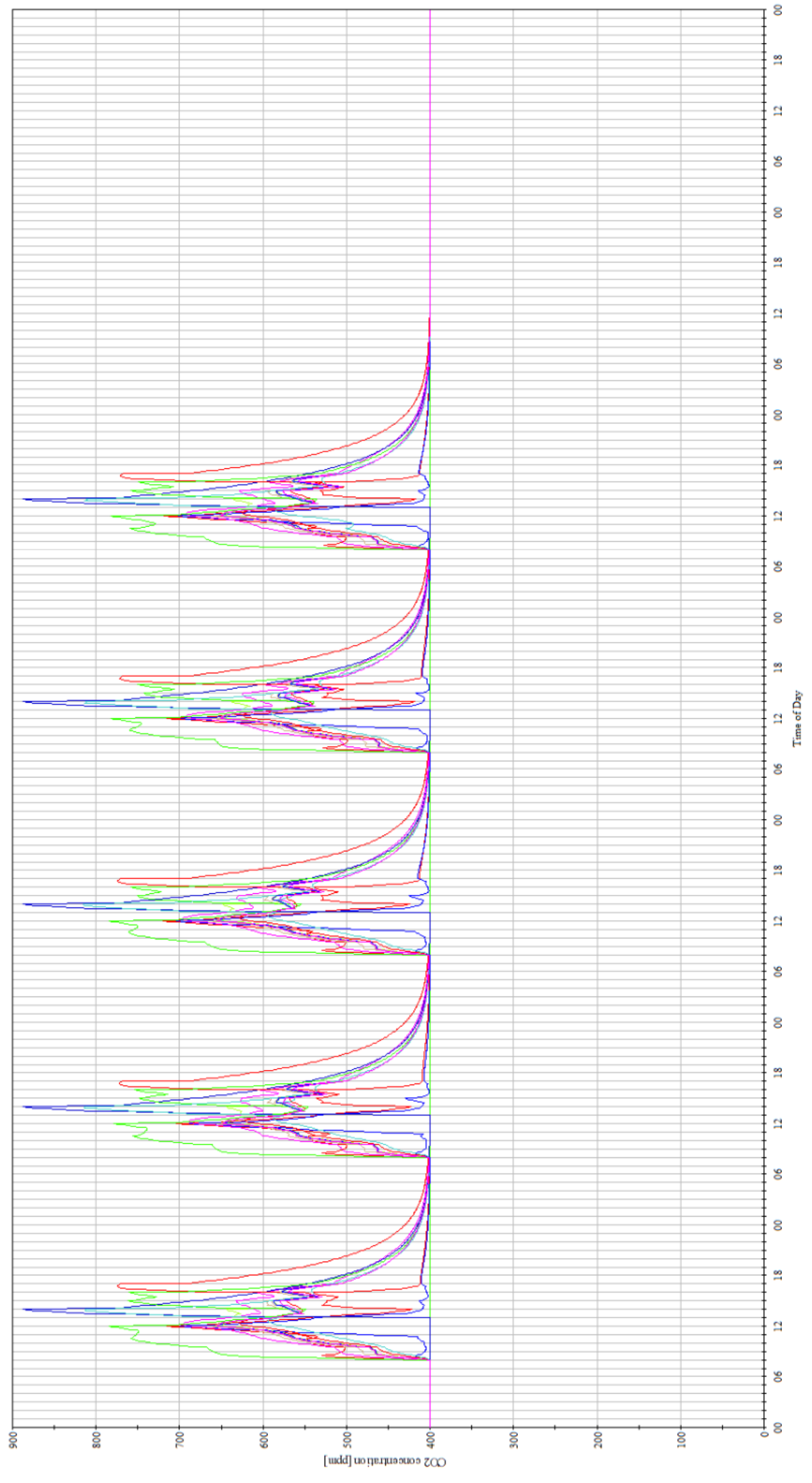


Fig.: H.29 Resulting CO_2 in the third floor when simulating building model A.2+B.1 during the transition.

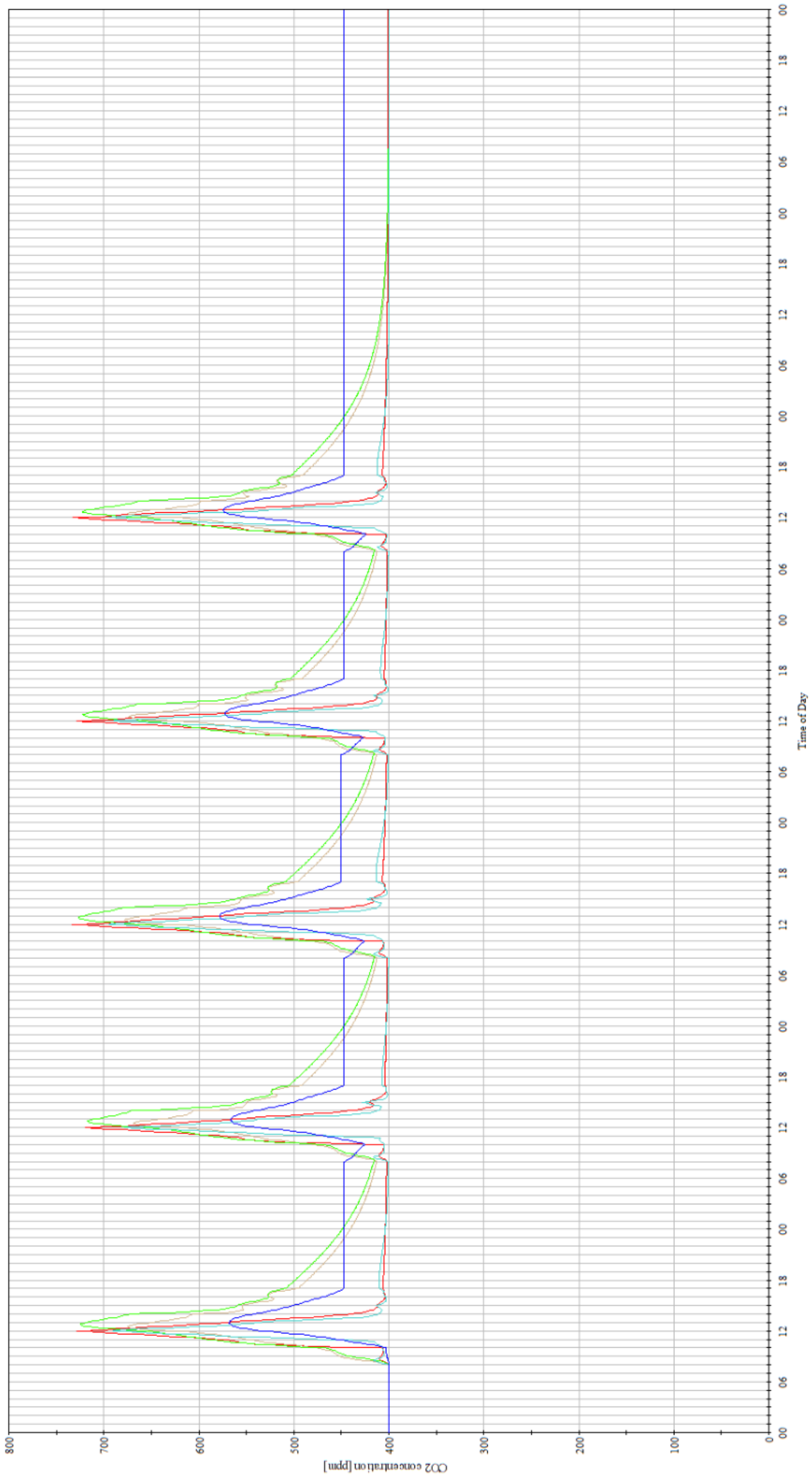


Fig.: H.30 Resulting CO_2 in the fourth floor when simulating building model A.2+B.1 during the transition

Model A.2+B.2

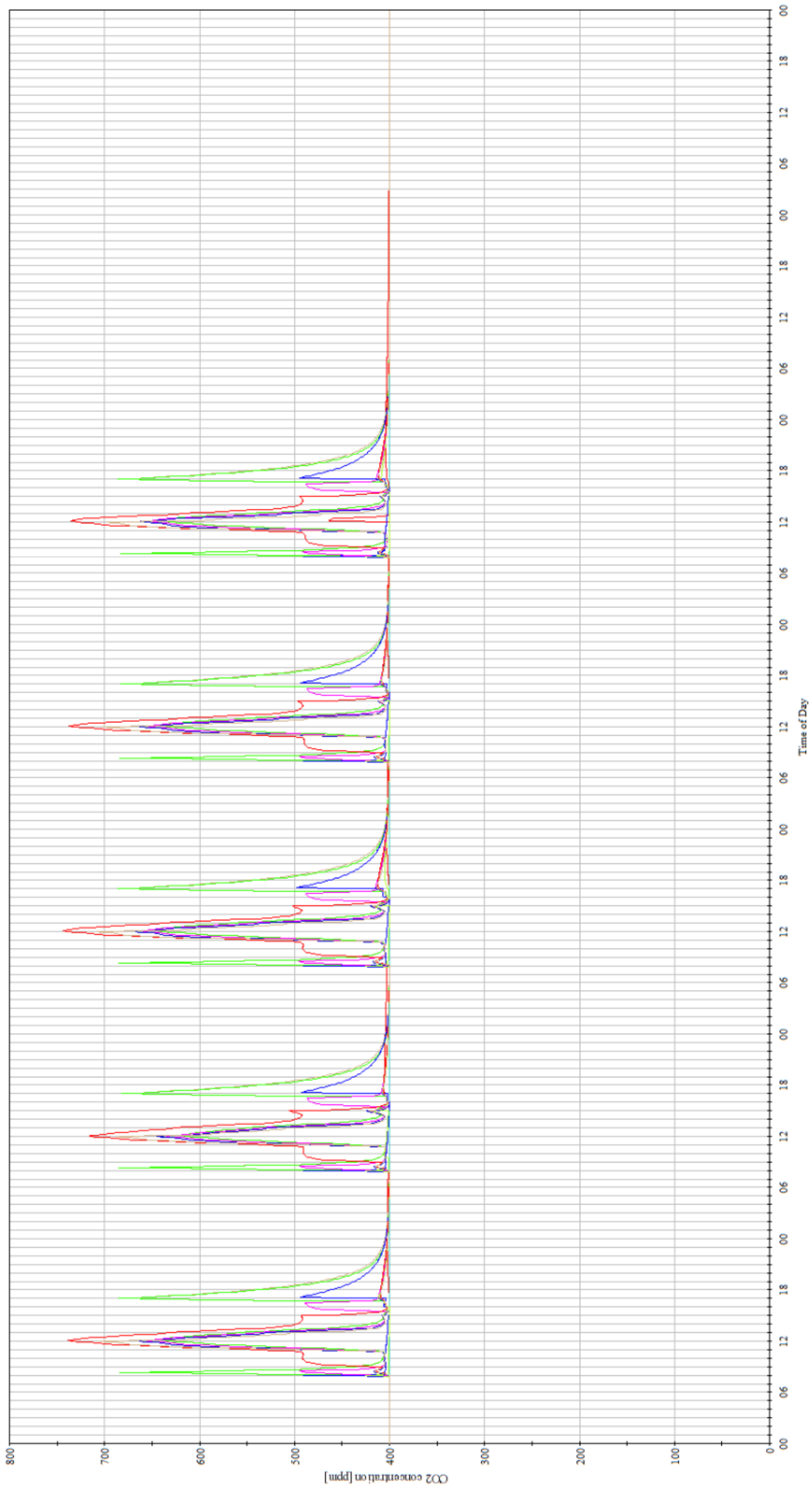


Fig.: H.31 Resulting CO_2 in the first floor when simulating building model A.2+B.2 during the transition.

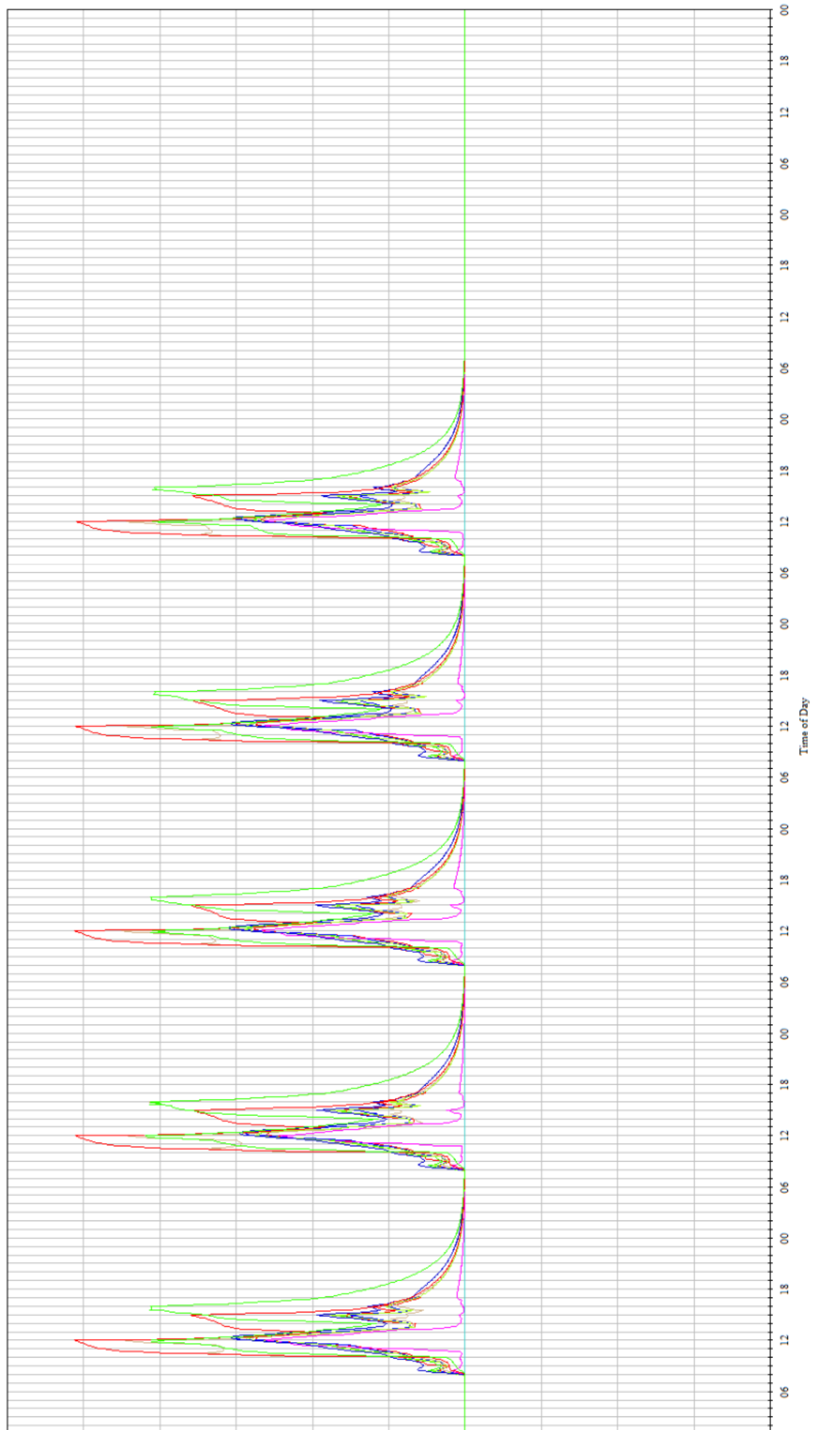


Fig.: H.32 Resulting CO_2 in the second floor when simulating building model A.2+B.2 during the transition.

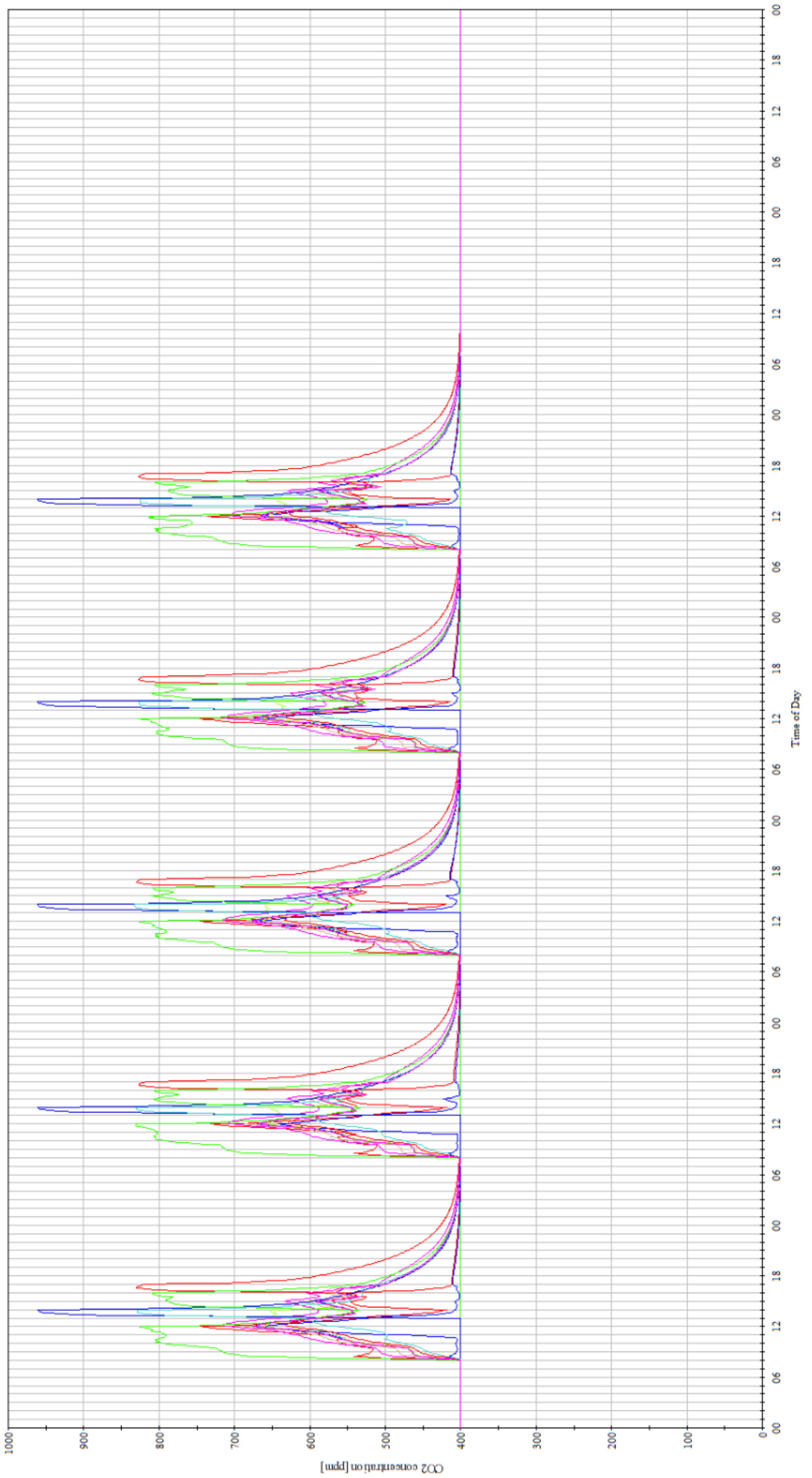


Fig.: H.33 Resulting CO_2 in the third floor when simulating building model A.2+B.2 during the transition.

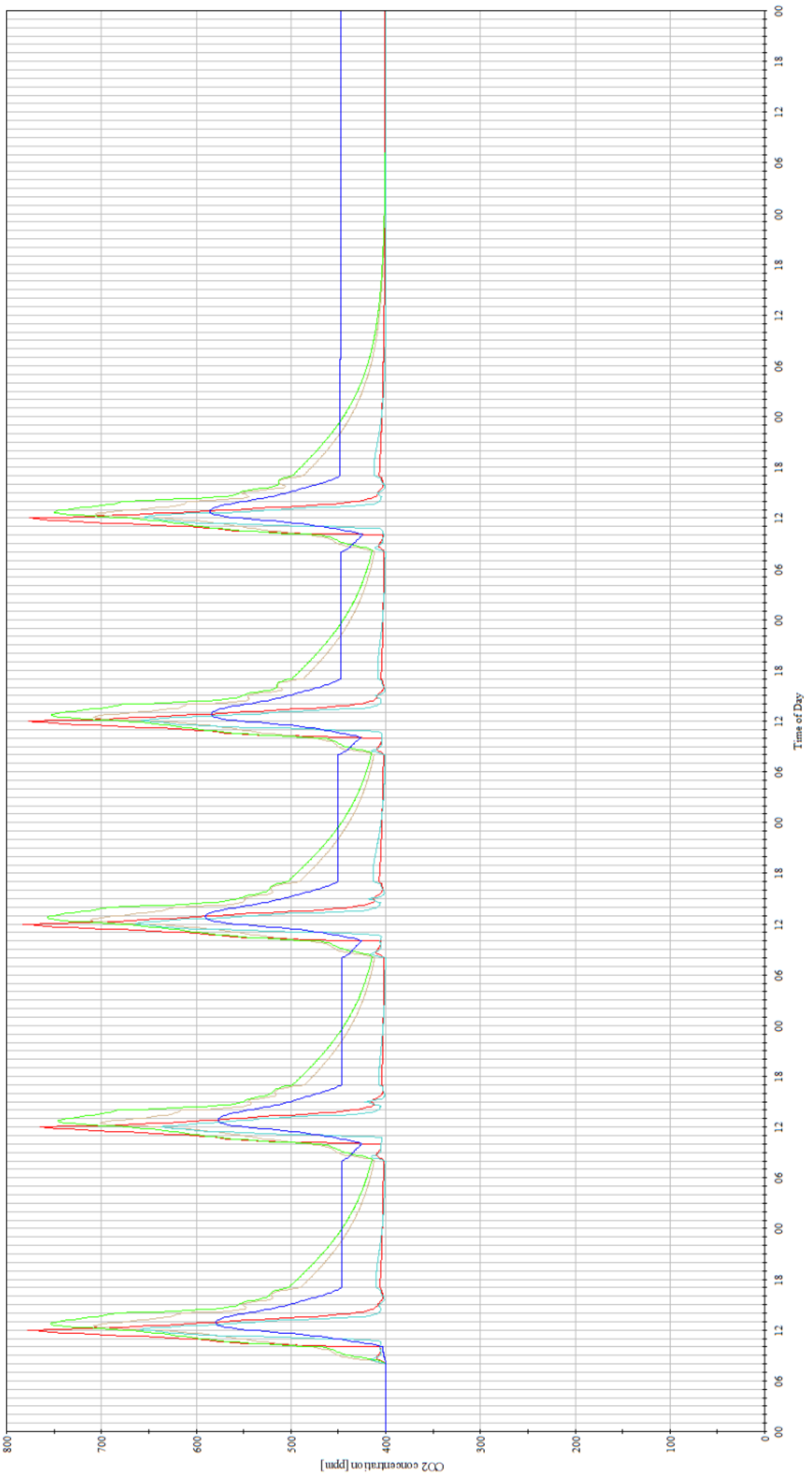
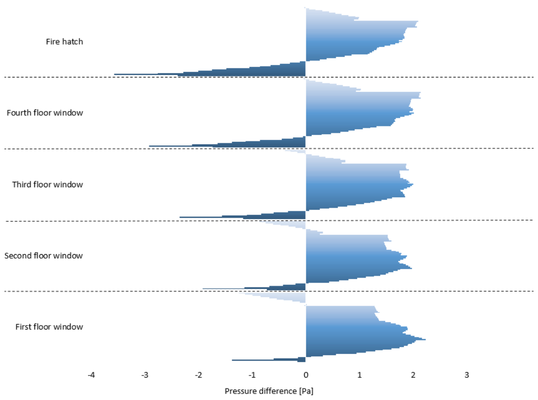


Fig.: H.34 Resulting CO_2 in the fourth floor when simulating building model A.2+B.1 during the transition

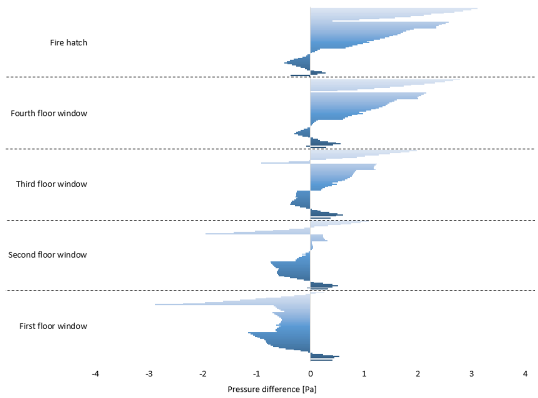
Appendix I

Summer week results

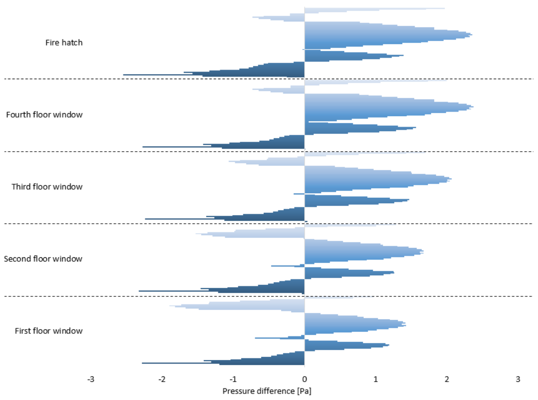
I.1 Resulting pressure profiles from simulations of Model A.1



(a) Tuesday



(b) Thursday



(c) Friday

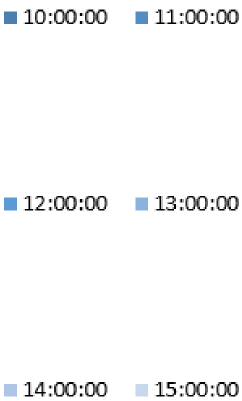
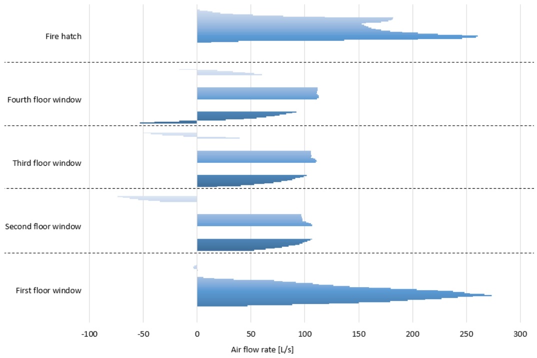
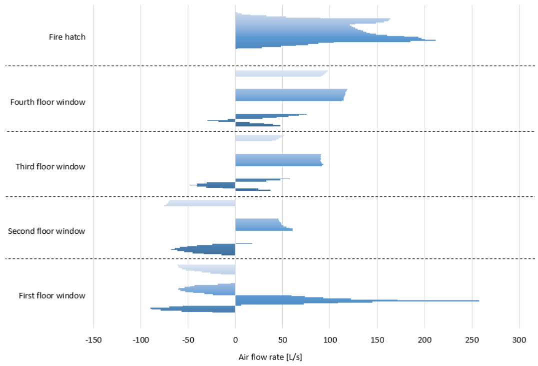


Fig.: I.1 Resulting pressure differences over openings at the east facade of Model A.1 during Tuesday, Thursday and Friday. The horizontal axis describes the pressure difference, while the elevation of the openings are according to the vertical axis. The color of the graph indicates the time.

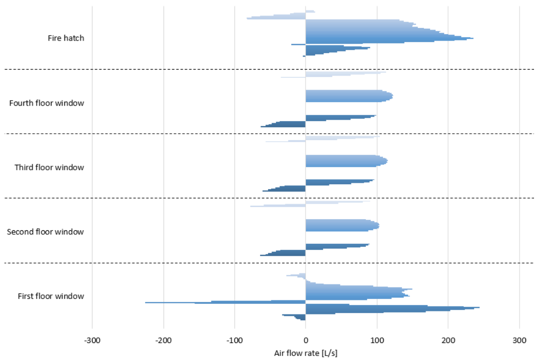
I.2 Resulting air flows from simulations of Model A.1



(a) Tuesday



(b) Thursday



(c) Friday

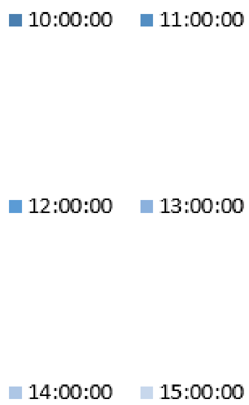
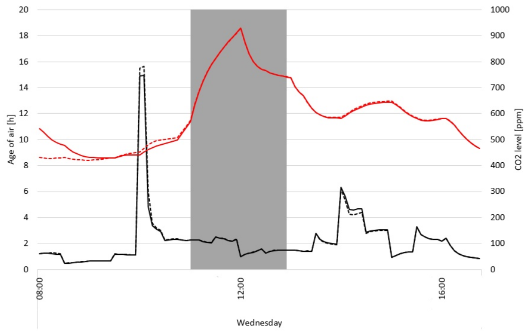
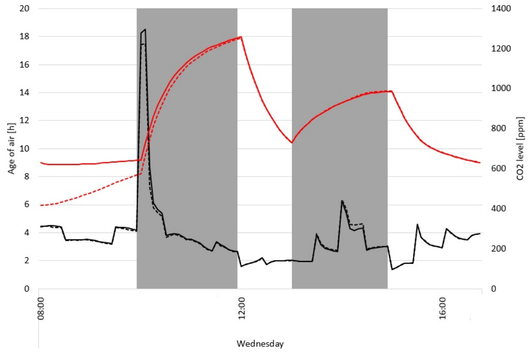


Fig.: I.2 Resulting air flows through openings at the east facade of Model A.1 during Tuesday, Thursday and Friday. The horizontal axis describes the air flow rate, while the elevation of the openings are according to the vertical axis. The color of the graph indicates the time.

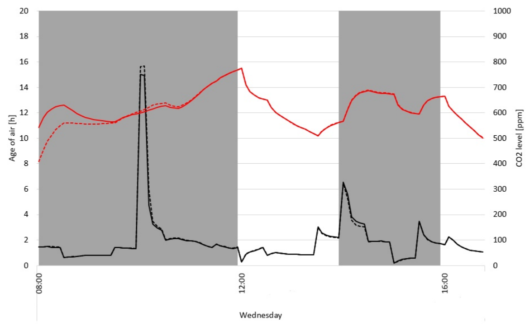
I.3 Resulting age of air vs. $CO2$ level from simulations of Model A.1 and A.3



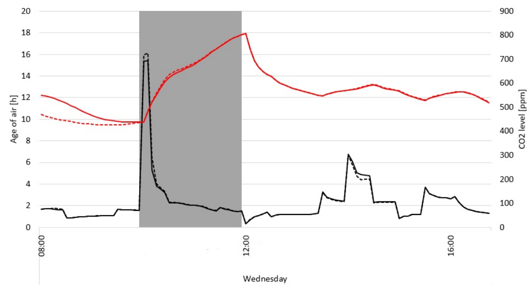
(**a**) First floor Cafeteria



(**b**) Second floor Meeting room



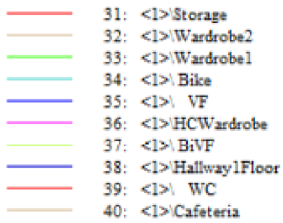
(**c**) Third floor Workplace 1



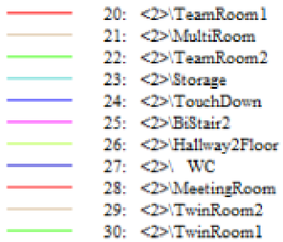
(**d**) Fourth floor Learning room

Fig.: I.3 The resulting age of air vs. CO_2 levels from simulations of Model A.1 and A.3 at Wednesday during the summer week.

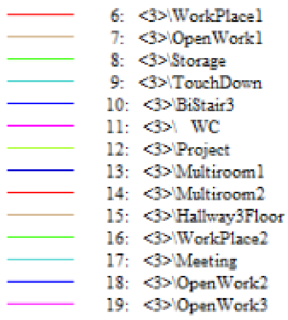
I.4 Resulting CO_2 levels from the simulations



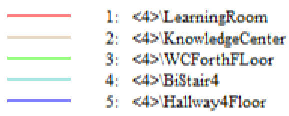
(a) First floor labels.



(b) Second floor labels.



(c) Third floor labels.



(d) Fourth floor labels.

Fig.: I.4 Labels describing the resulting CO_2 levels from the simulations.

Model A.1

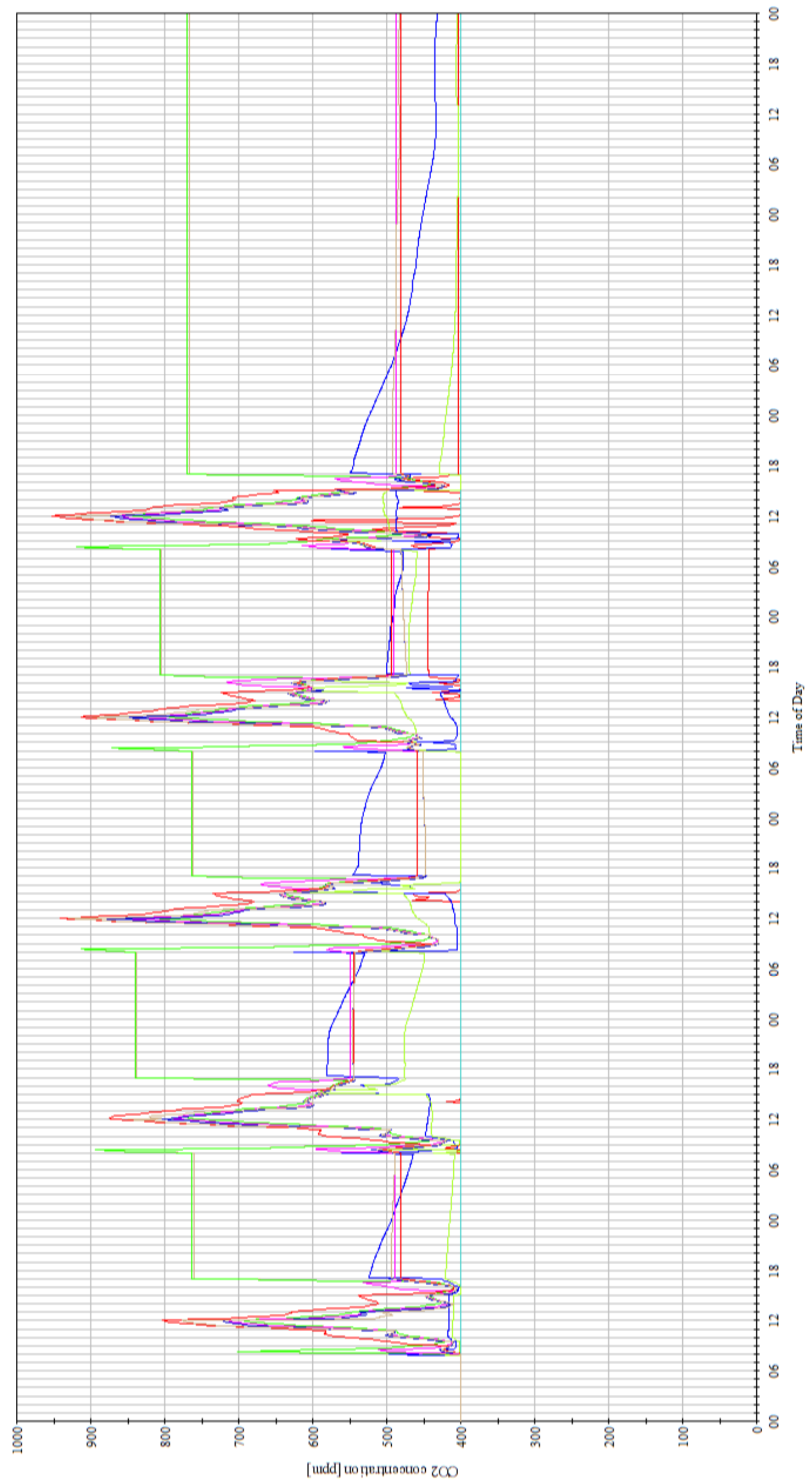


Fig.: I.5 Resulting CO_2 in the first floor when simulating building model A.1 during the summer.

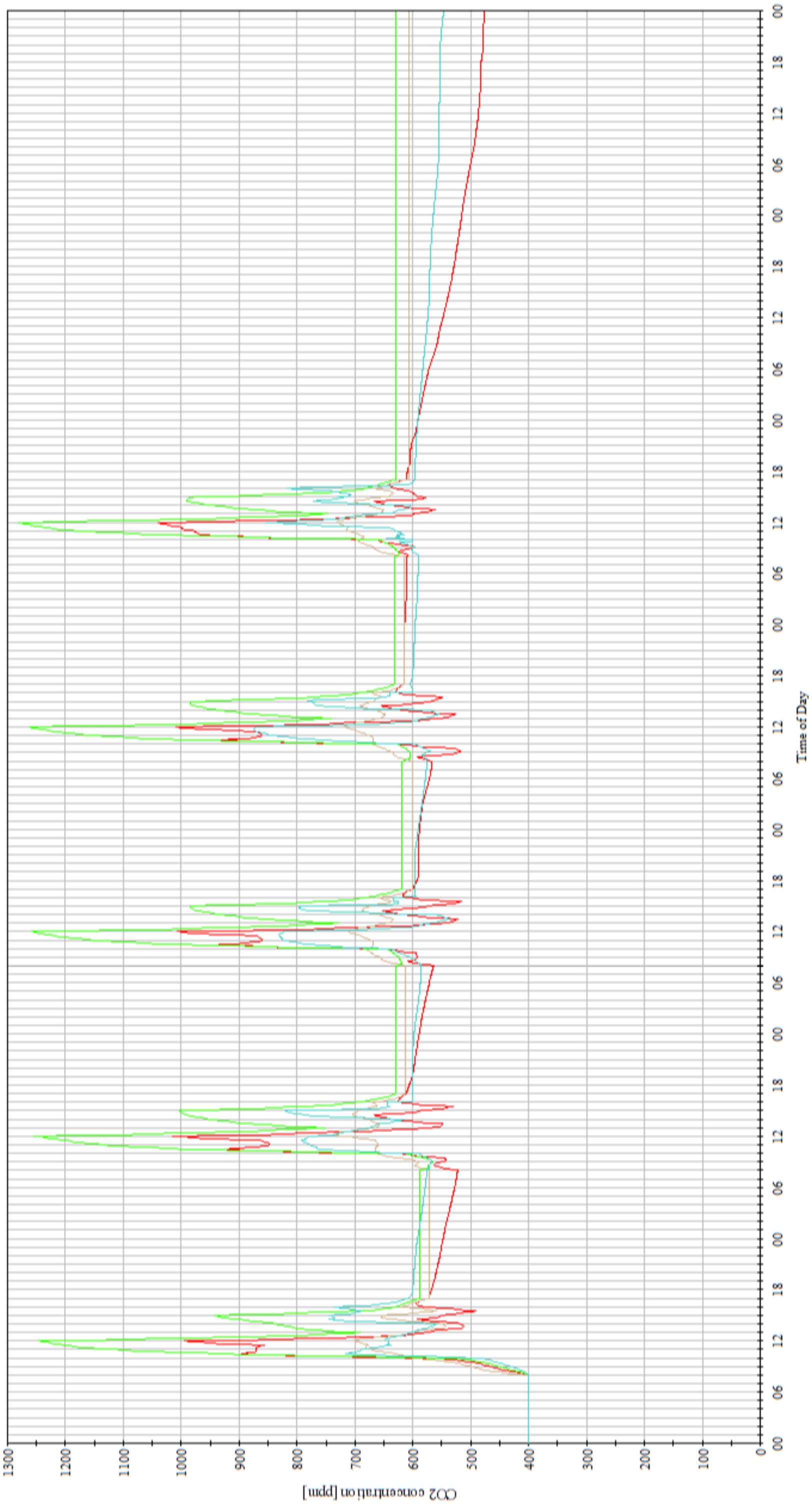


Fig.: I.6 Resulting CO_2 in the second floor when simulating building model A.1 during the summer.

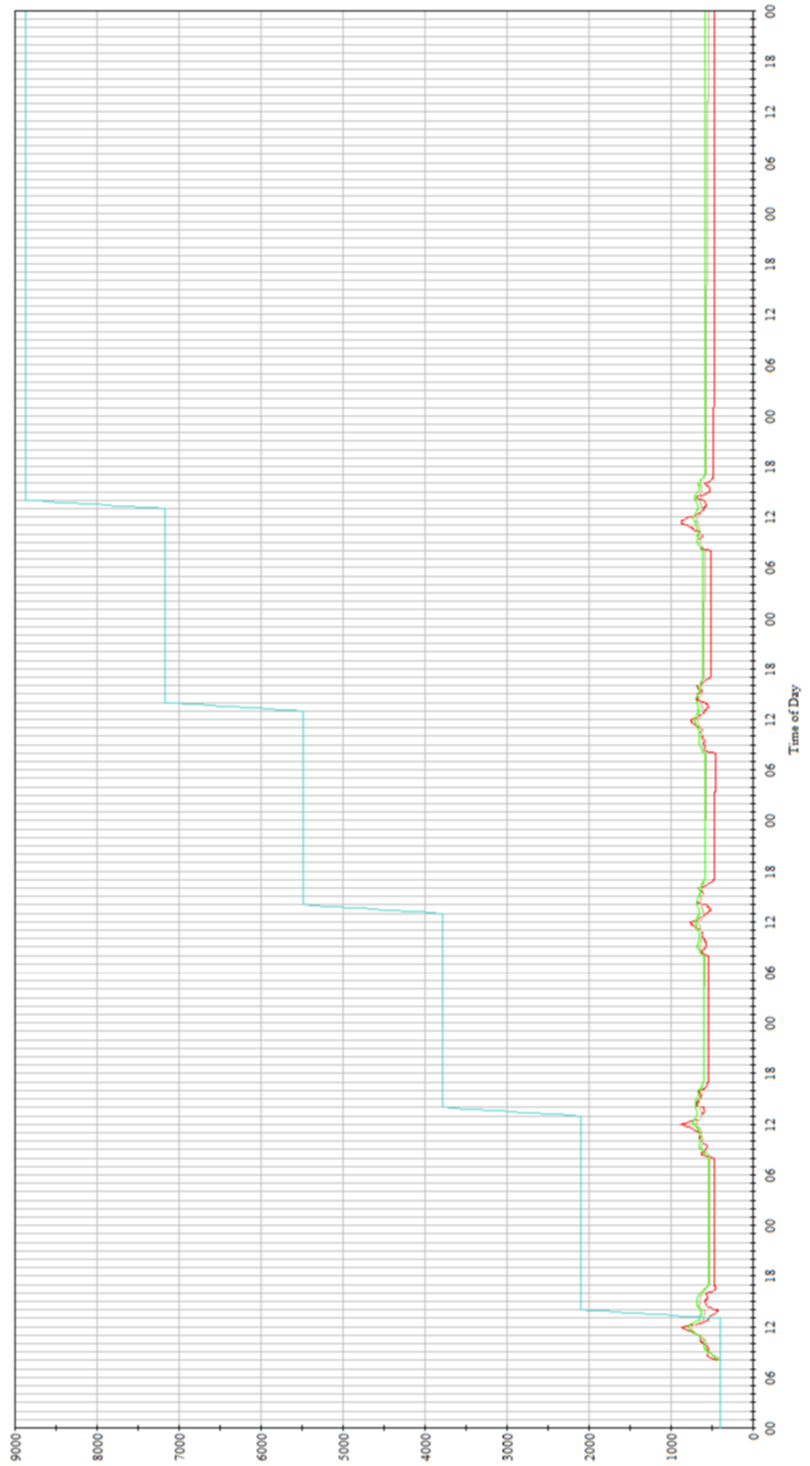


Fig.: I.7 Resulting CO_2 in the third floor when simulating building model A.1 during the summer.

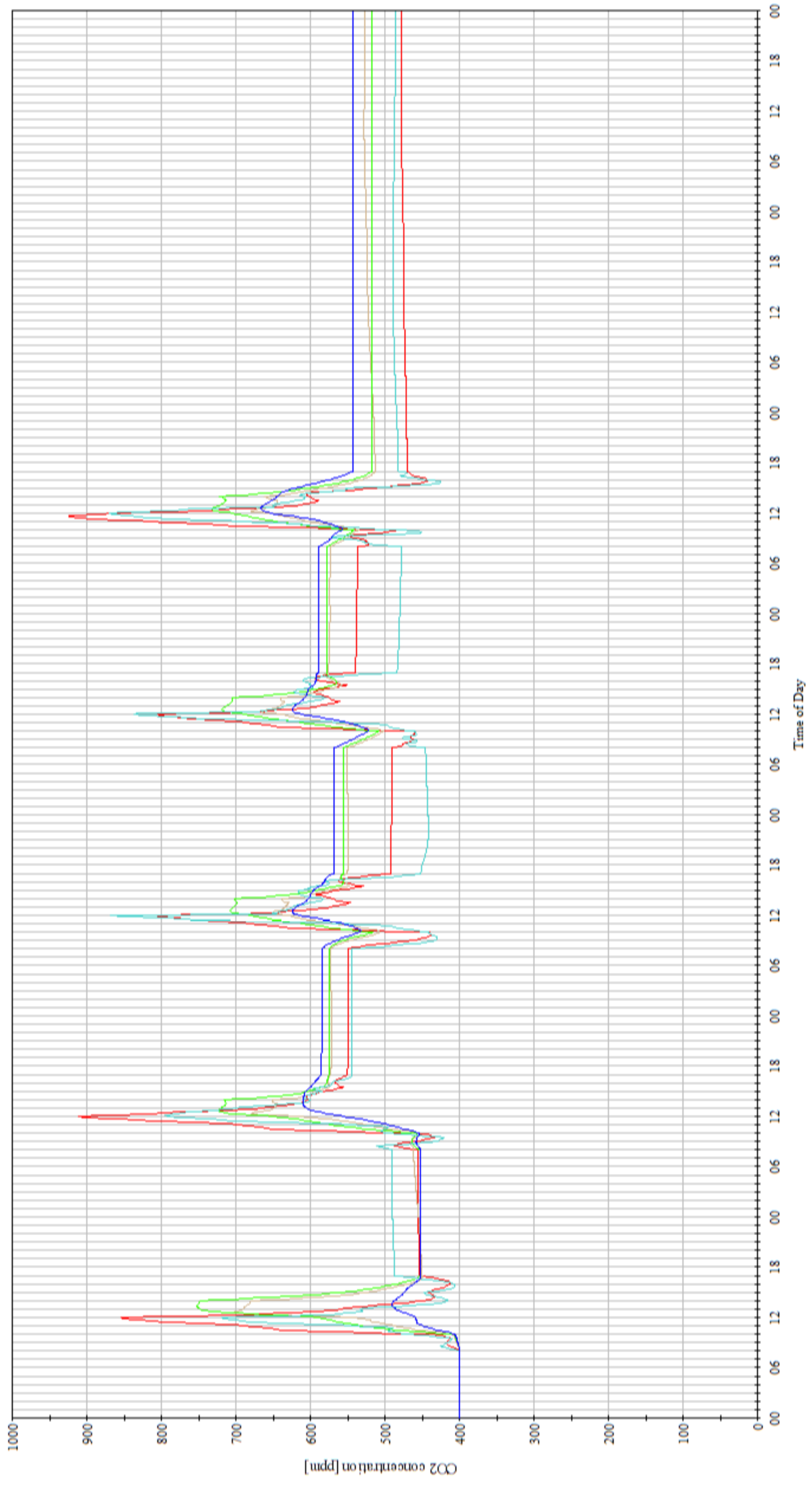


Fig.: I.8 Resulting CO_2 in the fourth floor when simulating building model A.1 during the summer.

Model A.1+night-open internal doors

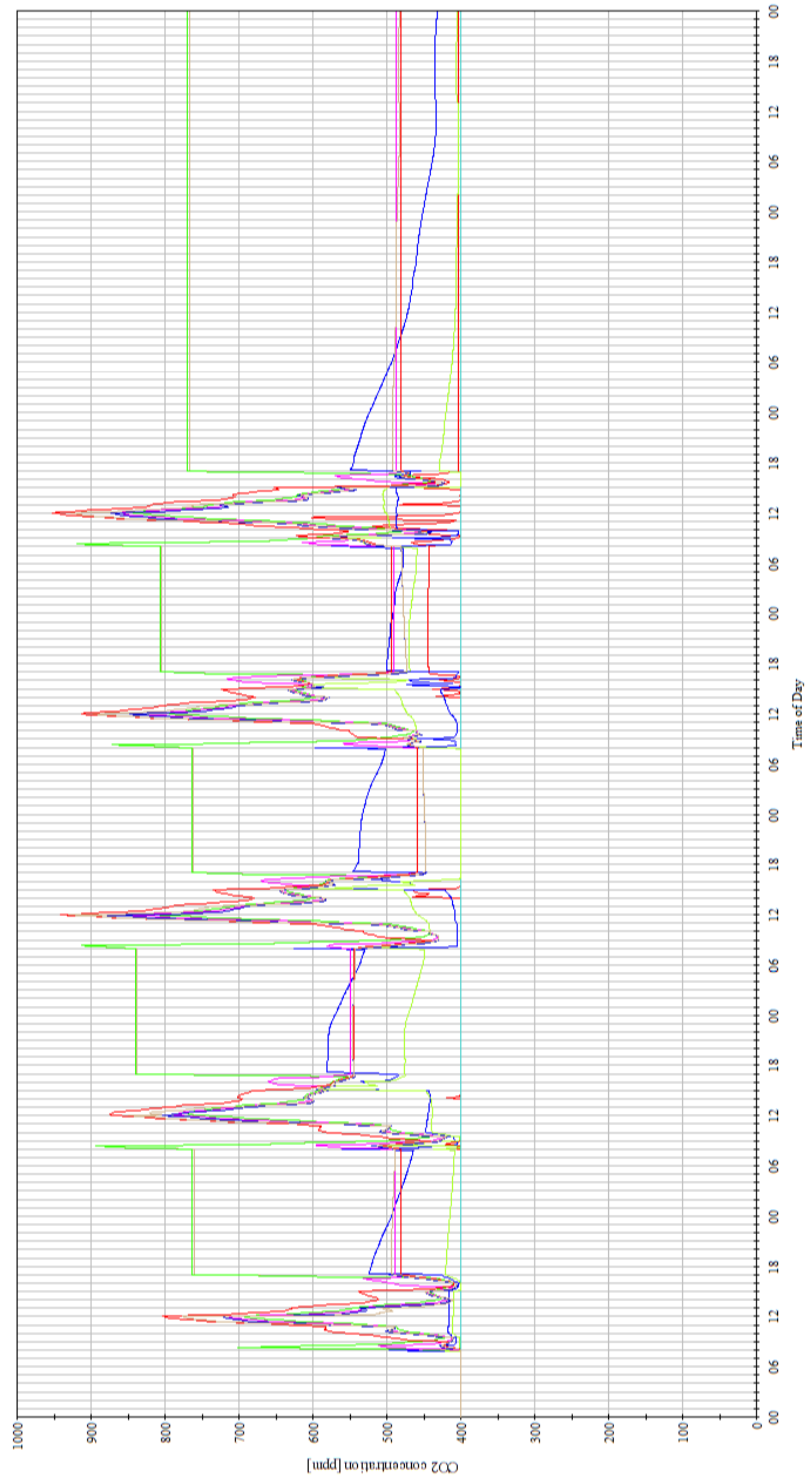


Fig.: I.9 Resulting CO_2 in the first floor when simulating building model A.1 with night-open internal doors during the summer.

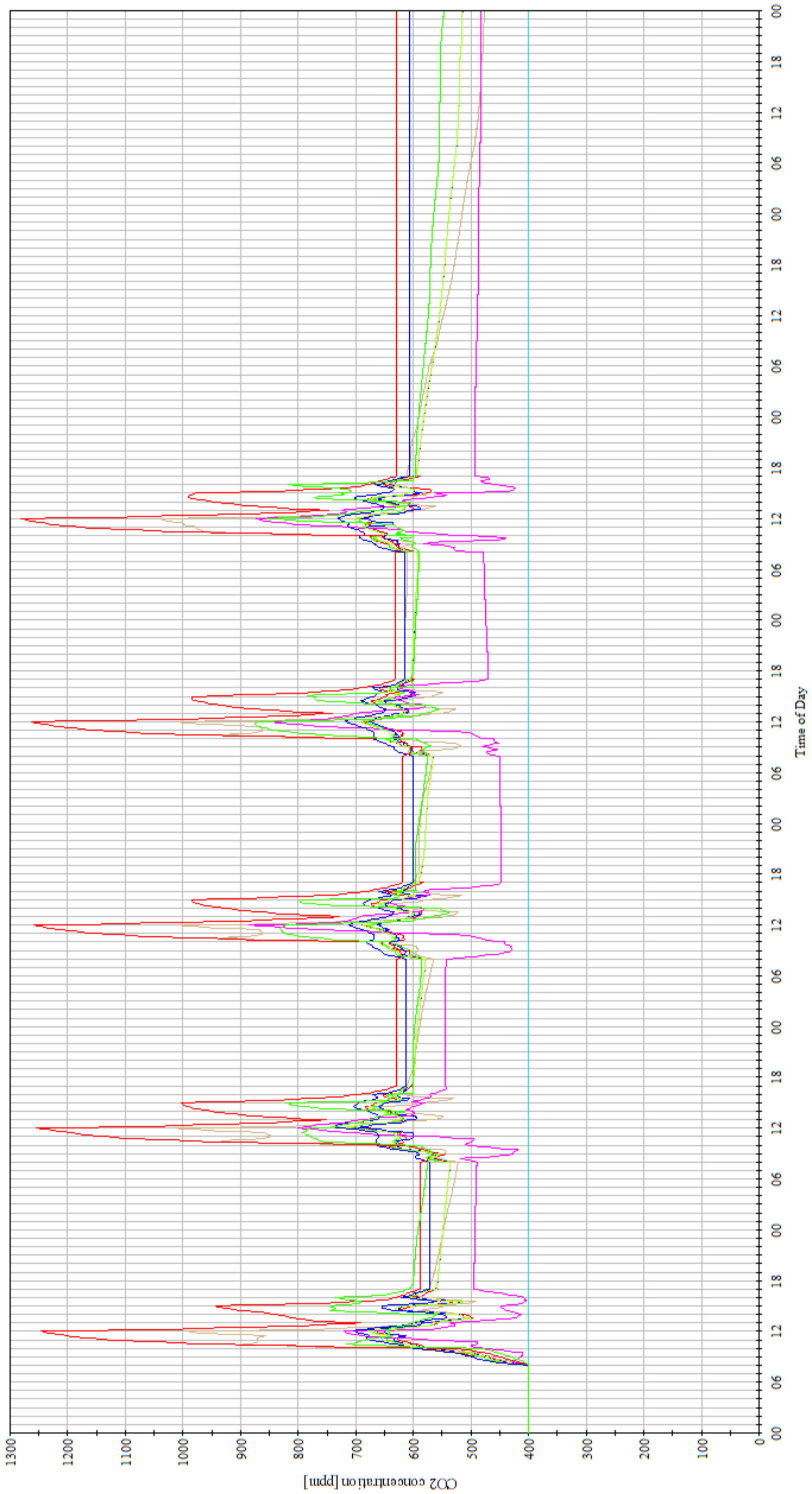


Fig.: I.10 Resulting CO_2 in the second floor when simulating building model A.1 with night-open internal doors during the summer.

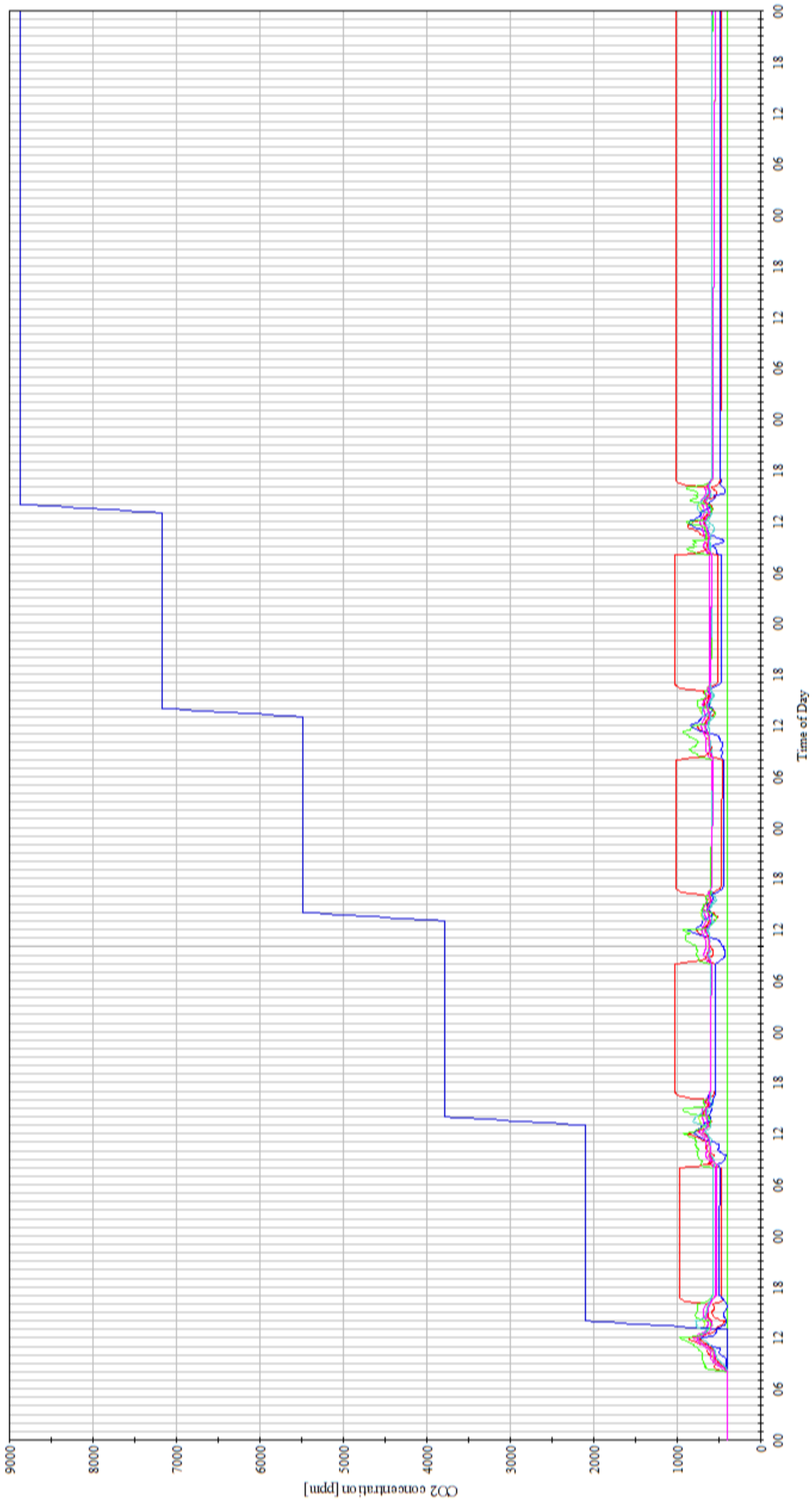


Fig.: I.11 Resulting CO_2 in the third floor when simulating building model A.1 with night-open internal doors during the summer.

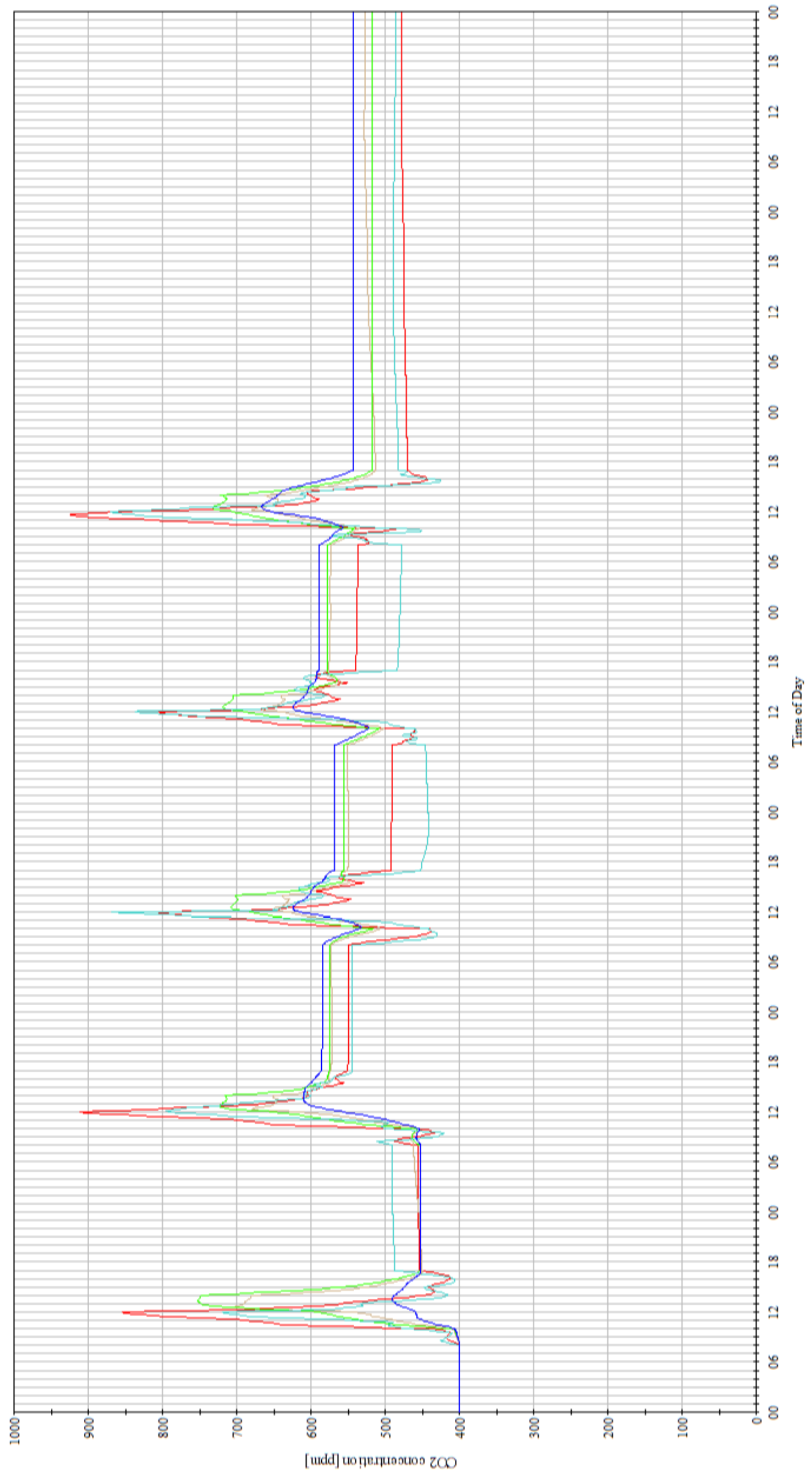


Fig.: I.12 Resulting CO_2 in the fourth floor when simulating building model A.1 with night-open internal doors during the summer.

Model A.1 + night-open internal doors + morning aeration

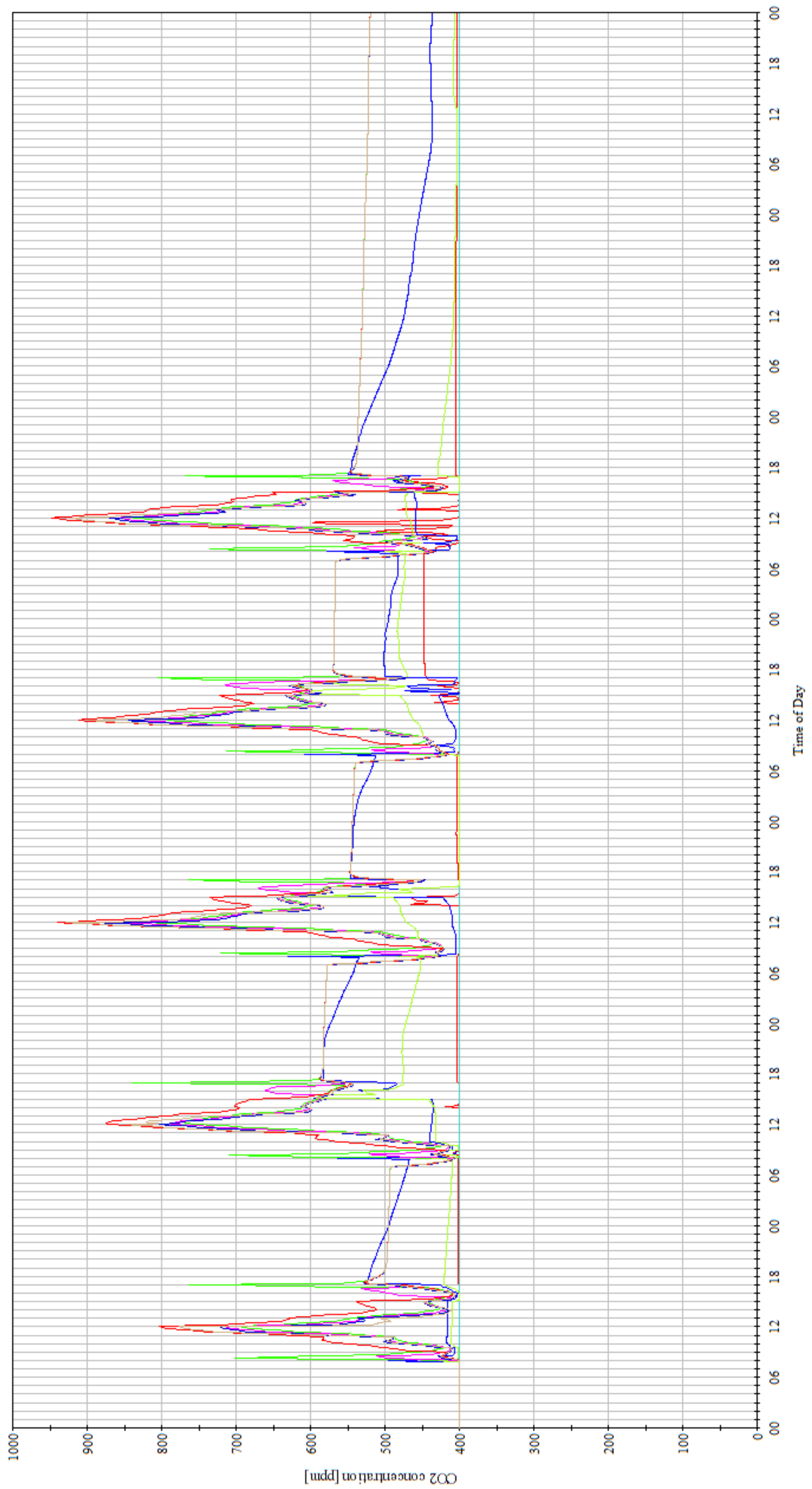


Fig.: I.13 Resulting CO_2 in the first floor when simulating building model A.1 with night-open internal doors and morning aeration during the summer.

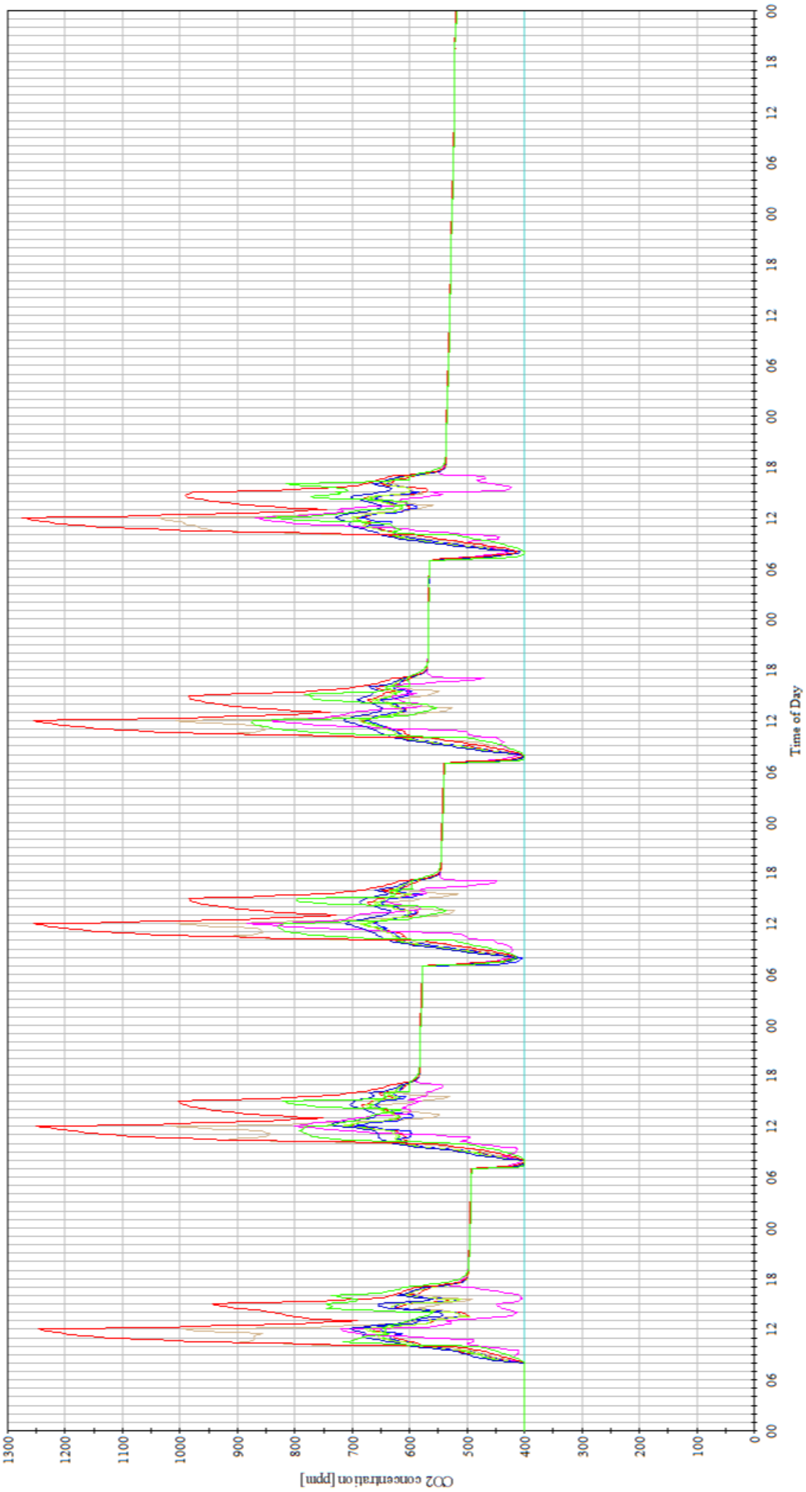


Fig.: I.14 Resulting CO_2 in the second floor when simulating building model A.1 with night-open internal doors and morning aeration during the summer.

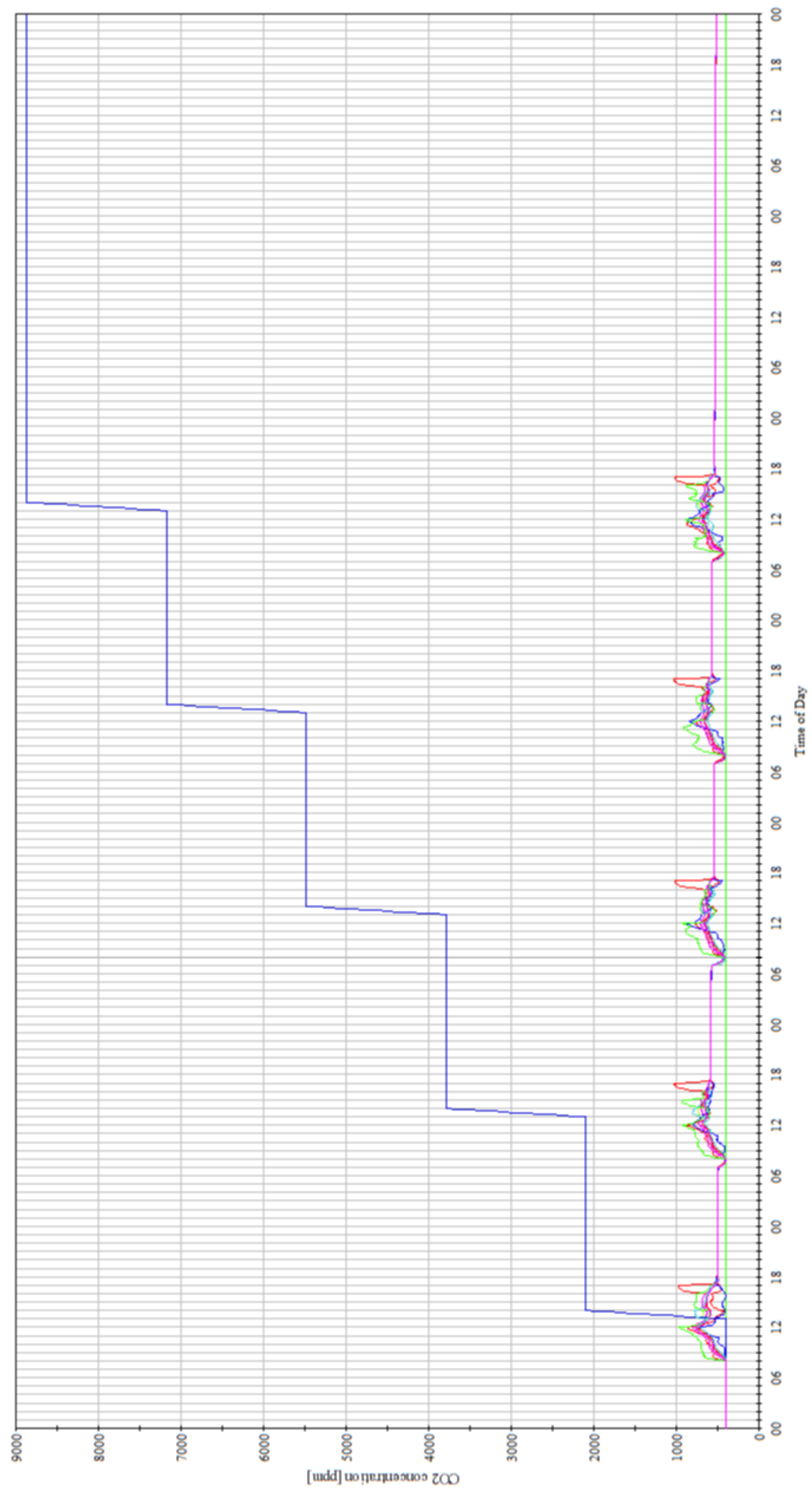


Fig.: I.15 Resulting CO_2 in the third floor when simulating building model A.1 with night-open internal doors and morning aeration during the summer.

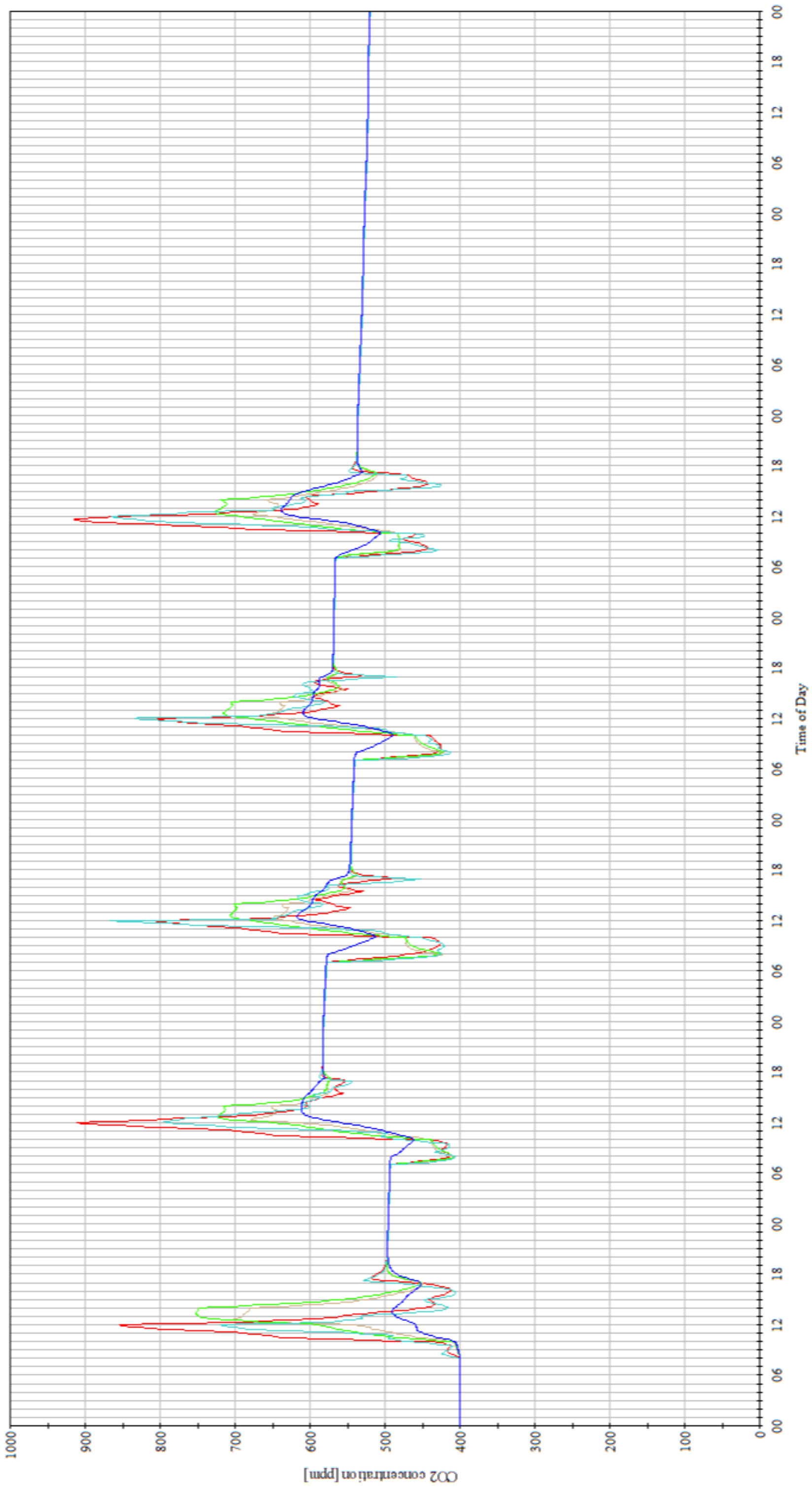


Fig.: I.16 Resulting CO_2 in the fourth floor when simulating building model A.1 with night-open internal doors and morning aeration during the summer.

Appendix J

Risk assessment

NTNU	Hazardous activity identification process	Prepared by	Number	Date
HSE		HSE section	HMSRV2601E	09.01.2013
		Approved by		Replaces
		The Rector		01.12.2006

Unit: *Department of Energy- and Process Engineering* **Date:** **04.06.2019**

Line manager: Anita Yttersian

Participants in the identification process (including their function)**: Maren Elise Leinum (student), Hans Martin Mathisen (supervisor)**

Short description of the main activity/main process: Master project for Maren Elise Leinum. Optimal combination of natural and mechanical ventilation in ZEB Flexible Lab.

Is the project work purely theoretical? (YES/NO): YES *Answer "YES" implies that supervisor is assured that no activities requiring risk assessment are involved in the work. If YES, briefly describe the activities below. The risk assessment form need not be filled out.*

Signatures: *Responsible supervisor:* *Student:*

ID nr.	Activity/process	Responsible person	Existing documentation	Existing safety measures	Laws, regulations etc.	Comment

Fig.: J.1 Risk assessment