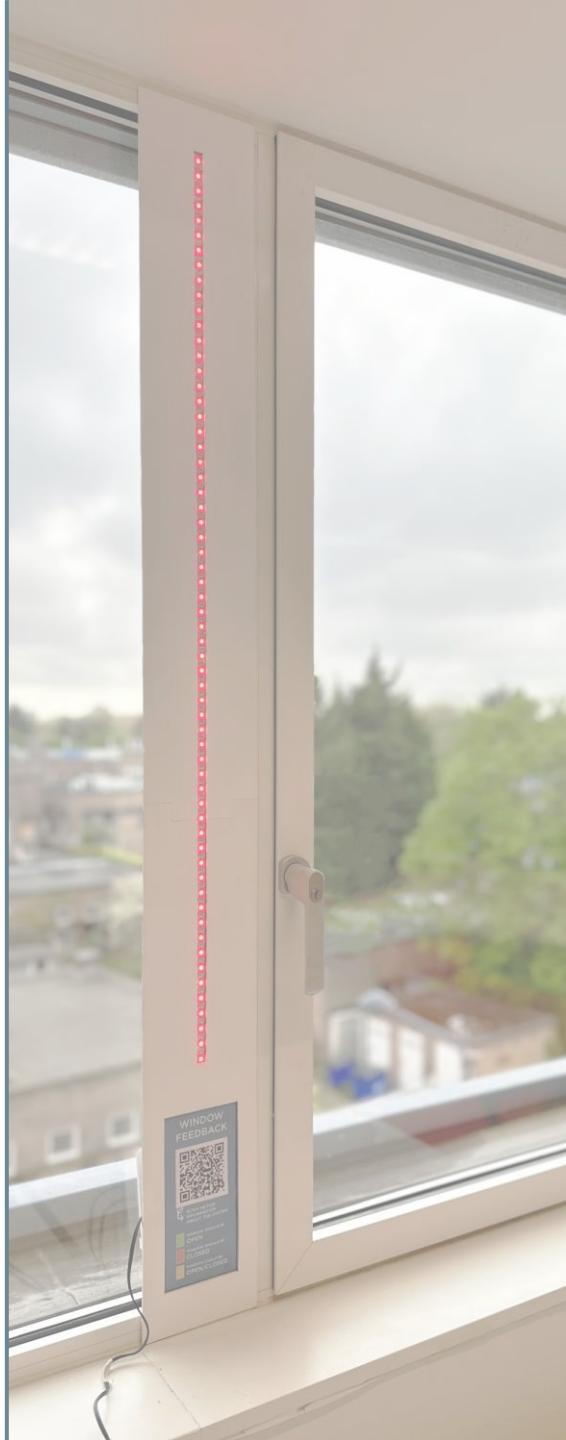
Human Window Interaction

To what extent do ambient light window feedback systems provide energy savings, human multi-domain comfort and indoor air quality in open-plan workplaces?



Serhan Yuksel Alessandra Luna Navarro - Atze Boerstra – Maarten Meijs 19 June 2023

Effective window operation

iStock (2023)

Indoor air quality

iStock (2023)

Indoor air quality

iStock (2023)

Outdoor air quality

New York, USA

iStock (2023)

Outdoor air quality

Delft, Netherlands

iStock (2023)

Outdoor air quality

Tata Steel, IJmuiden, Netherlands

iStock (2023)

Thermal comfort

iStock (2023)

Energy efficiency

iStock (2023)

Impact window

Thermal environment

Indoor air quality

Occupant’s satisfaction

Energy efficiency

iStock (2023)

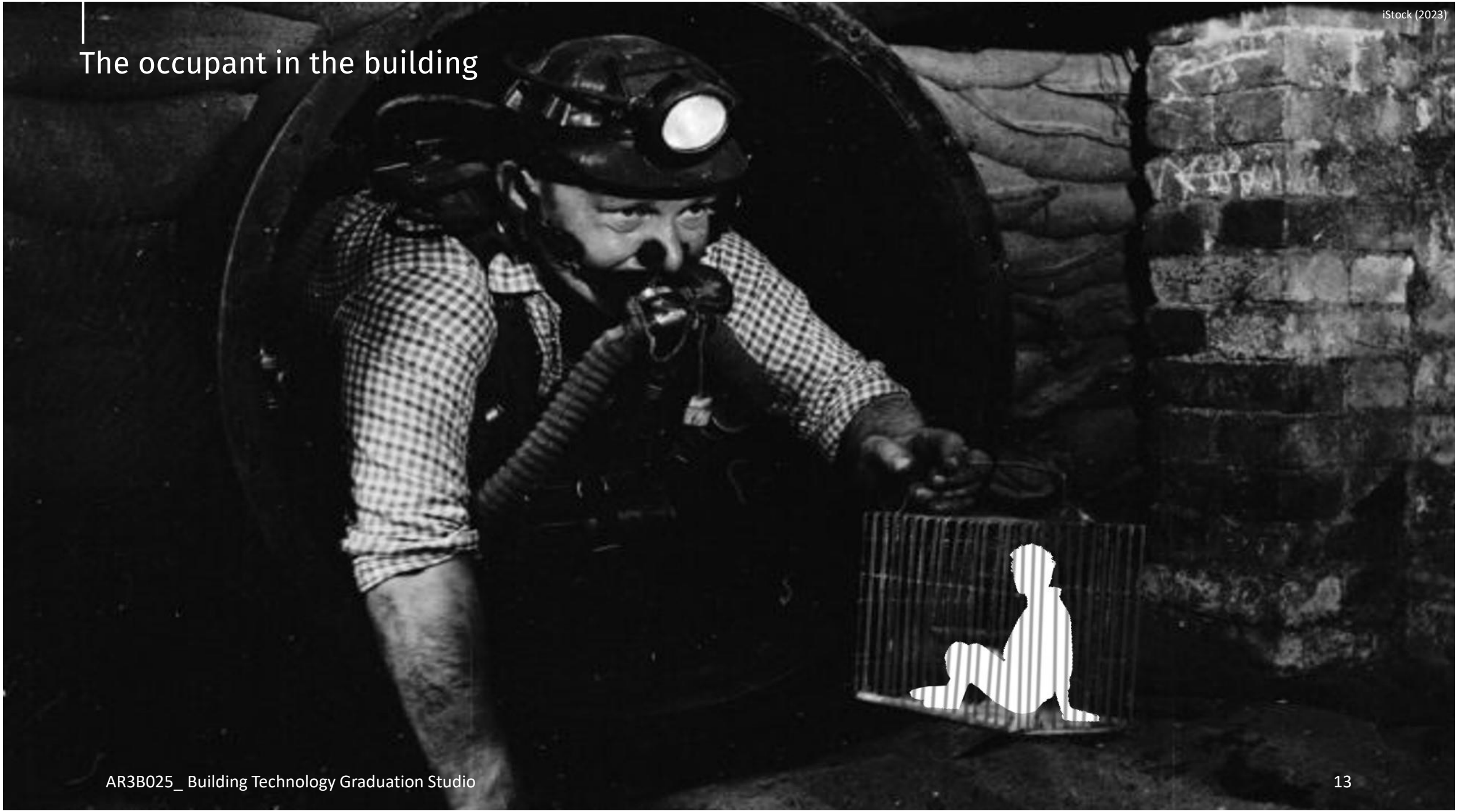
Window feedback

iStock (2023)

The canary in the coal mine

iStock (2023)

The occupant in the building



iStock (2023)

Introduction

Problem statement

(Istock, 2023)

Window feedback system

Manual window control

- Risk of inefficient energy use
- Occupants can satisfy their comfort

Automated window control

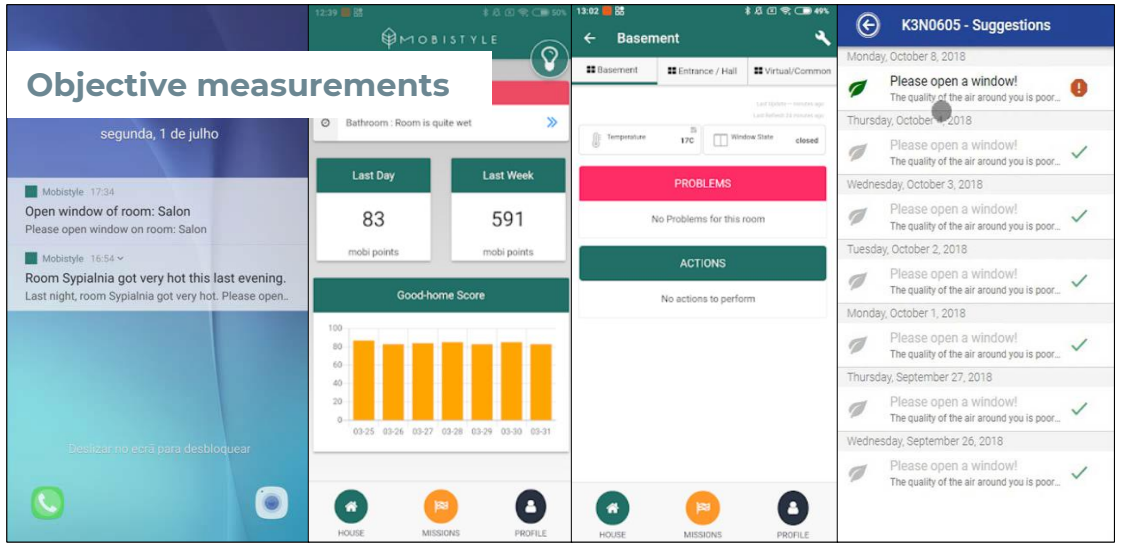
- Energy efficient window operation
- At the expense of occupants' comfort, satisfaction and productivity

Introduction

Problem statement

- There is a lack of evidence to what extent window feedback systems are able to provide a successful cooperation between occupants and windows

- Ackerly and Brager (2013)
- Extent to which existing windows feedback systems play a role in occupant behaviour and response.
- 16 buildings in the US



- Mobistyle (2020) & Avella et al. (2011)
- How behavioural change of occupants can be stimulated with feedback

Introduction

Research question

To what extent do ambient light window feedback systems provide energy savings, human multi-domain comfort and indoor air quality in open-plan workplaces?

Introduction

Research question

*To what extent do **ambient light window feedback systems** provide energy savings, human multi-domain comfort and indoor air quality in open-plan workplaces?*

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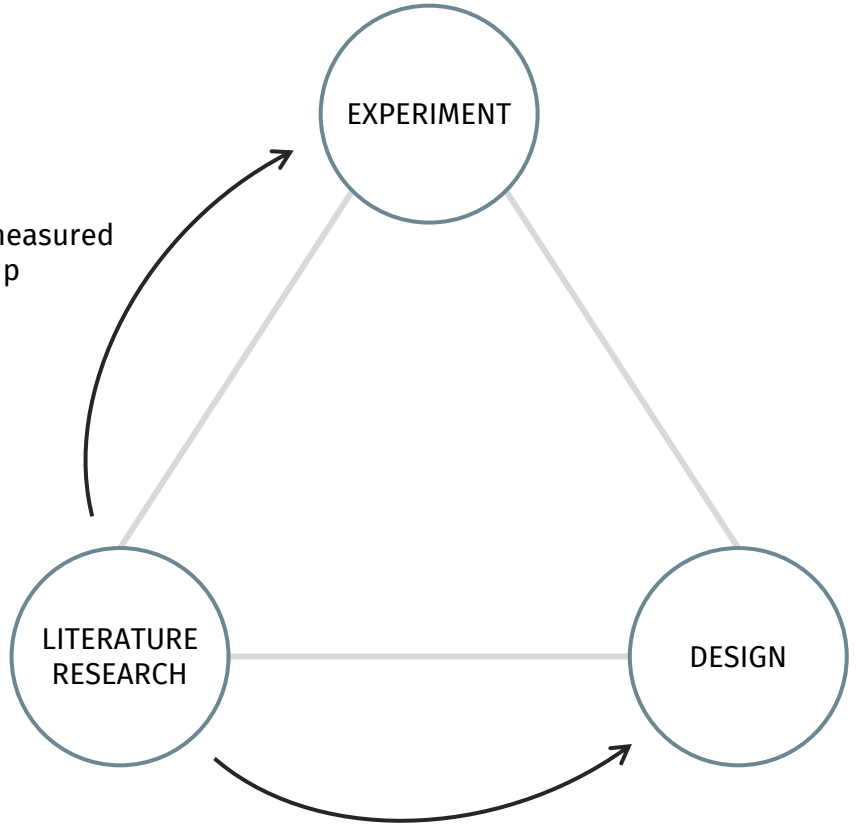
Methodology
Research

- Existing and new situation
- Objective and subjective measurements



- Parameters to be measured
- Measurement set-up
- Survey design

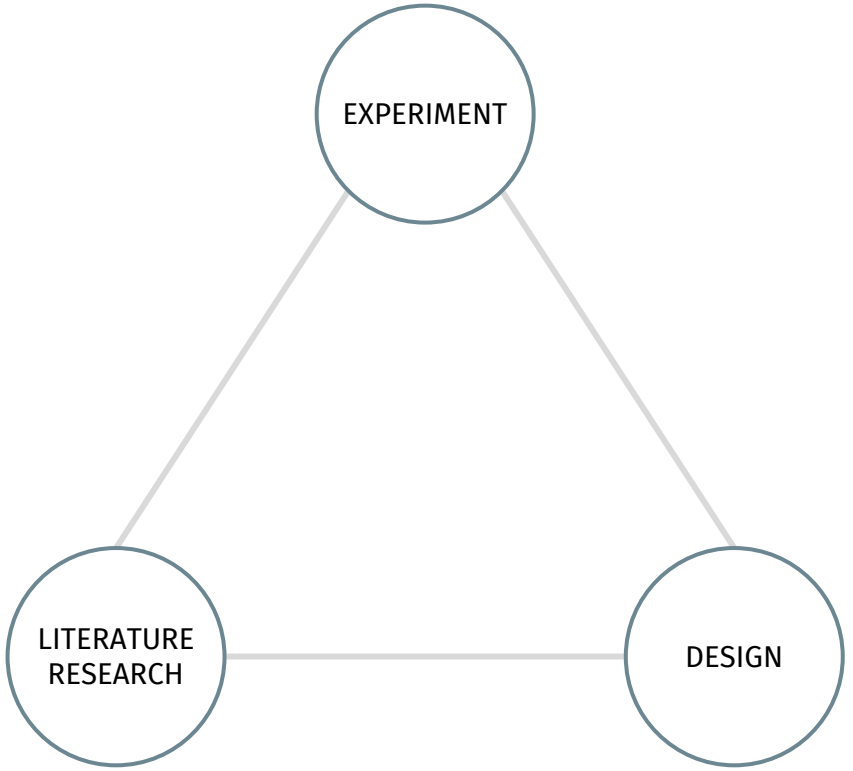
- Drivers window operation
- Window control and feedback
- Thermal environment
- Indoor air quality
- Energy efficiency

- Algorithm design
- Window feedback design

- Parameters for algorithm
- Design guidelines

Methodology
Research

- Existing and new situation
- Objective and subjective measurements



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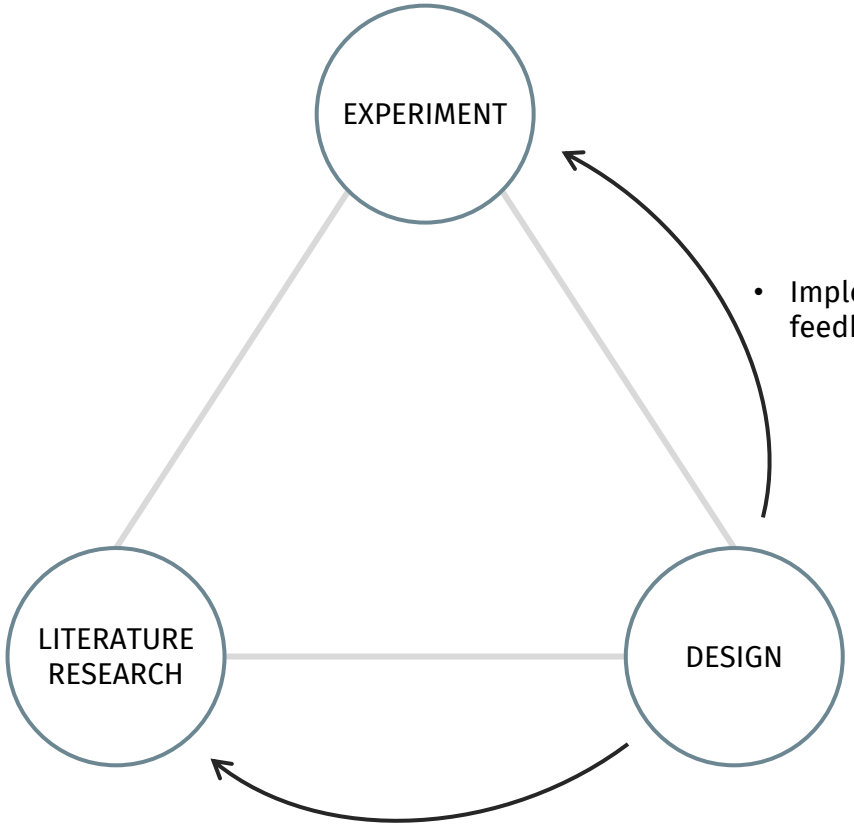


- Implementation window feedback system

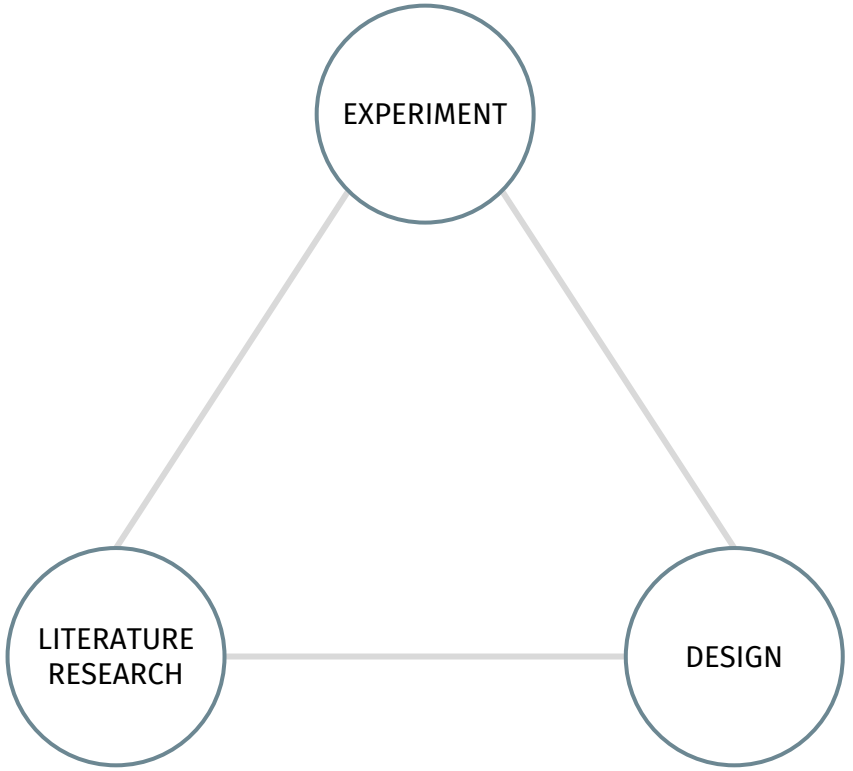
- Drivers window operation
- Window control and feedback
- Thermal environment
- Indoor air quality
- Energy efficiency

- Algorithm design
- Window feedback design

- Lack of knowledge
- Base for further developments

Methodology
Research

- Existing and new situation
- Objective and subjective measurements



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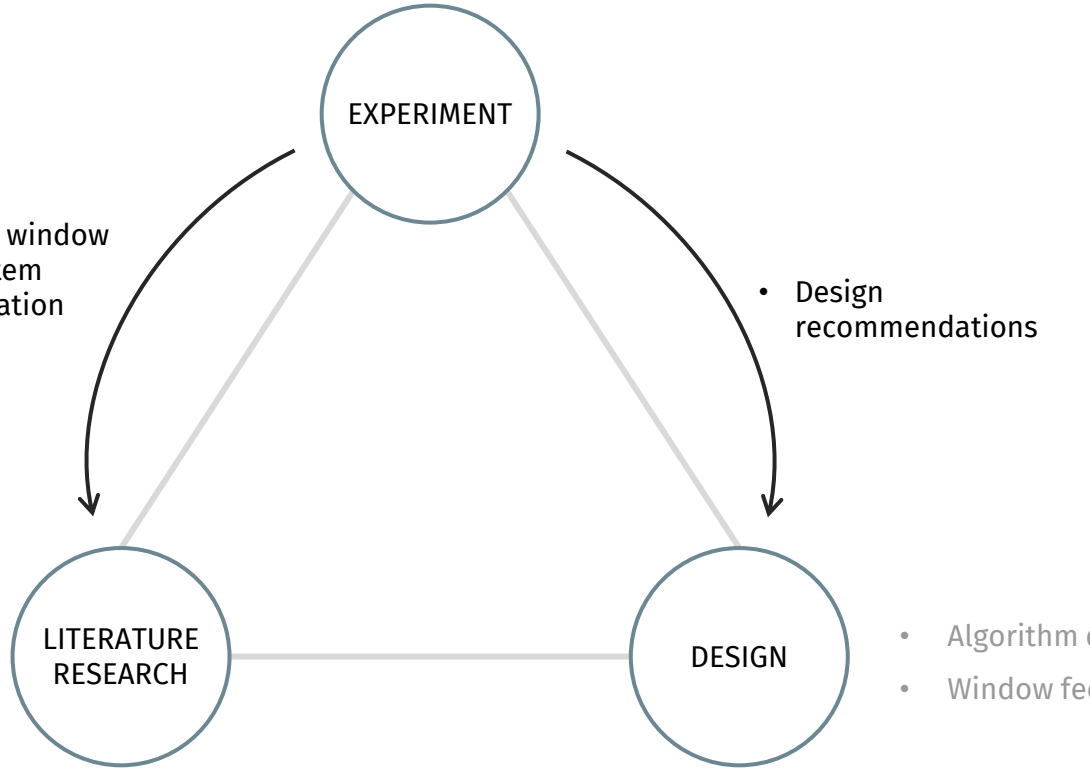

- Ambient light window feedback system
- Window operation

- Design recommendations

- Drivers window operation
- Window control and feedback
- Thermal environment
- Indoor air quality
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- Algorithm design
- Window feedback design

Literature Research

Window opening behaviour

Drivers of human window opening behaviour:

External		Internal		
Physical	**Contextual**	**Psychological**	**Physiological**	**Social**
Outdoor temperature Indoor temperature Air velocity Relative humidity Solar radiation CO2 concentration PM2.5 concentration Noise	Occupancy Window Design Distance to façade Façade orientation Thermal mass Security Installations (HVAC) Interior doors Rainfall	Expectations Concerns Habits Lifestyle/schedule Knowledge/education Stress level	Age Gender Health Clothing Activity level Food and beverages	Social norms Interrelationships

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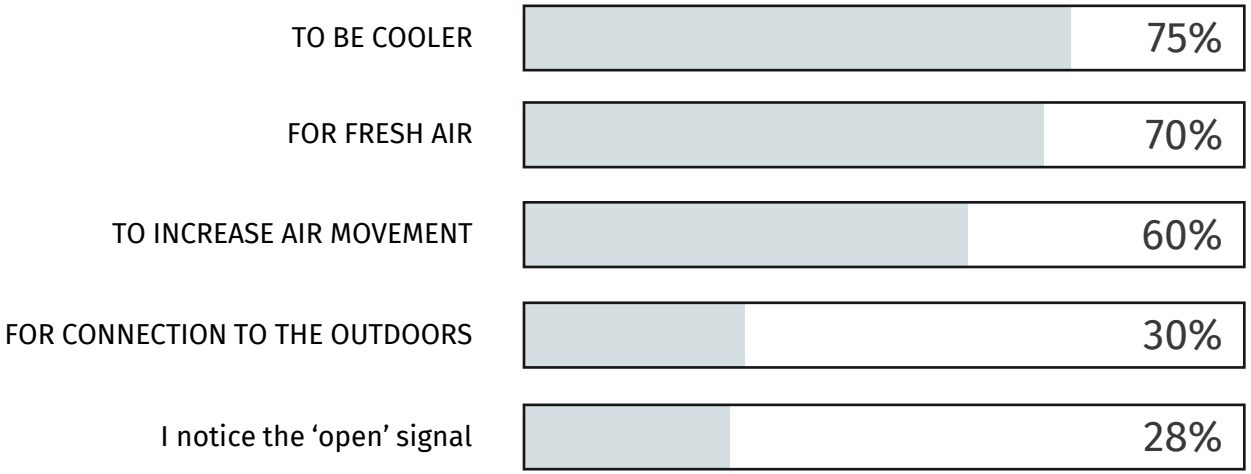

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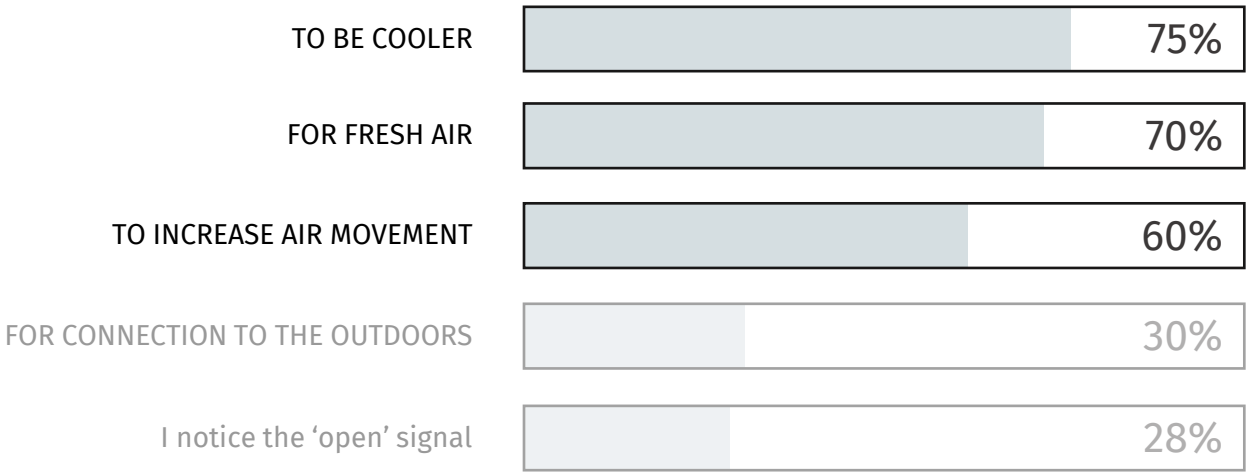

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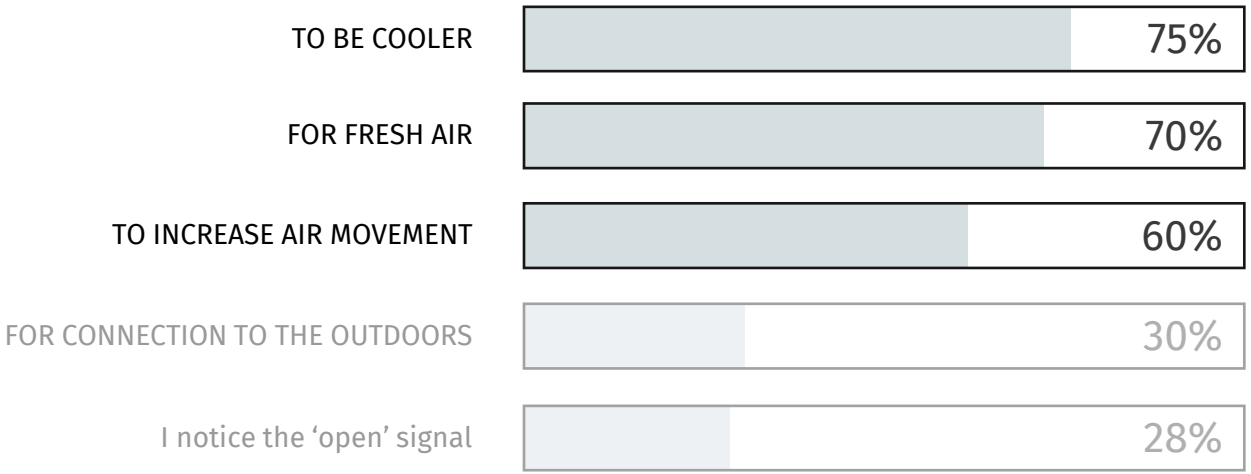

Reasons for window closing:

HEAT LOSS

RAIN

WIND

Literature Research

Parameters for measurements and evaluation

Thermal comfort

Heat balance approach

- Indoor air temperature
- Indoor mean radiant temperature
- Indoor air velocity
- Air humidity
- Metabolism
- Clothing

Adaptive approach

- Monthly mean outdoor air temperature

Indoor Air Quality

- Carbon dioxide (CO_2)
- Particulate matter (PM_{10} & $PM_{2.5}$)
- Volatile Organic Compounds (VOC)
- Formaldehyde (HCHO)
- Radon (Rn)
- Ozone (O_3)
- Carbon monoxide (CO)

Energy efficiency

- Indoor temperature
- Outdoor temperature
- Window opening time
- Air flow rate
    - Air velocity
    - Openable window area

    OR

    - CO_2 concentration
    - Number of occupants

Literature Research

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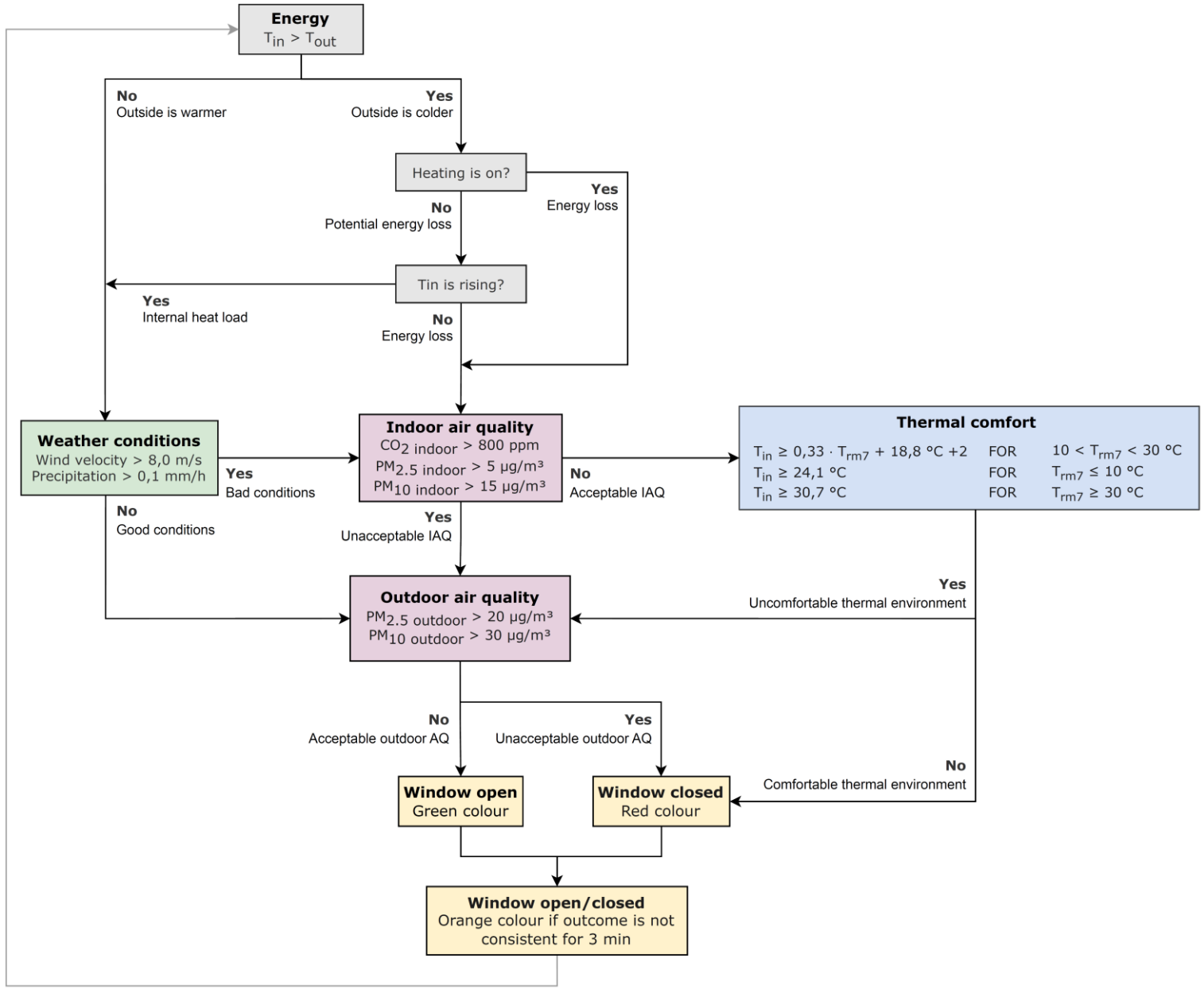
Design

Algorithm

Based on 2 principles:

1. To enhance energy efficiency, the window should be closed when the outdoor temperature is colder and should be open when the outdoor temperature is warmer.

2. The health of occupants is more important than energy efficiency and occupants' comfort.



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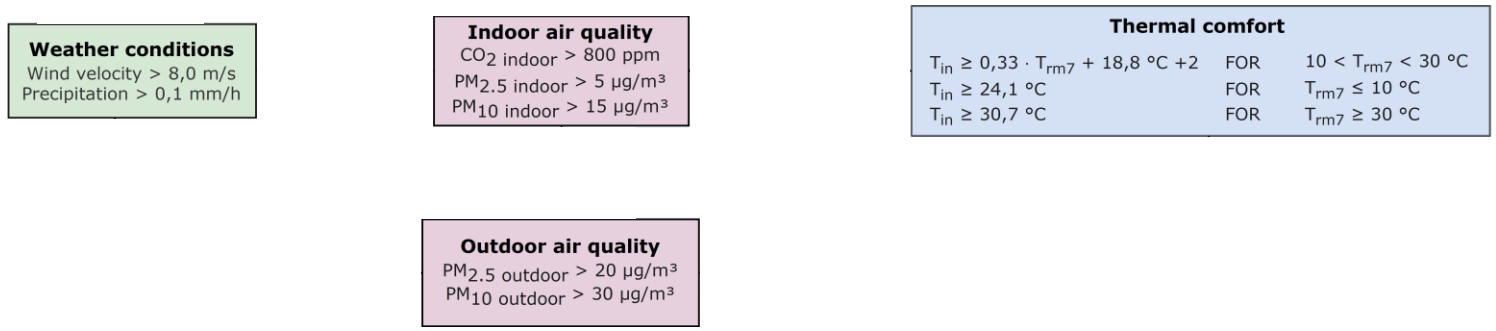

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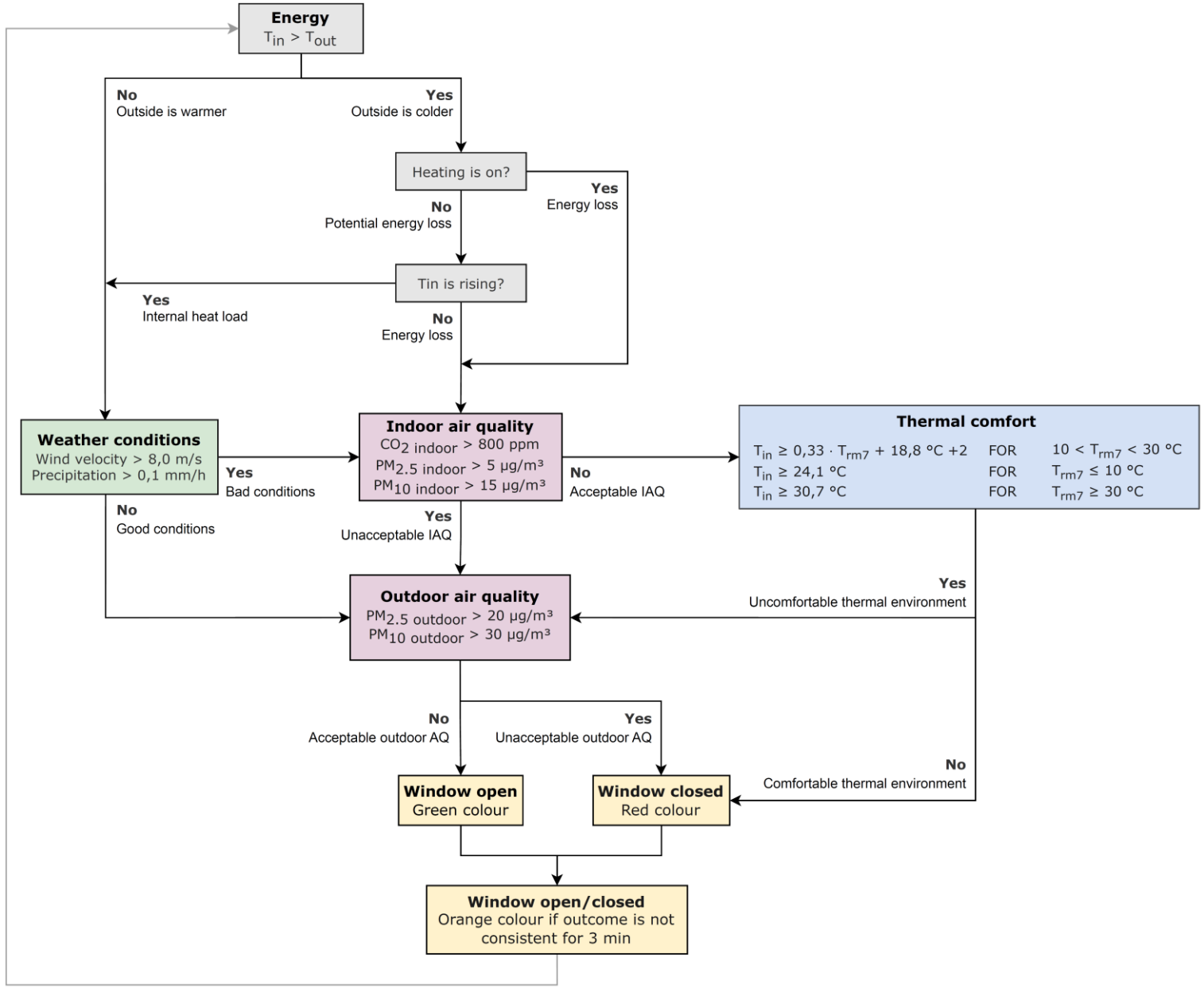
Important limitations:

1. Operative temperature
2. Outdoor noise
3. Sun radiation
4. Internal drivers
5. Outdoor air quality more important than indoor air quality



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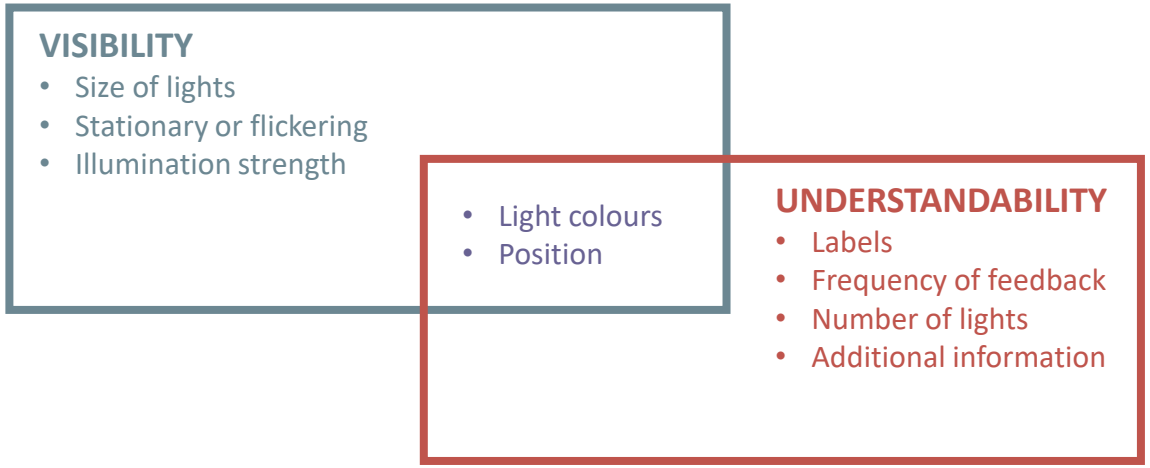
```
import time
import paho.mqtt.client as mqtt
import paho.mqtt.publish as publish
import sys
from time import sleep
from urllib.request import urlopen

import datetime as dt
import matplotlib.pyplot as plt
import matplotlib.animation as animation

from requests_html import HTMLSession
from bs4 import BeautifulSoup
import requests
import re

import numpy as np

Broker = "192.168.4.1"

#CO2
co2_1=""
co2_2=""

#PM 2.5
pm25_1=""
pm25_2=""

#PM 10
pm100_1=""
pm100_2=""

#Indoor temperature
temp_1=""
temp_2=""
```

Design

Window feedback system

- Ackerly and Brager (2013) as starting point

- Bigger, blinking and higher illumination strength are better perceptible (Lu et al., 2016; Matviienko et al, 2015)

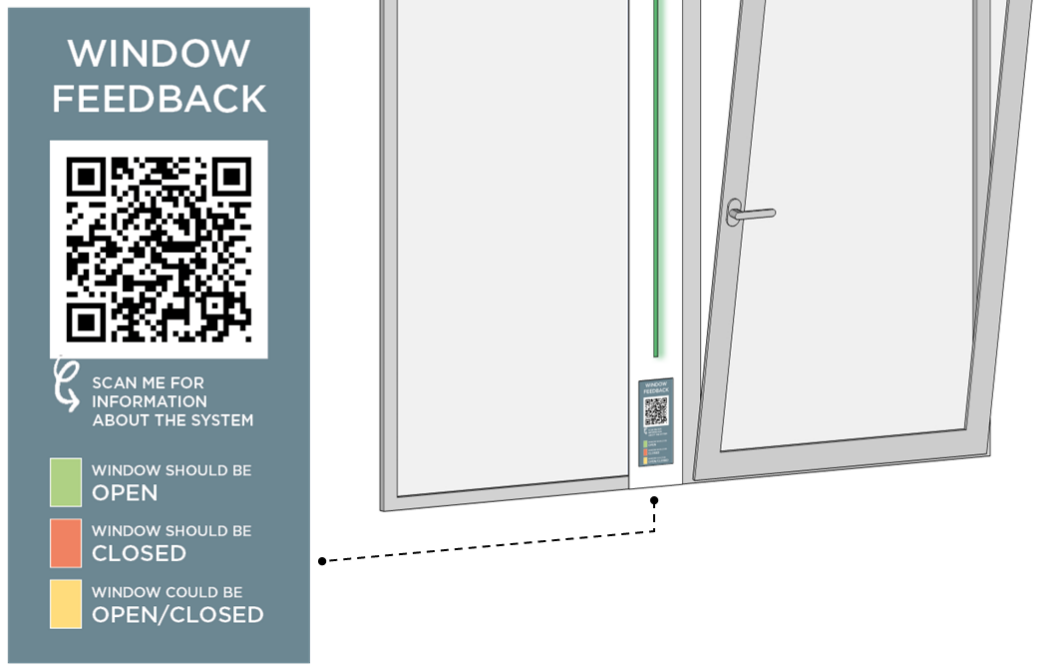


- Limit number of lights (Matviienko et al., 2015)
- Understandability can be improved with additional information and labels

- Red and green colour are the most evident choice
- Most visible position near the centre of the table
- Most understandable position near the openable window

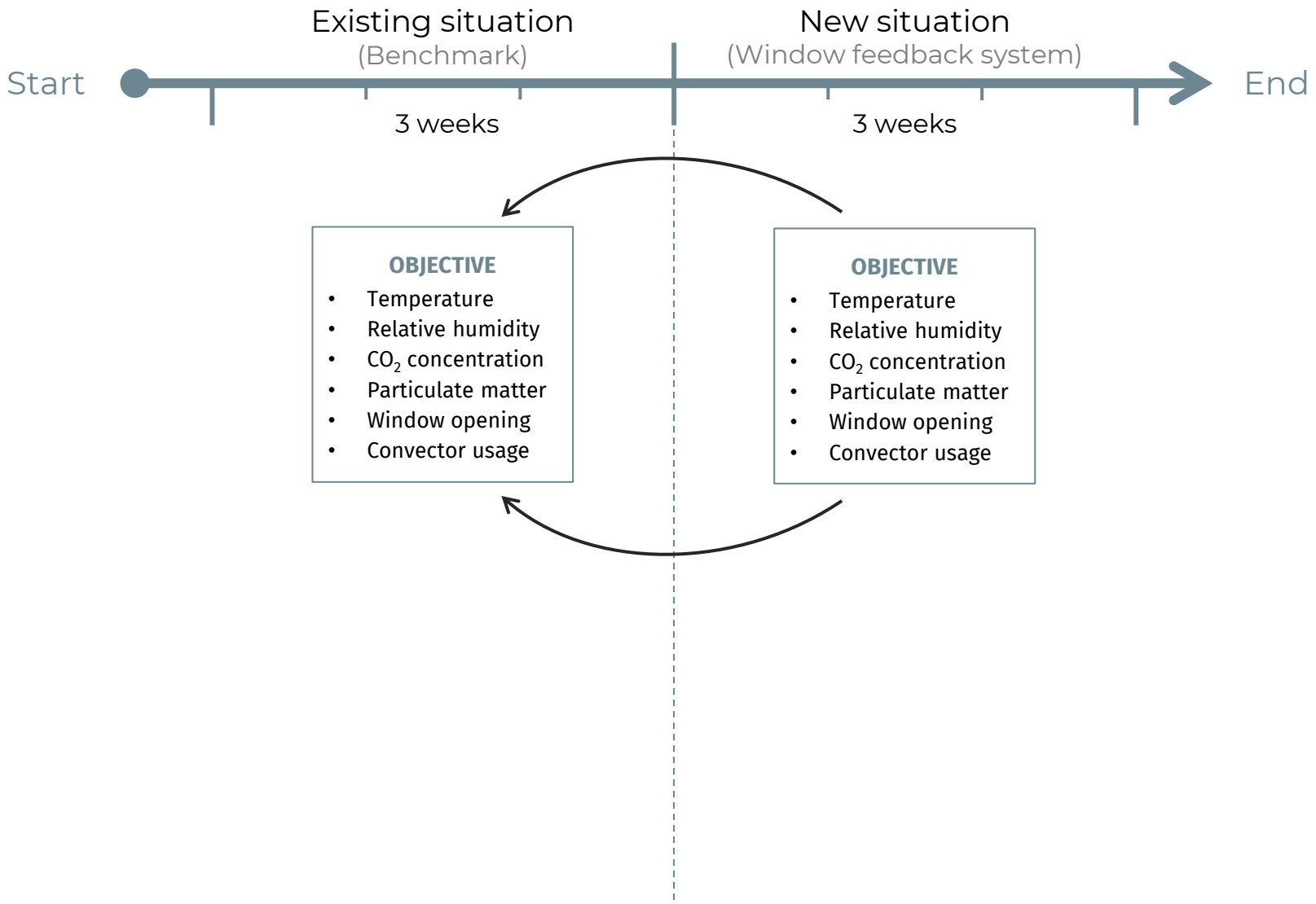
Design

Window feedback system



Experiment

Methodology



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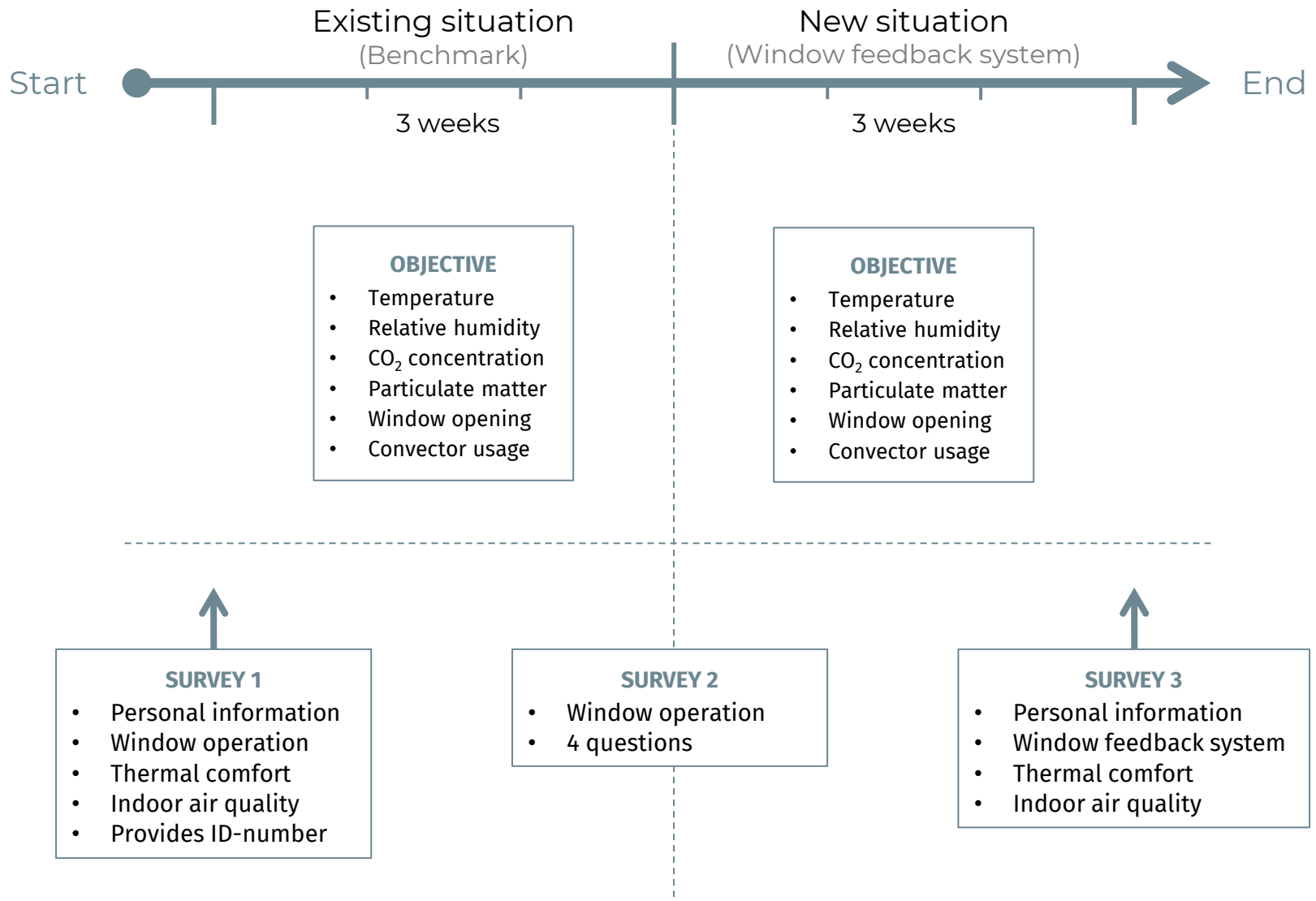

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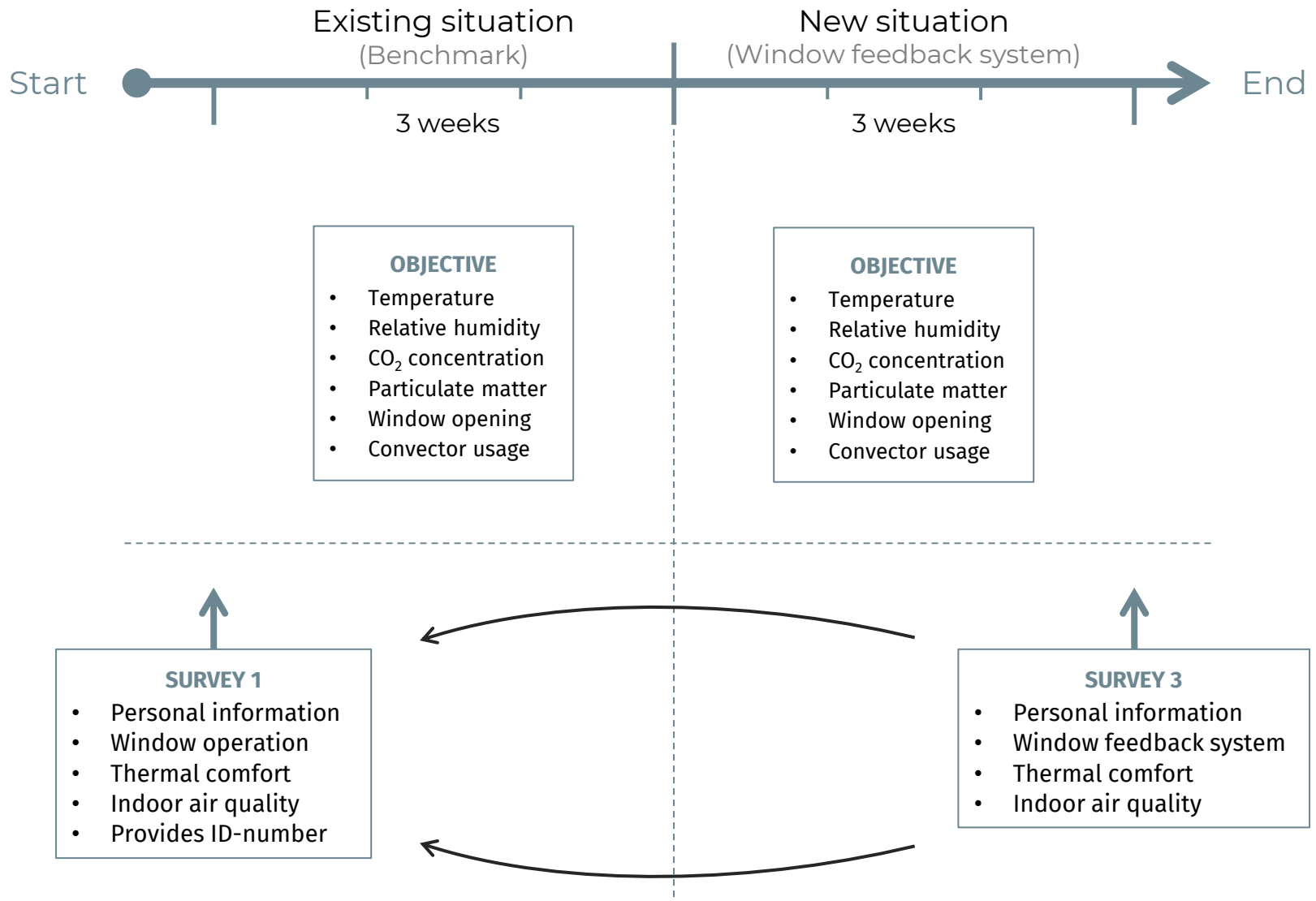

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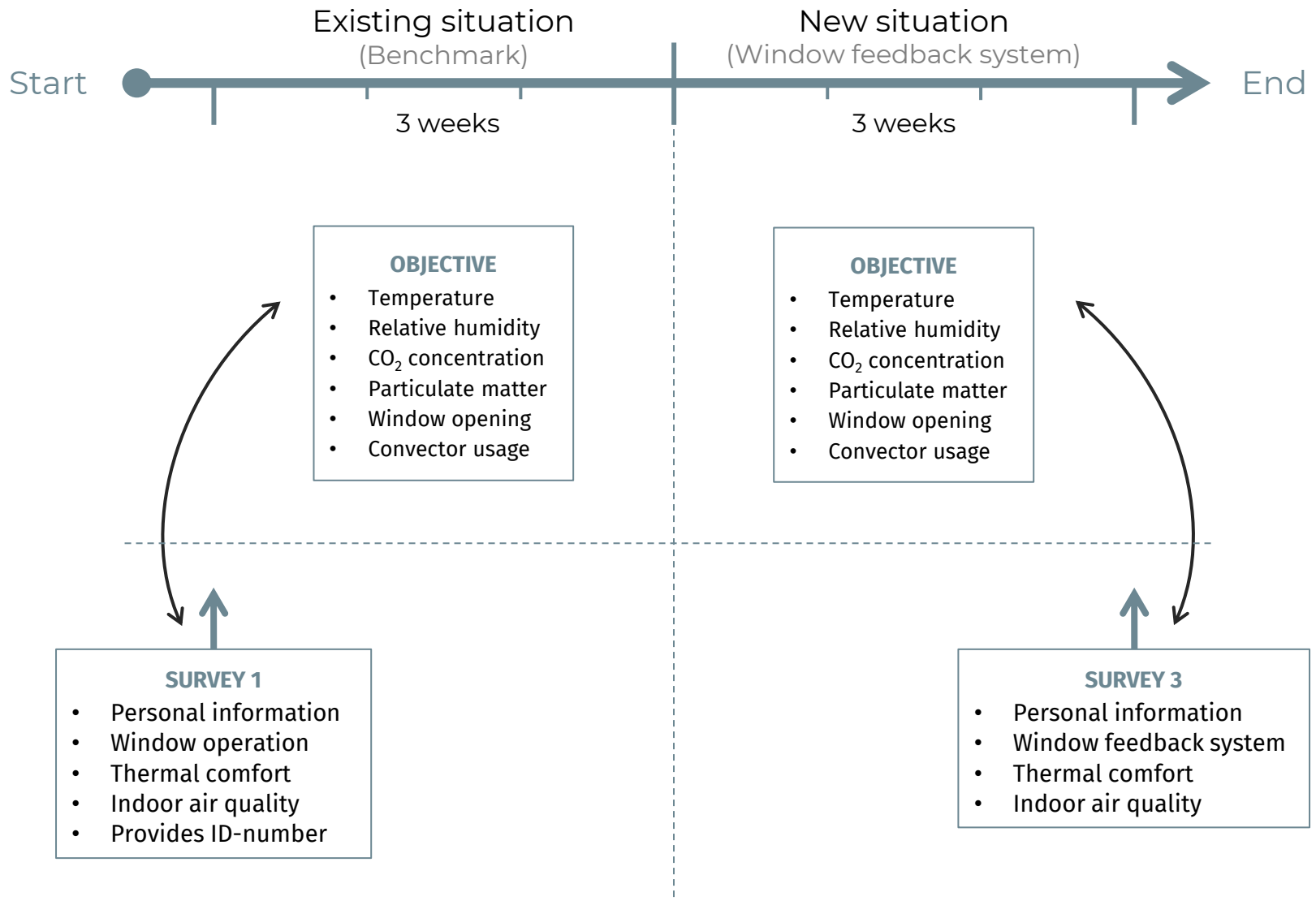


Experiment

Measurement set-up

LEGEND

Building

- open — Openable window
- Convector

Main system

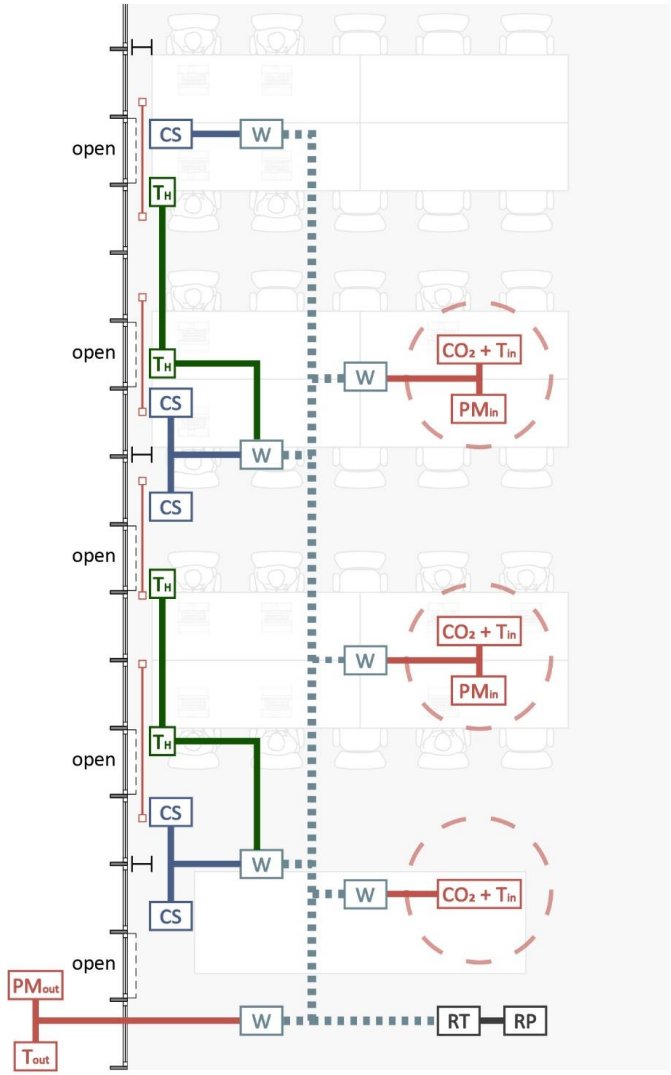
- RP — Raspberry Pi
- RT — Router
- W — Wemos

Sensors

- T_H — Surface temperature convector
- CS — Magnetic contact sensor window
- CO_2 — CO_2 concentration
- T_{in} — Indoor temperature
- T_{out} — Outdoor temperature
- PM_{in} — Indoor particulate matter
- PM_{out} — Outdoor particulate matter

Output

- LED — LED-light



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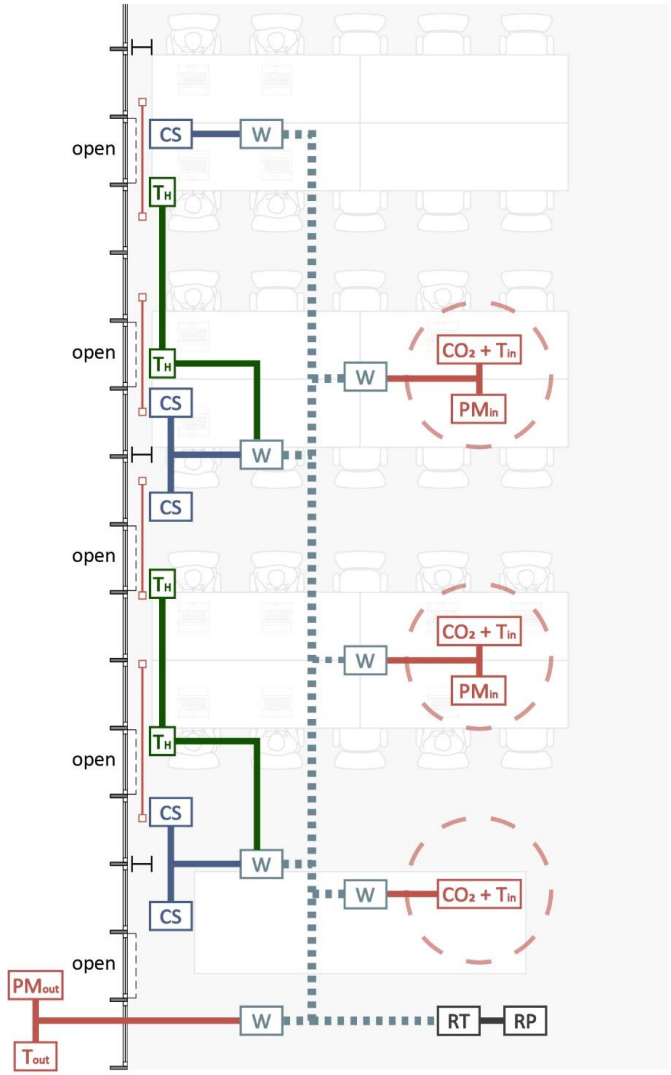


Important limitations:

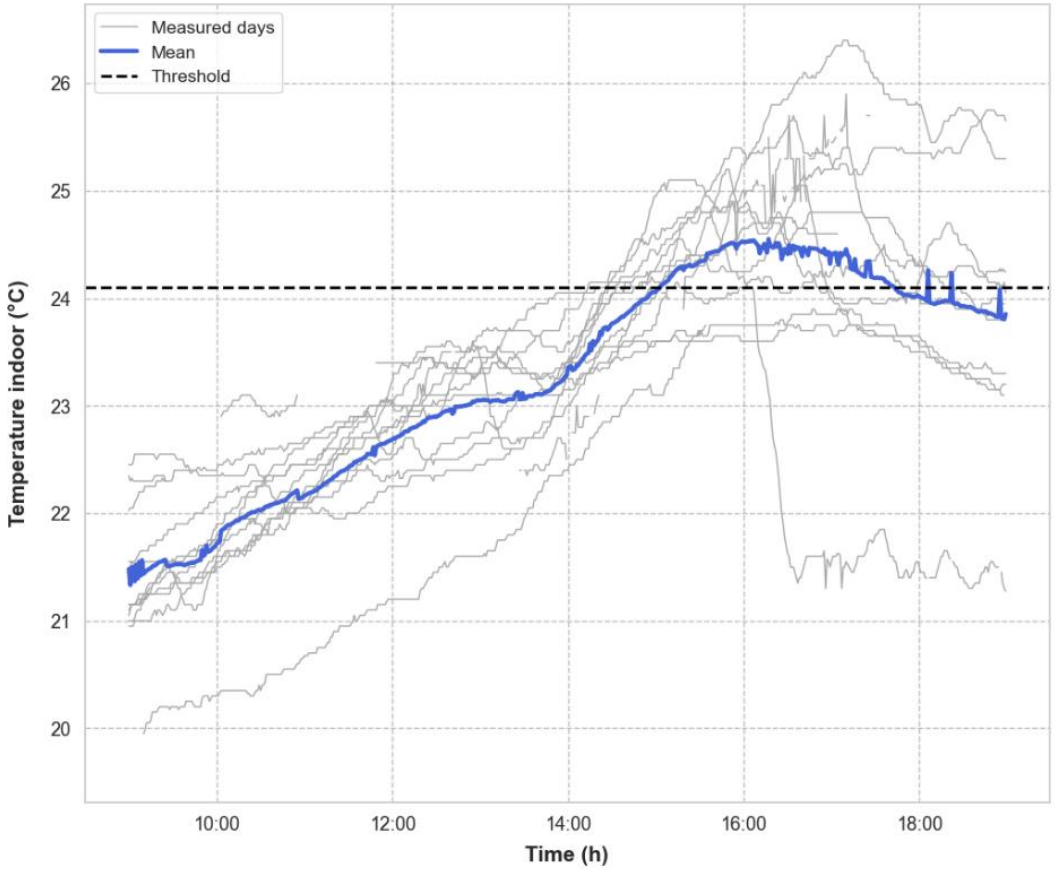
1. Measurement set-up assumes a micro-climate
2. Duration of the experiment

Results & Discussion

Existing situation

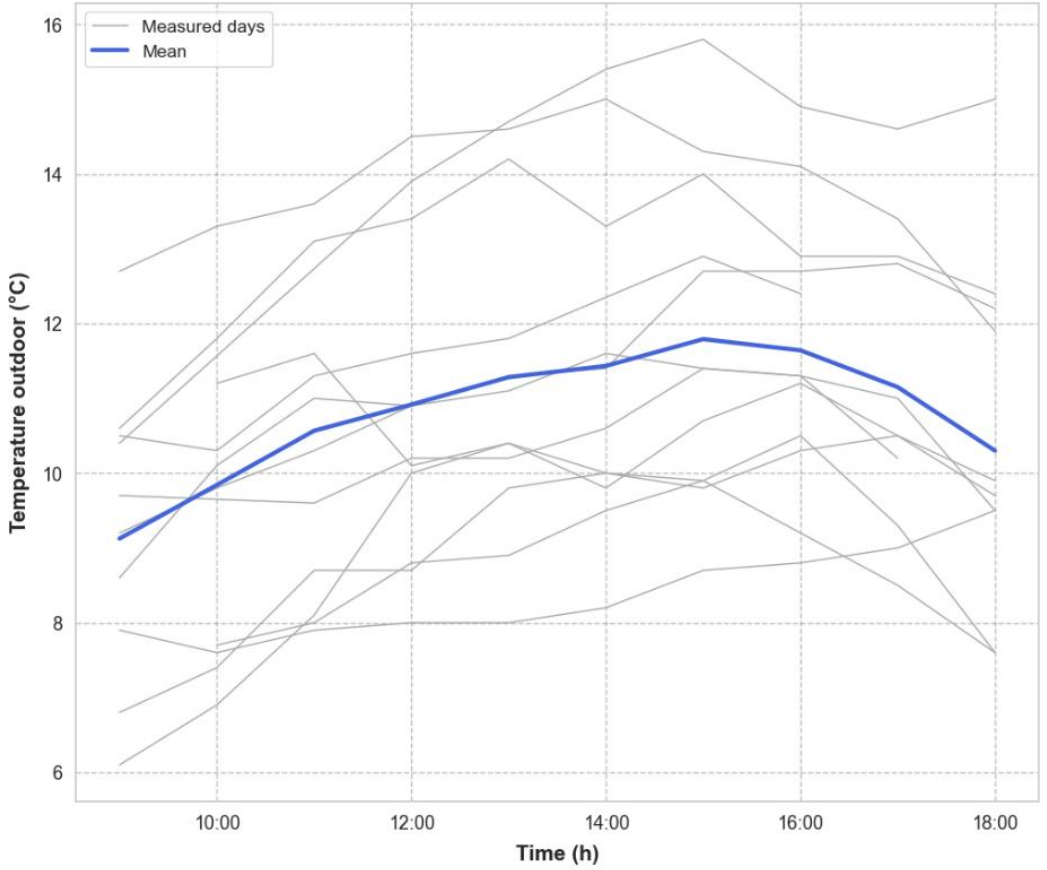
Temperature indoor:

- Maximum value = 26,5 °C
- Minimum value = 19,5 °C
- Median = ± 23,3 °C
- Mean = ± 23,2 °C
- Mean difference sensors = 0,23 °C
- Threshold = 24,1 °C
- Total time exceeded = 1664 min
- Mean exceedance per day = 2 : 19 [h : min]



Temperature outdoor:

- Maximum value = 15,8 °C
- Minimum value = 6,1 °C
- Median = ± 10,5 °C
- Mean = ± 10,8 °C

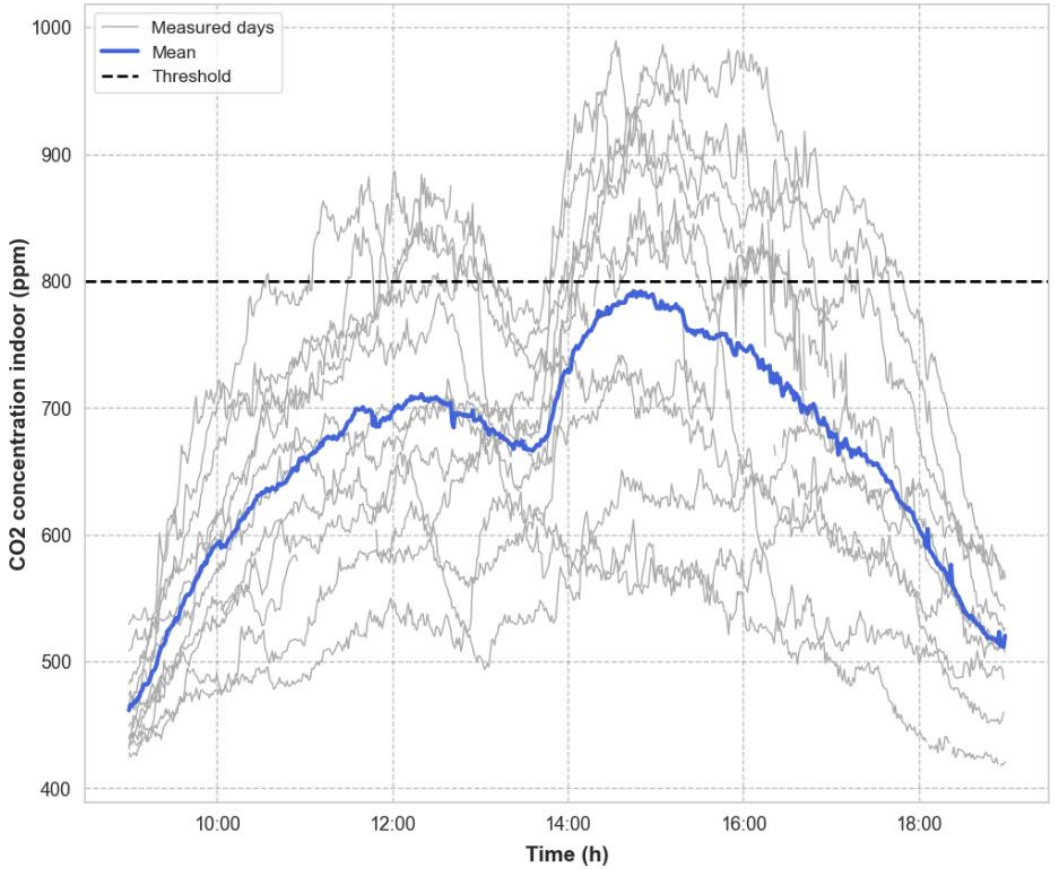


Results & Discussion

Existing situation

CO_2 concentration indoor:

- Maximum value = 1047 ppm
- Minimum value = 414 ppm
- Median = ± 660 ppm
- Mean = ± 672 ppm
- Mean difference sensors = 23 ppm
- Threshold = 800 ppm
- Total time exceeded = 1353 min
- Mean exceedance per day = 1 : 53 [h : min]

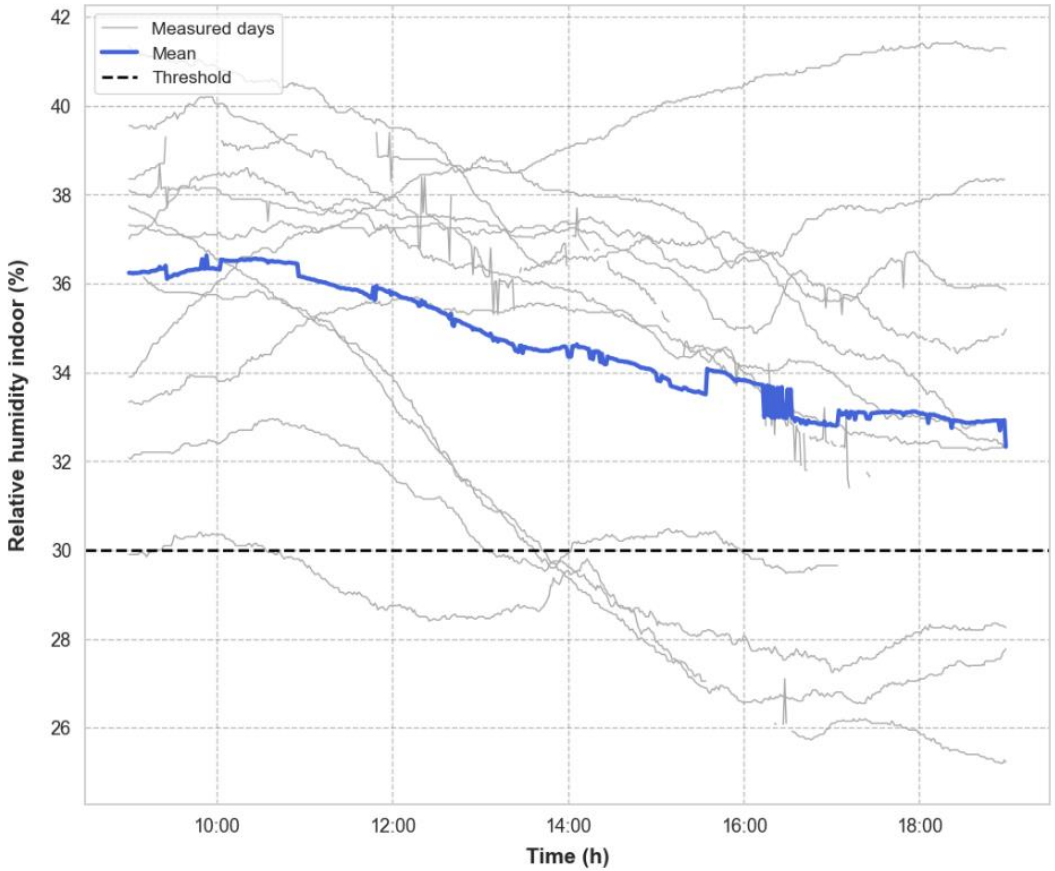


Results & Discussion

Existing situation

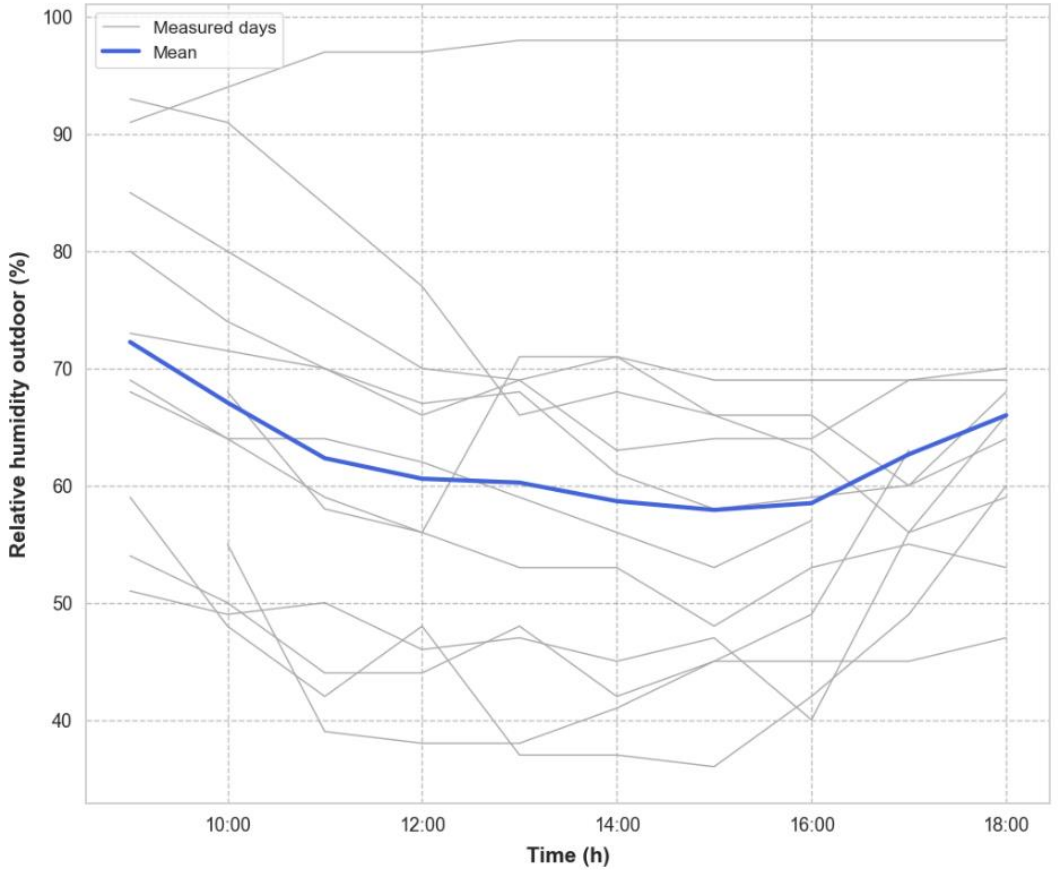
Relative humidity indoor:

- Maximum value = 42,3 %
- Minimum value = 23,4 %
- Median = ± 35,3 %
- Mean = ± 34,3 %
- Mean difference sensors = 1,51 %
- Threshold = 30 %
- Total time exceeded = 1239 min
- Mean exceedance per day = 1 : 43 [h : min]



Relative humidity outdoor:

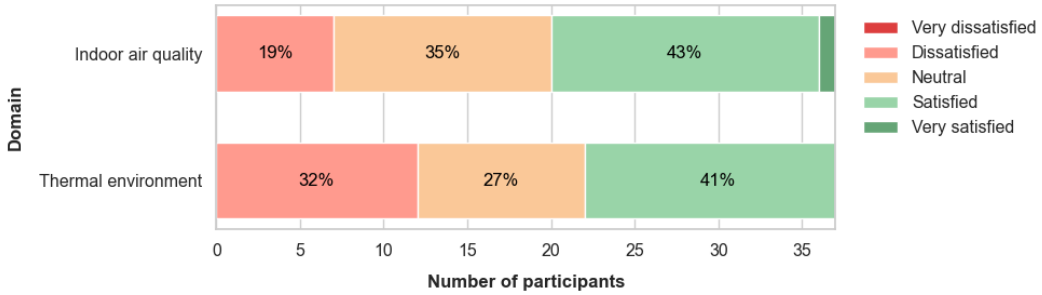
- Maximum value = 98,0 %
- Minimum value = 36,0 %
- Median = ± 63,0 %
- Mean = ± 62,6 %



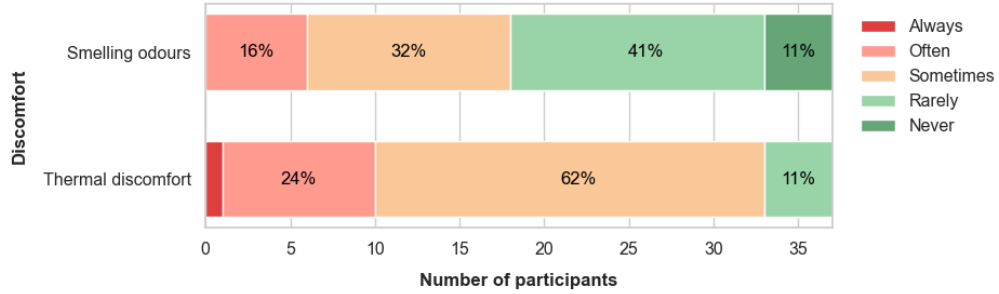
Results & Discussion

Existing situation

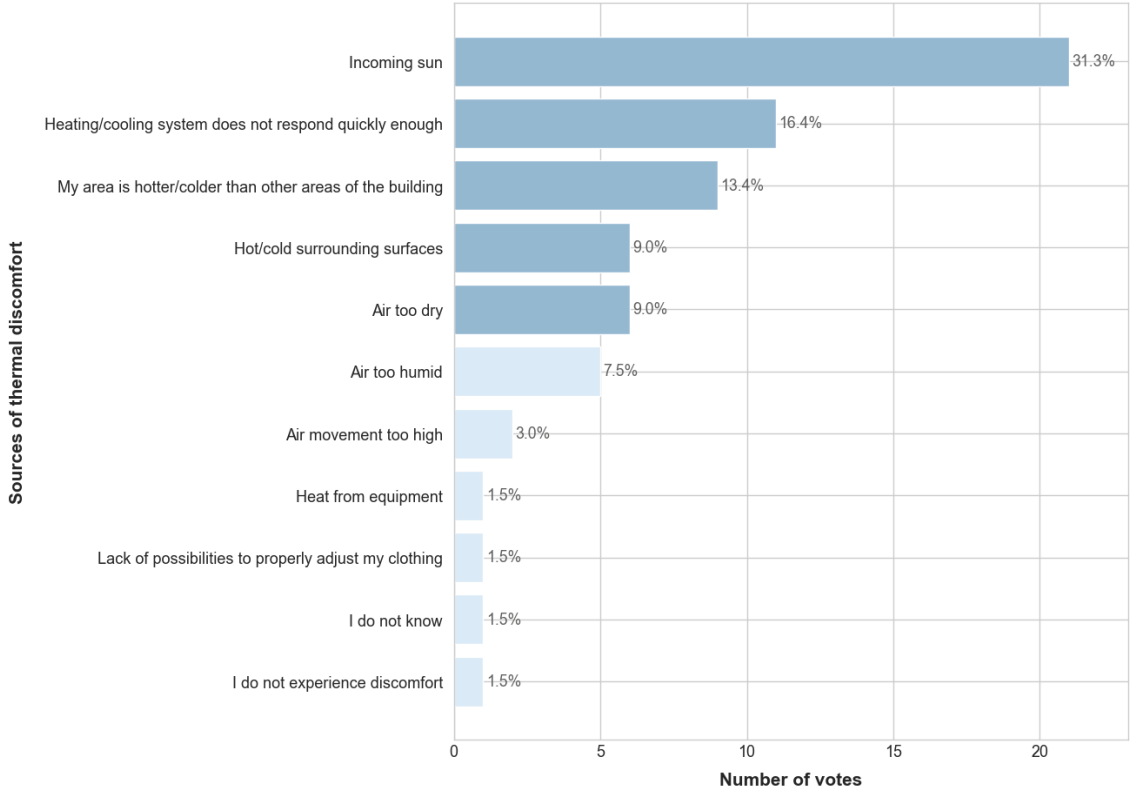
Satisfaction indoor environment:



Discomfort indoor environment:



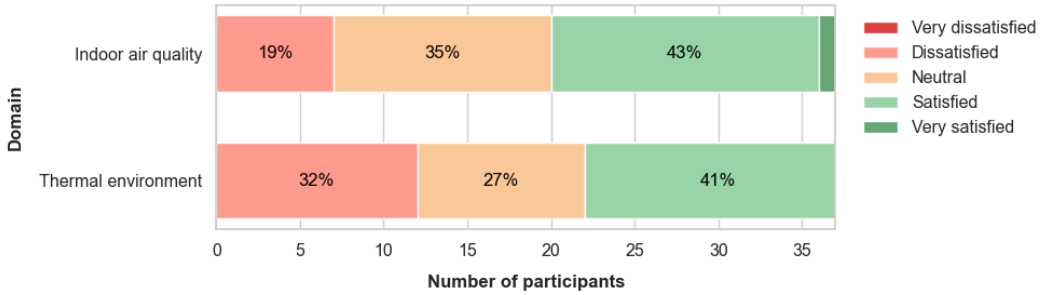
Sources thermal discomfort:



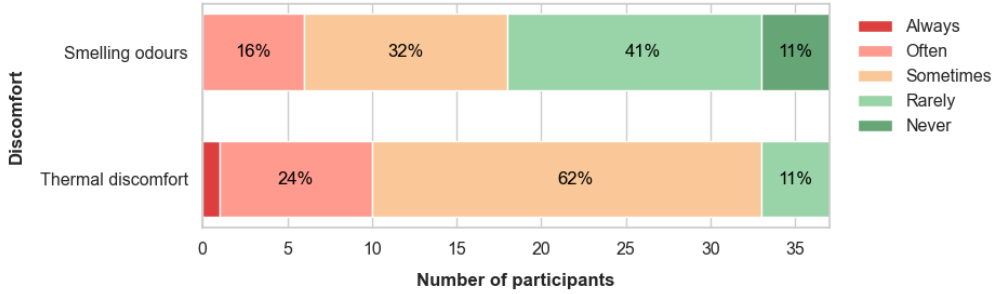
Results & Discussion

Existing situation

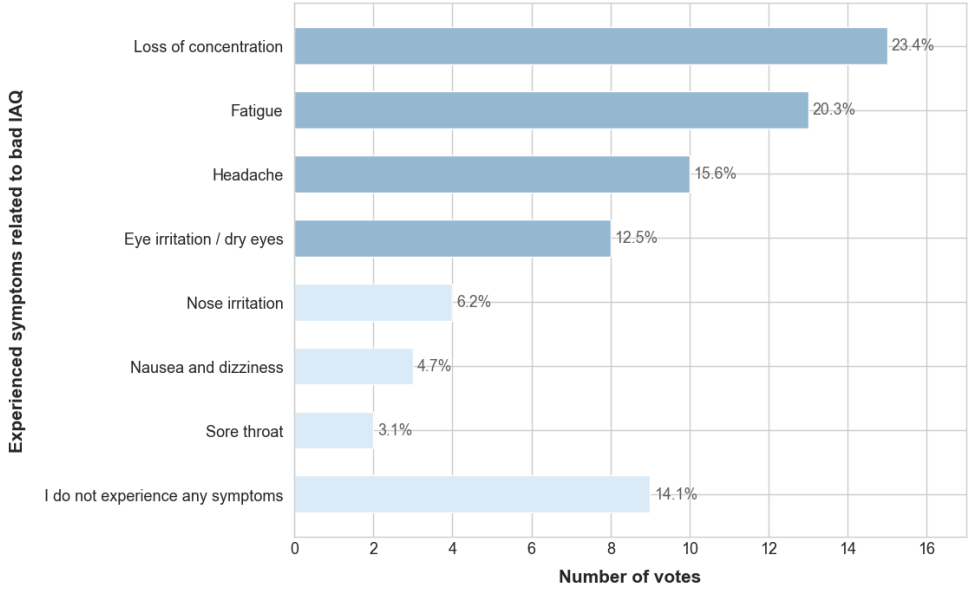
Satisfaction indoor environment:



Discomfort indoor environment:



Symptoms related to bad IAQ

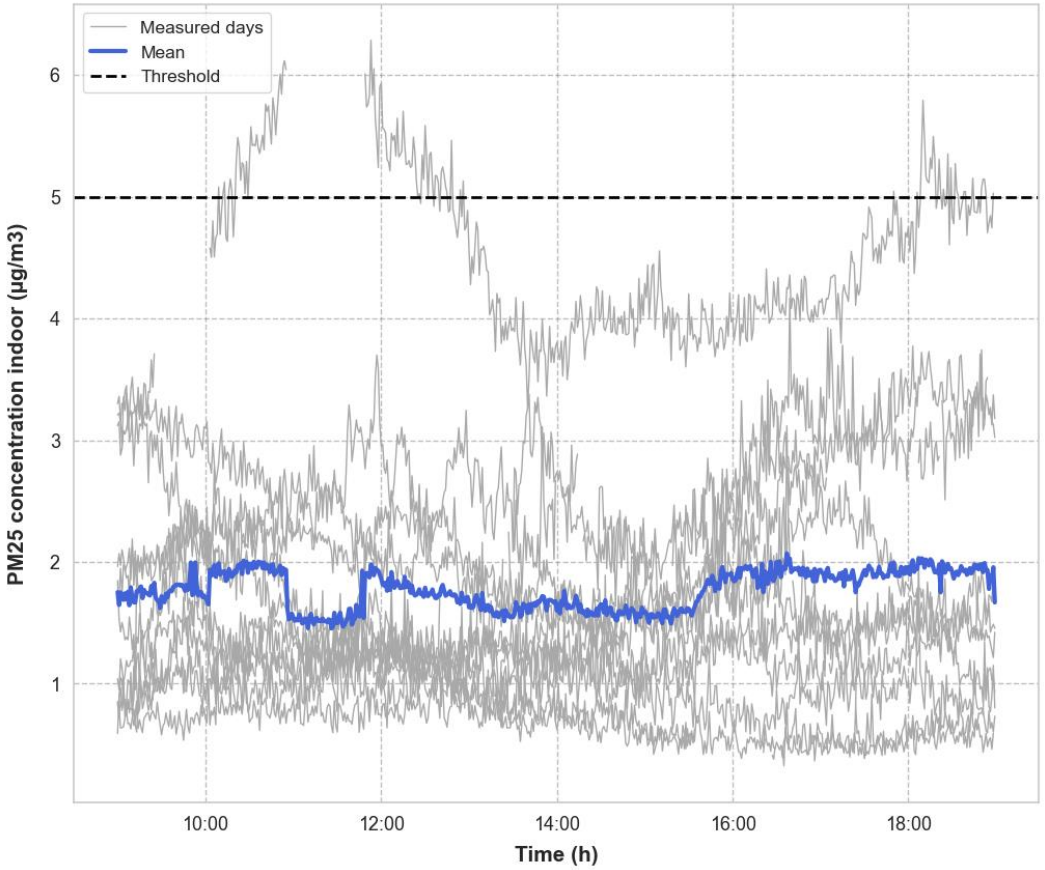


Results & Discussion

Existing situation

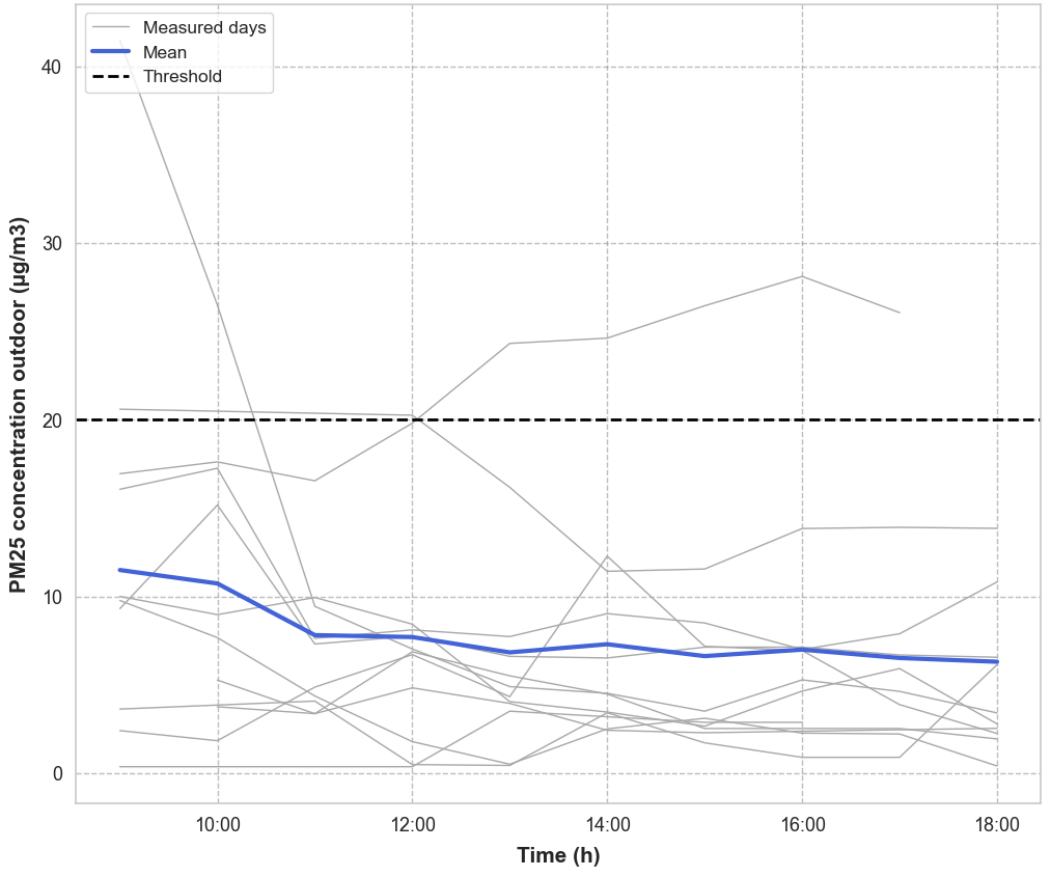
$PM_{2.5}$ concentration indoor:

- Maximum value = 6,54 µg/m3
- Minimum value = 0,28 µg/m3
- Median = ± 1,45 µg/m3
- Mean = ± 1,76 µg/m3
- Mean difference sensors = 0,23 µg/m3
- Threshold = 5 µg/m3
- Total time exceeded = 124 min
- Mean exceedance per day = 0 : 10 [h : min]



$PM_{2.5}$ concentration outdoor:

- Maximum value = 41,46 µg/m3
- Minimum value = 0,38 µg/m3
- Median = ± 5,49 µg/m3
- Mean = ± 7,92 µg/m3
- Threshold = 20 µg/m3
- Total time exceeded = 602 min
- Mean exceedance per day = 0 : 50 [h : min]

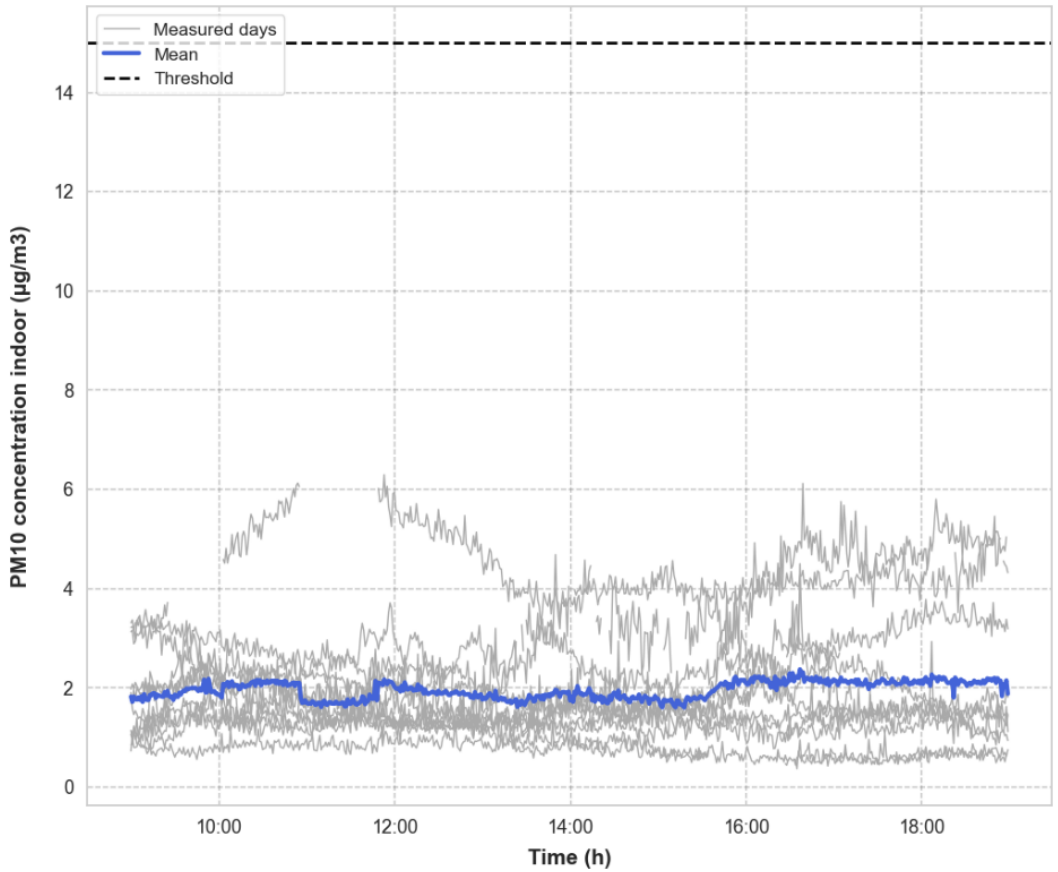


Results & Discussion

Existing situation

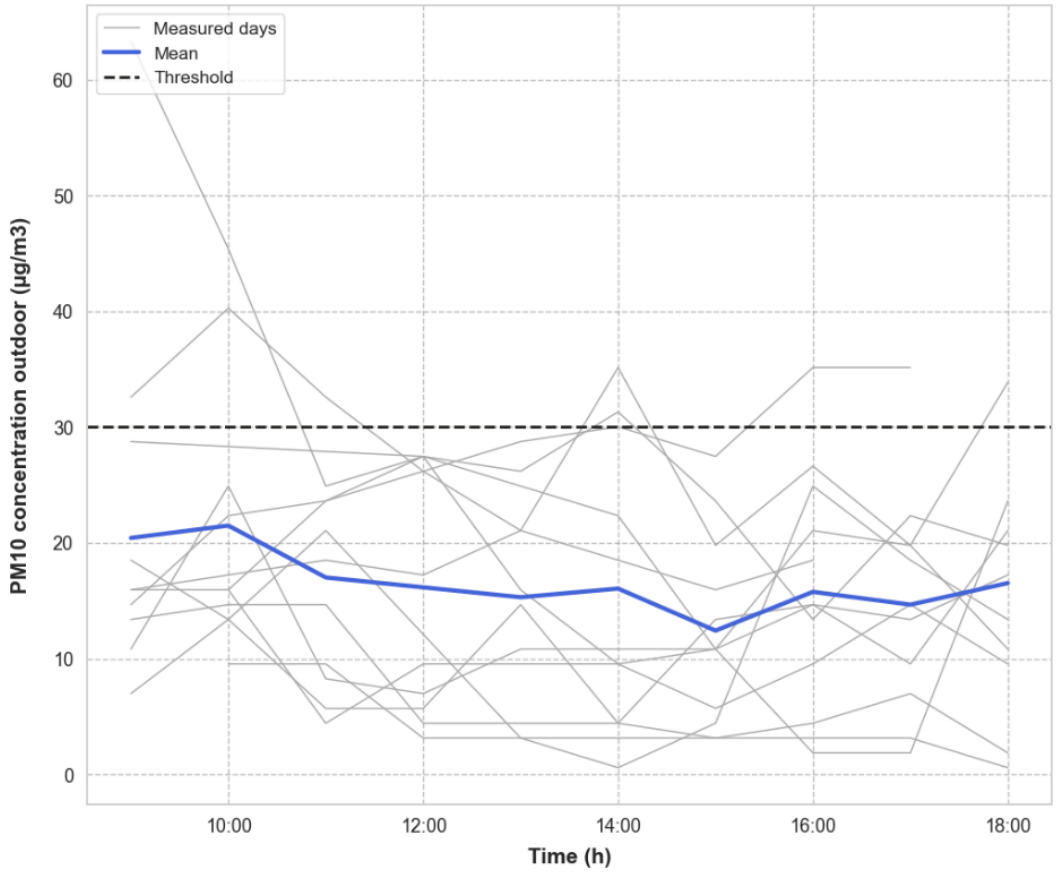
PM_{10} concentration indoor:

- Maximum value = 6,73 µg/m3
- Minimum value = 0,31 µg/m3
- Median = ± 1,60 µg/m3
- Mean = ± 1,94 µg/m3
- Mean difference sensors = 0,27 µg/m3
- Threshold = 15 µg/m3
- Total time exceeded = 0 min
- Mean exceedance per day = 0 : 0 [h : min]



PM_{10} concentration outdoor:

- Maximum value = 63,31 µg/m3
- Minimum value = 0,59 µg/m3
- Median = ± 15,51 µg/m3
- Mean = ± 16,63 µg/m3
- Threshold = 30 µg/m3
- Total time exceeded = 593 min
- Mean exceedance per day = 0 : 49 [h : min]

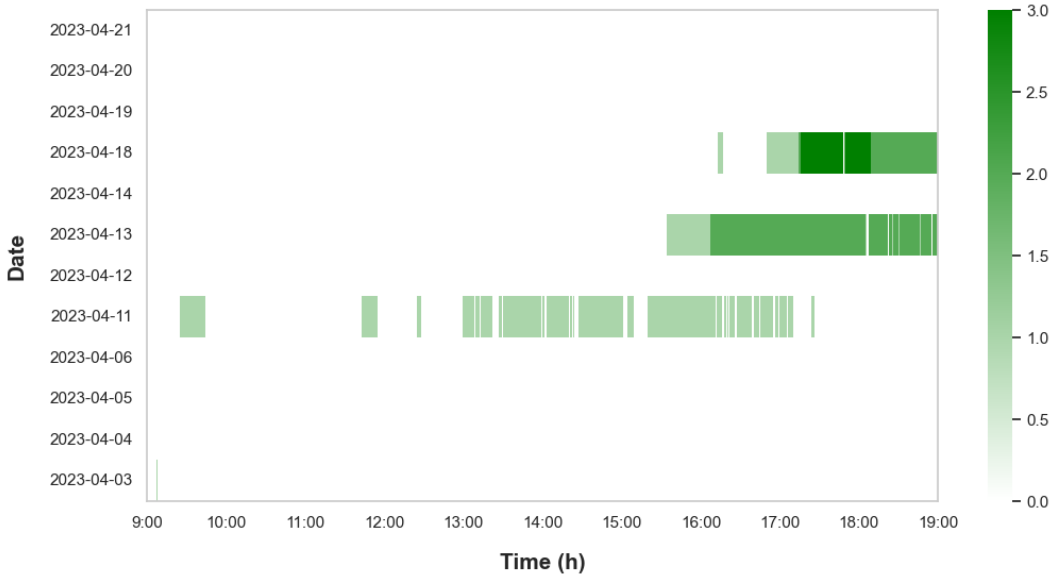


Results & Discussion

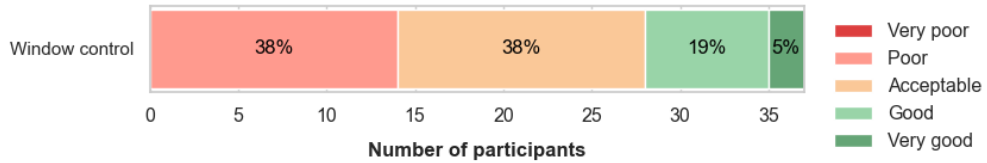
Existing situation

Window opening time:

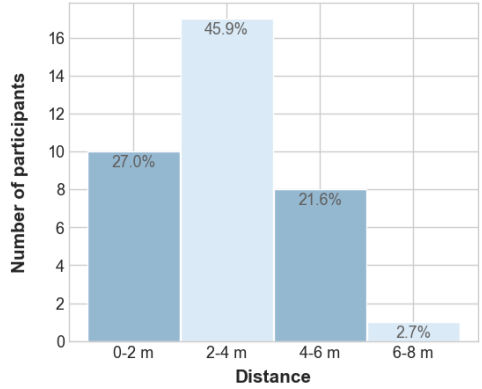
- Mean window opening time per workday = 0 : 48 [h : min]]



Perceived window control:



Distance to window:



"Some windows only allow tilting and that could be a limitation"

"Opening operation is limited to only inclination"

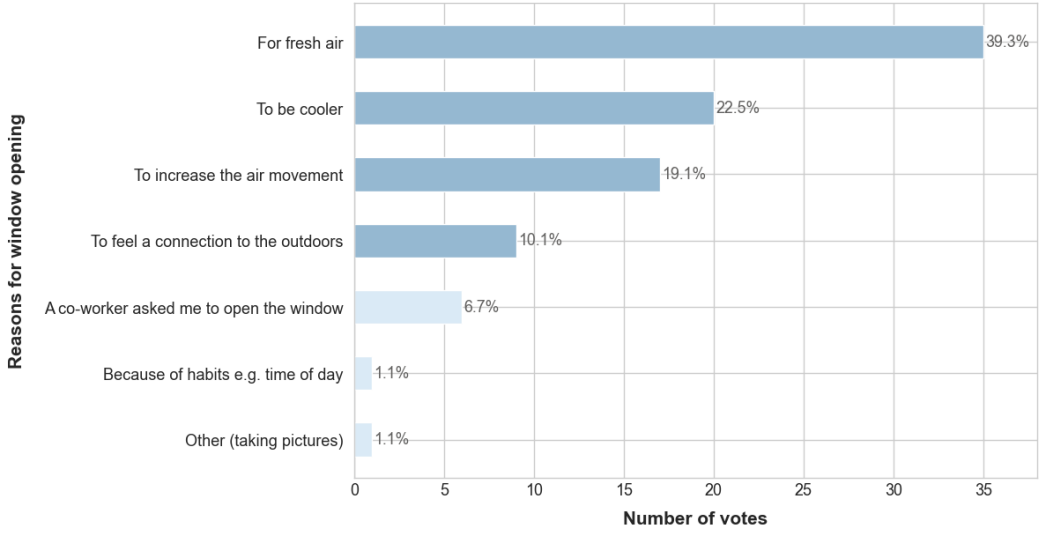
"Window settings are either 0 or 1 with no in between options"

"Should be more user friendly "

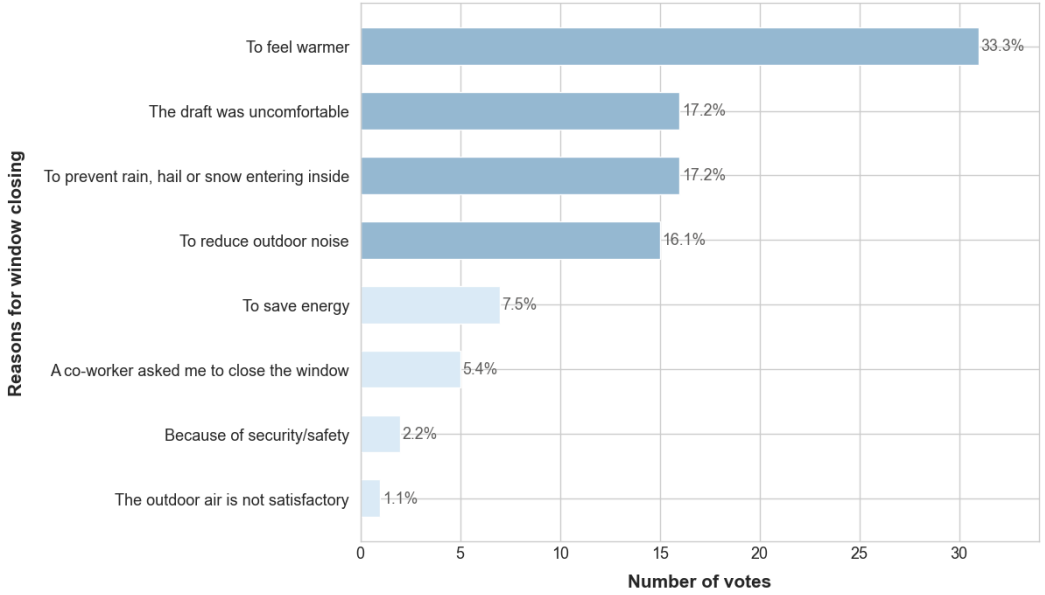
Results & Discussion

Existing situation

Reasons for window opening:



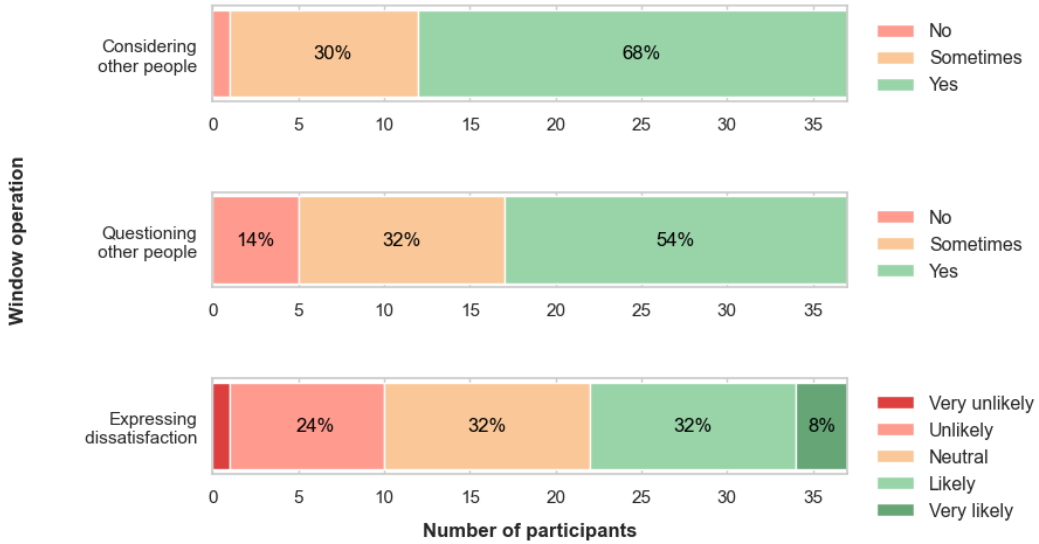
Reasons for window closing:



Results & Discussion

Existing situation

Social interaction when operating a window:

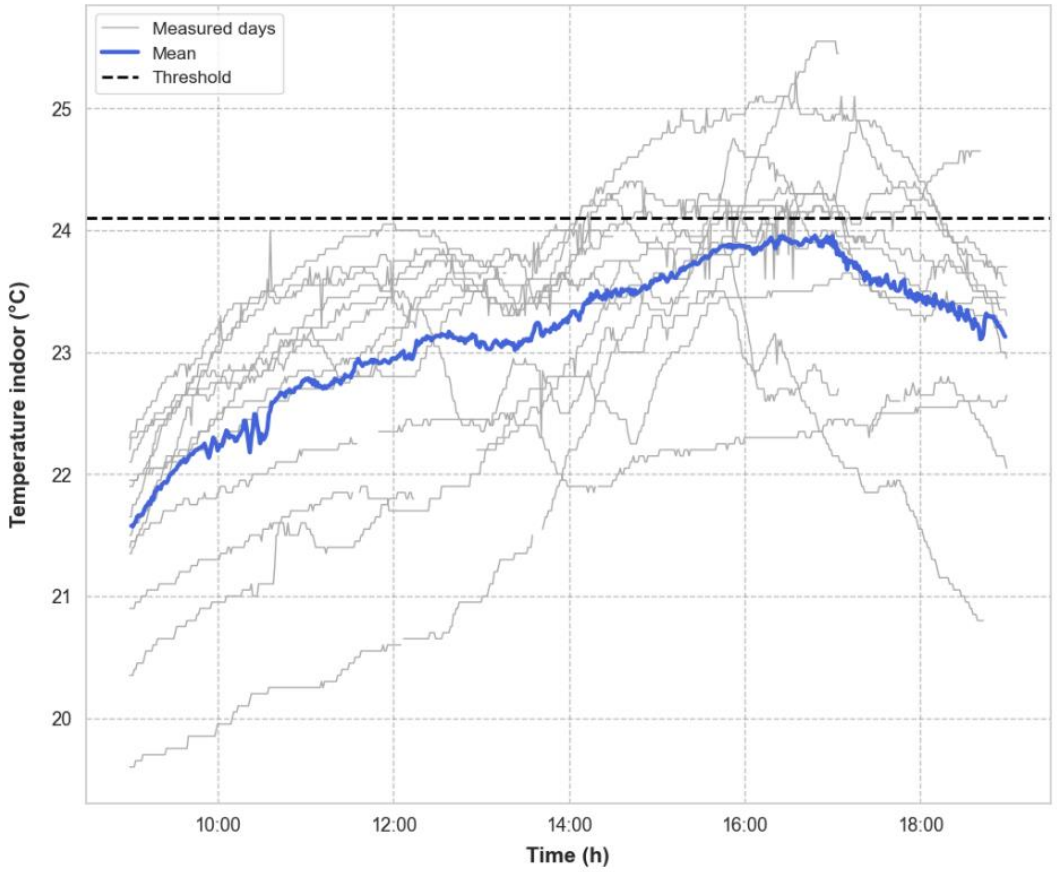


Results & Discussion

New situation

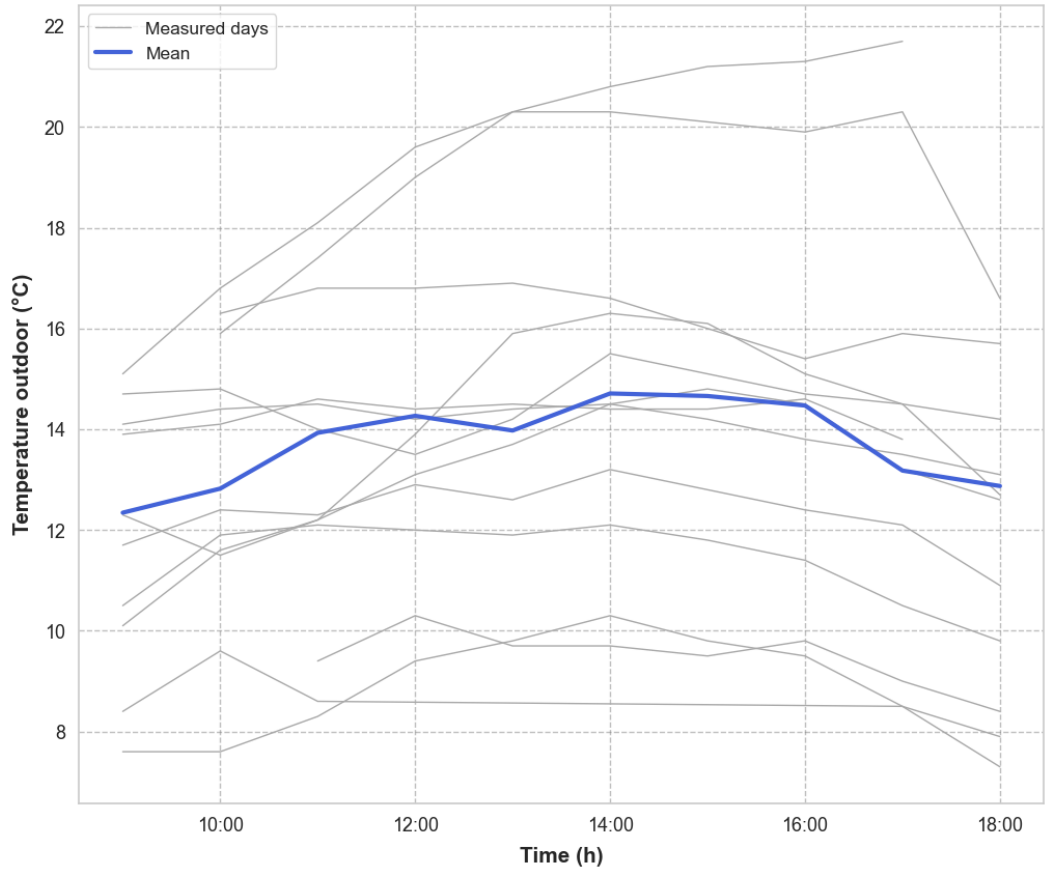
Temperature indoor:

- Maximum value = 25,7 °C
- Minimum value = 19,5 °C
- Median = ± 23,3 °C
- Mean = ± 23,0 °C
- Mean difference sensors = 0,22 °C
- Threshold = ± 24,1 °C
- Total time exceeded = 674 min
- Mean exceedance per day = 0 : 52 [h : min]



Temperature outdoor:

- Maximum value = 21,7 °C
- Minimum value = 7,3 °C
- Median = ± 13,8 °C
- Mean = ± 13,7 °C

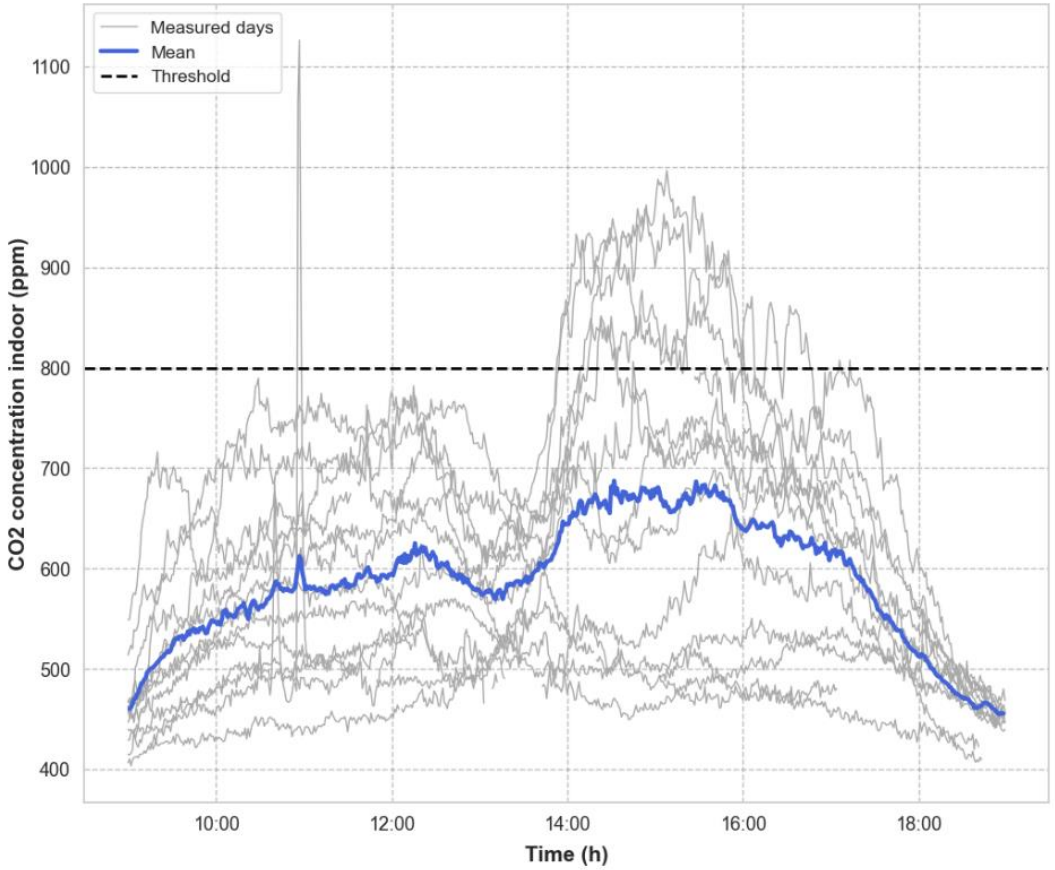


Results & Discussion

New situation

CO_2 concentration indoor:

- Maximum value = 1315 ppm
- Minimum value = 384 ppm
- Median = ± 569 ppm
- Mean = ± 596 ppm
- Mean difference sensors = 44 ppm
- Threshold = 800 ppm
- Total time exceeded = 492 min
- Mean exceedance per day = 0 : 38 [h : min]

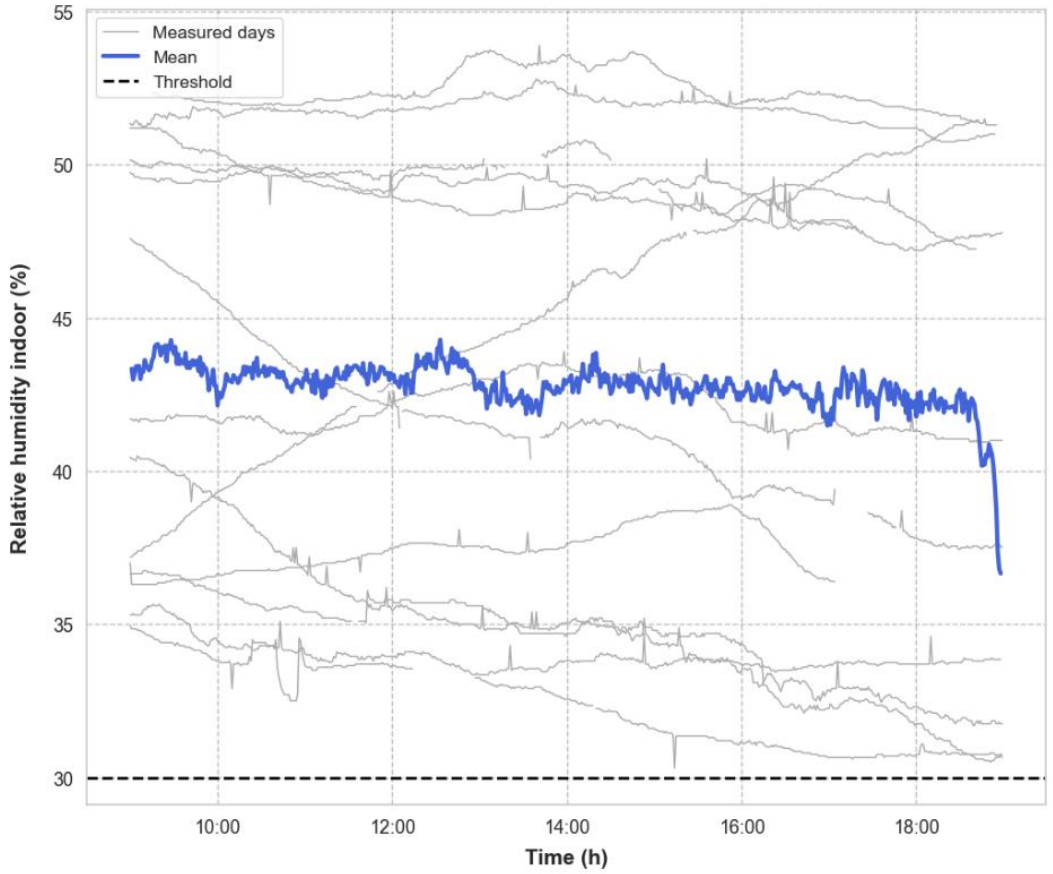


Results & Discussion

New situation

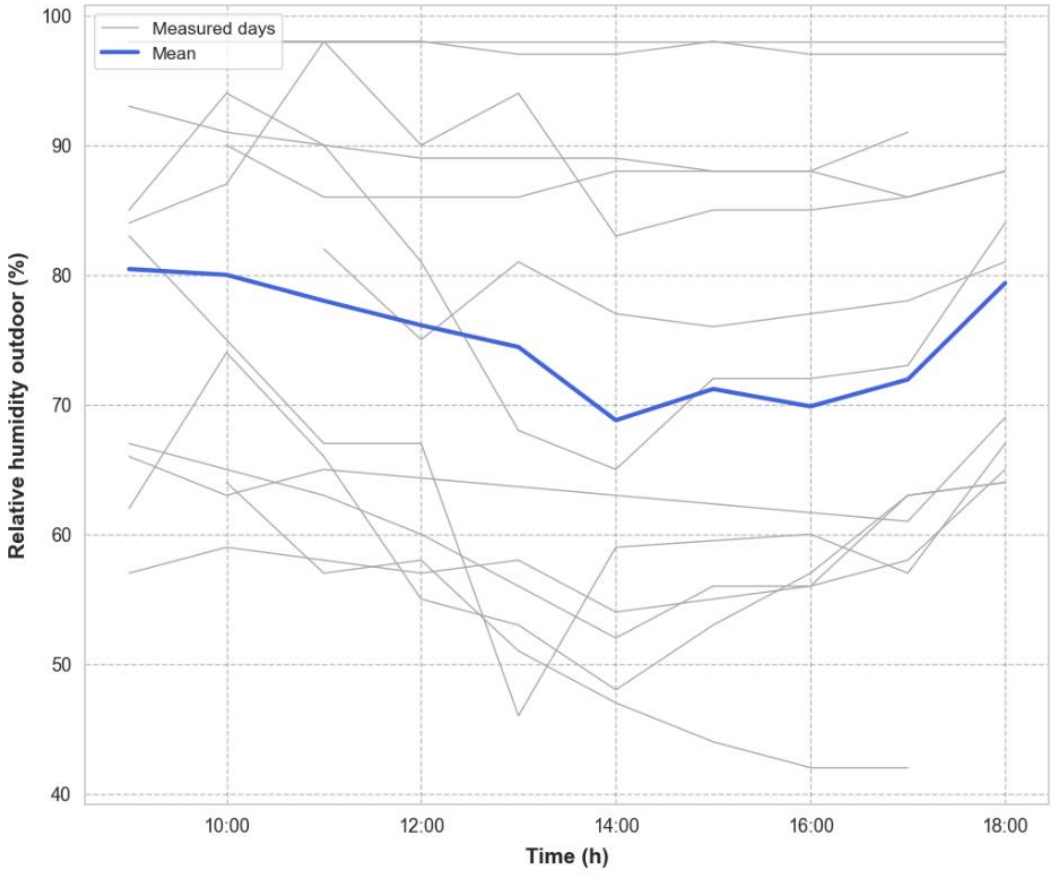
Relative humidity indoor:

- Maximum value = 54,5 %
- Minimum value = 16,3 %
- Median = ± 42,0 %
- Mean = ± 42,5 %
- Mean difference sensors = 1,02 %
- Threshold = 30 %
- Total time exceeded = 0 min
- Mean exceedance per day = 0 : 0 [h : min]



Relative humidity outdoor:

- Maximum value = 98,0 %
- Minimum value = 42,0 %
- Median = ± 76,0 %
- Mean = ± 75,2 %

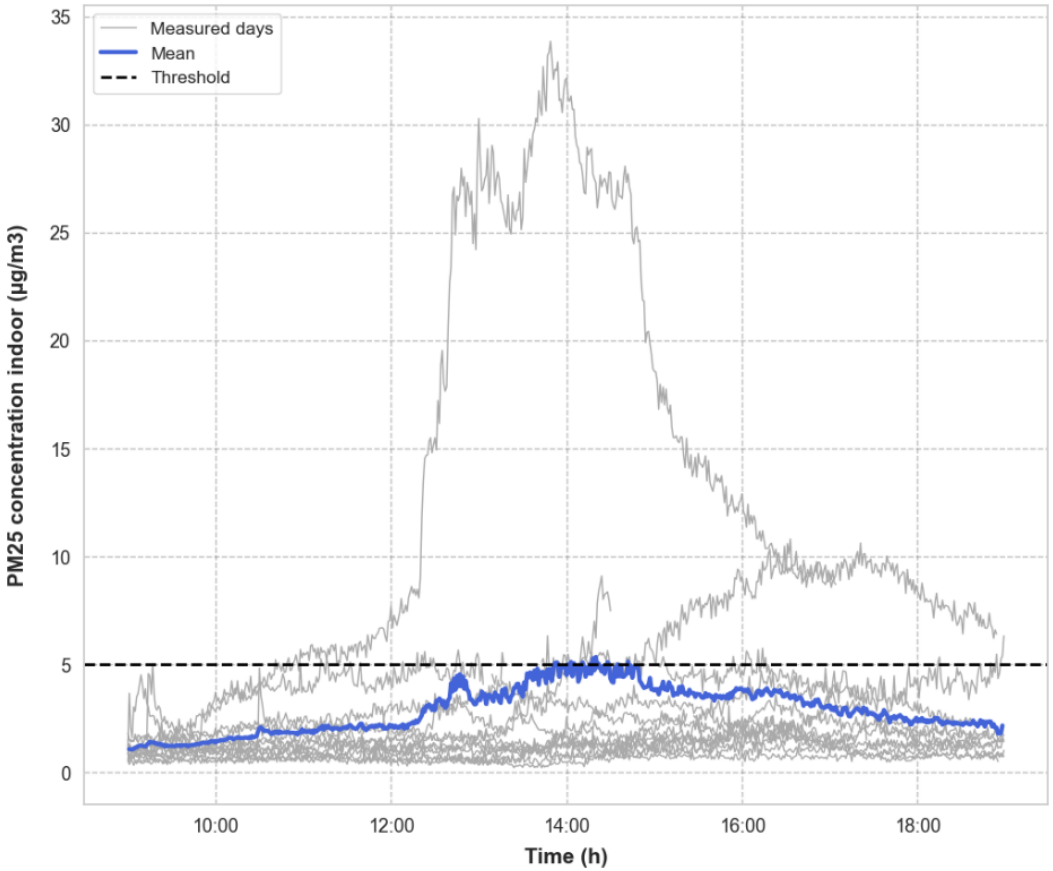


Results & Discussion

New situation

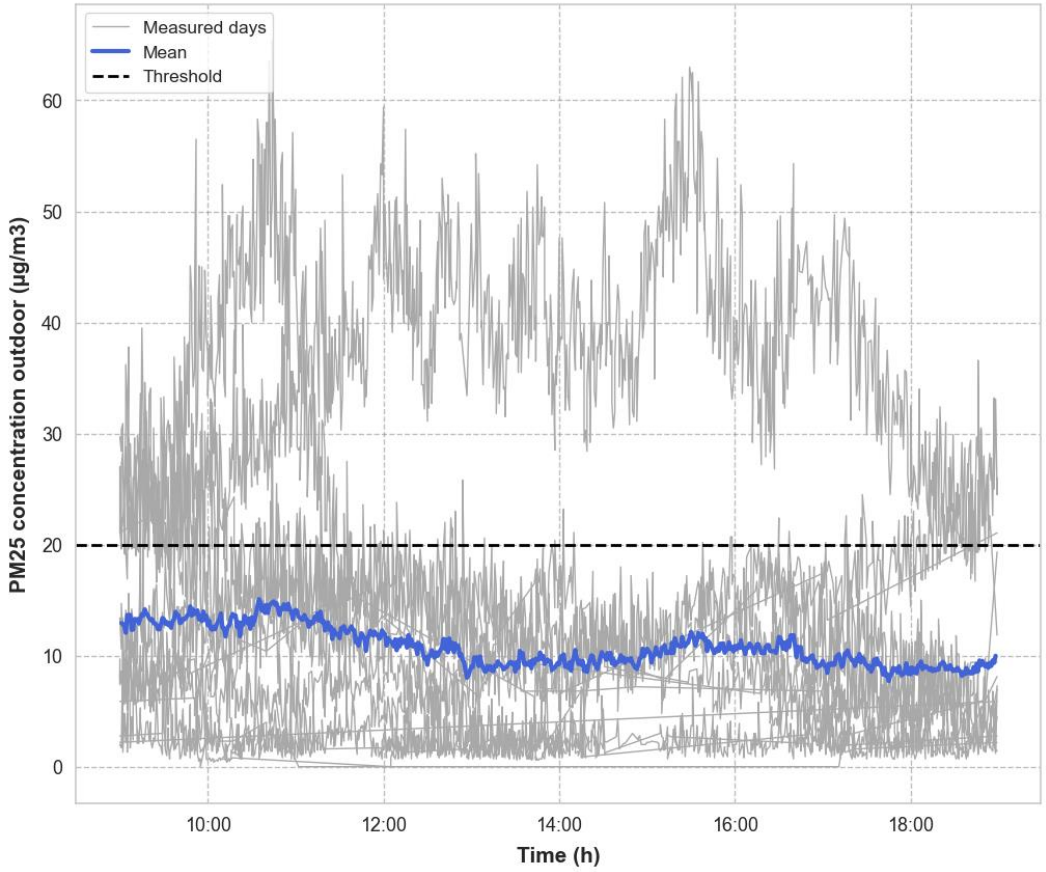
$PM_{2.5}$ concentration indoor:

- Maximum value = 33,71 µg/m3
- Minimum value = 0,15 µg/m3
- Median = ± 1,59 µg/m3
- Mean = ± 2,99 µg/m3
- Mean difference sensors = 0,36 µg/m3
- Threshold = 5 µg/m3
- Total time exceeded = 1030 min
- Mean exceedance per day = 1 : 19 [h : min]



$PM_{2.5}$ concentration outdoor:

- Maximum value = 65,40 µg/m3
- Minimum value = 0,36 µg/m3
- Median = ± 7,50 µg/m3
- Mean = ± 10,8 µg/m3
- Threshold = 20 µg/m3
- Total time exceeded = 1397 min
- Mean exceedance per day = 1 : 47 [h : min]

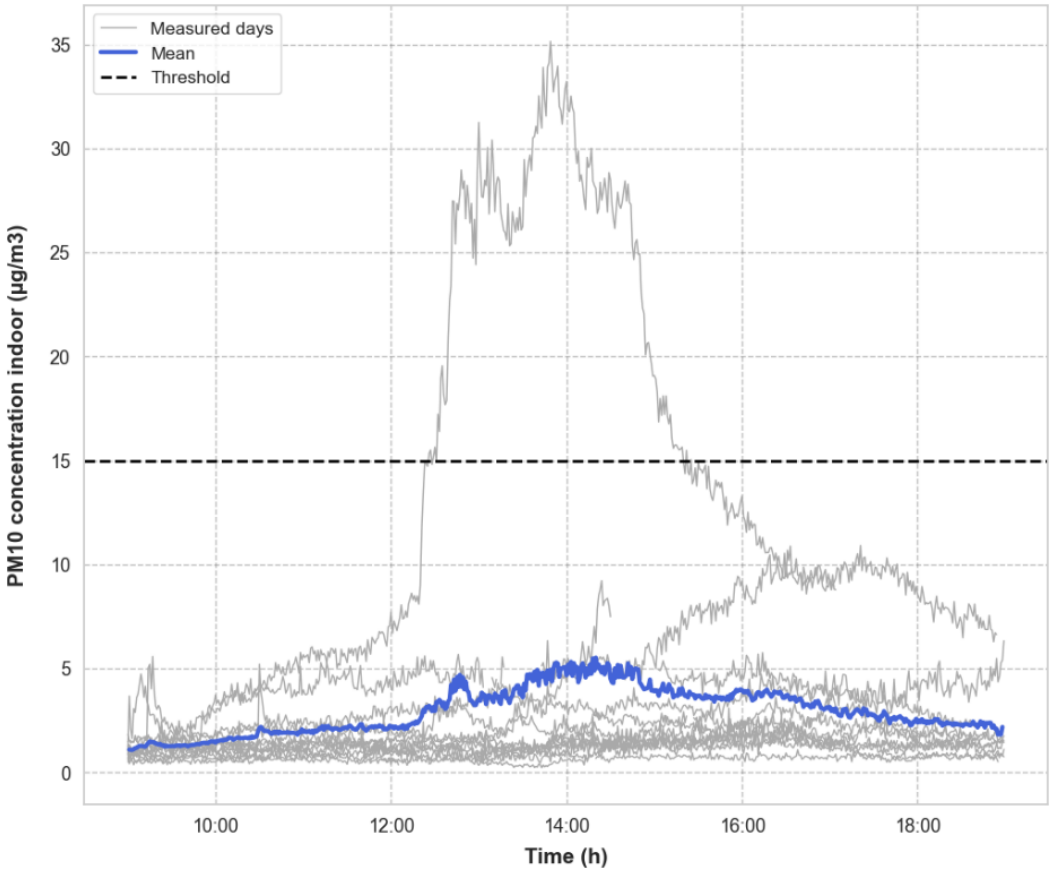


Results & Discussion

New situation

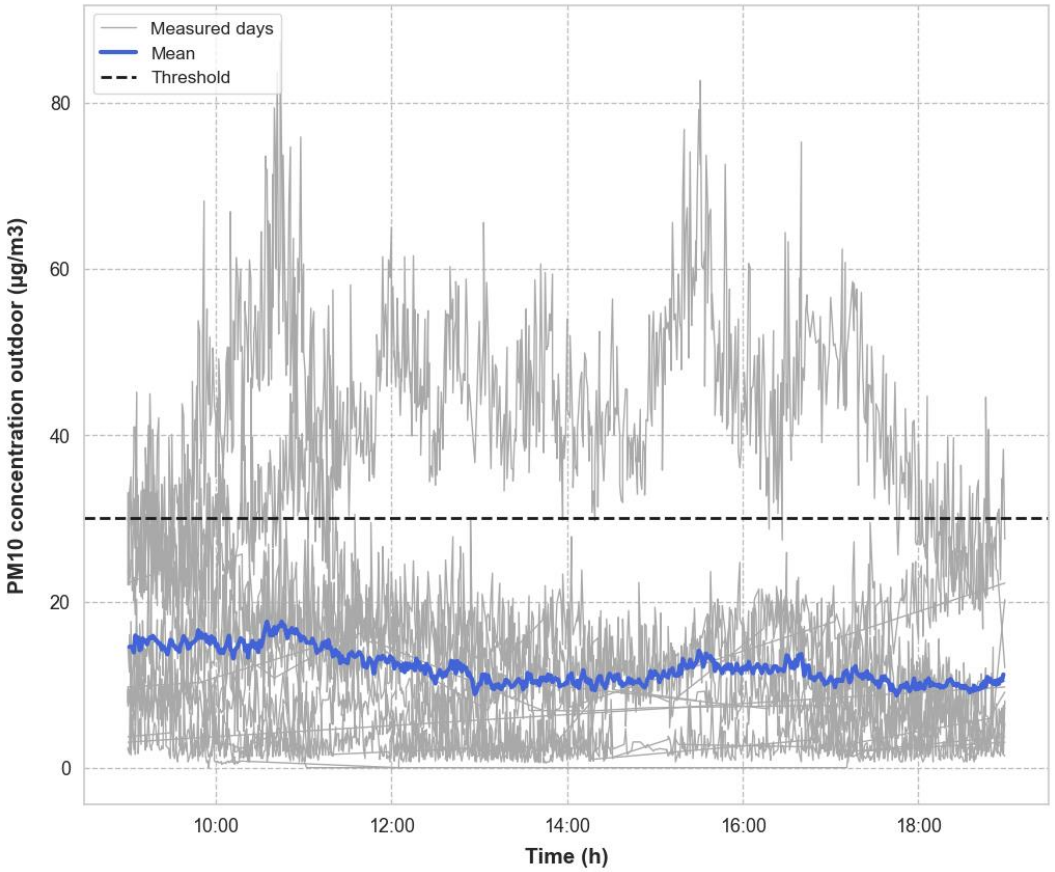
PM_{10} concentration indoor:

- Maximum value = 36,65 µg/m3
- Minimum value = 0,16 µg/m3
- Median = ± 1,54 µg/m3
- Mean = ± 2,89 µg/m3
- Mean difference sensors = 0,38 µg/m3
- Threshold = 15 µg/m3
- Total time exceeded = 252 min
- Mean exceedance per day = 0 : 19 [h : min]



PM_{10} concentration outdoor:

- Maximum value = 87,40 µg/m3
- Minimum value = 0,49 µg/m3
- Median = ± 8,49 µg/m3
- Mean = ± 12,14 µg/m3
- Threshold = 30 µg/m3
- Total time exceeded = 593 min
- Mean exceedance per day = 1 : 12 [h : min]

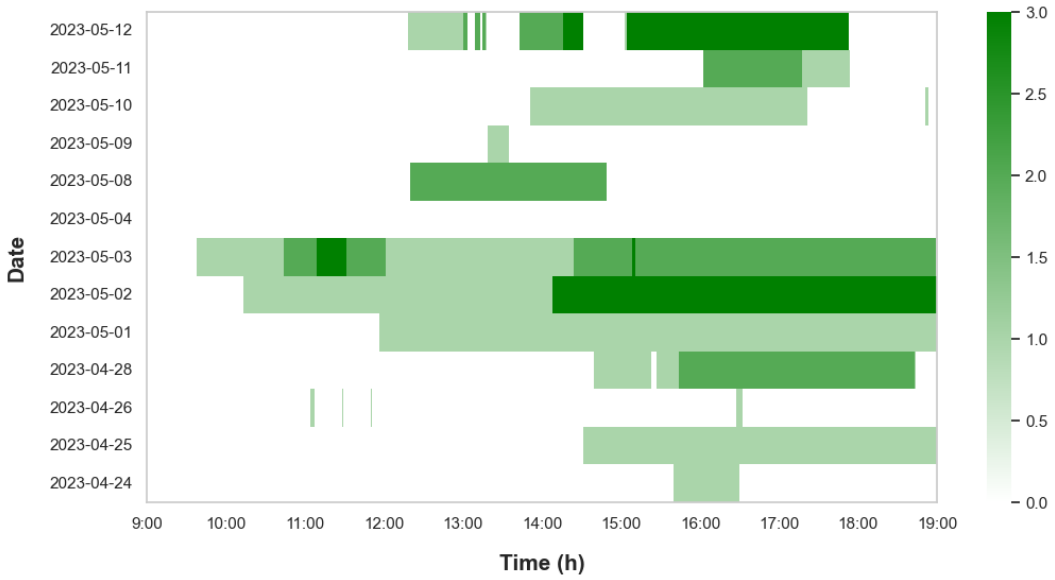


Results & Discussion

New situation

Window opening time:

- Mean window opening time per workday = 4 : 39 [h : min]]



Results & Discussion

Comparison

Parameter	Exceedance existing situation [mean per workday]	Exceedance new situation [mean per workday]	Ratio	Improvement
Indoor temperature	2 hours 19 minutes	52 minutes	- 63 %	Yes

Results & Discussion

Comparison

Parameter	Exceedance existing situation [mean per workday]	Exceedance new situation [mean per workday]	Ratio	Improvement
Indoor temperature	2 hours 19 minutes	52 minutes	- 63 %	Yes
Indoor relative humidity	1 hour 43 minutes	-	-	Yes

Results & Discussion

Comparison

Parameter	Exceedance existing situation [mean per workday]	Exceedance new situation [mean per workday]	Ratio	Improvement
Indoor temperature	2 hours 19 minutes	52 minutes	- 63 %	Yes
Indoor relative humidity	1 hour 43 minutes	-	-	Yes
Indoor CO_2	1 hour 53 minutes	38 minutes	- 66 %	Yes

Results & Discussion

Comparison

Parameter	Exceedance existing situation [mean per workday]	Exceedance new situation [mean per workday]	Ratio	Improvement
Indoor temperature	2 hours 19 minutes	52 minutes	- 63 %	Yes
Indoor relative humidity	1 hour 43 minutes	-	-	Yes
Indoor CO_2	1 hour 53 minutes	38 minutes	- 66 %	Yes
Indoor $PM_{2.5}$	10 minutes	1 hour 19 minutes	+ 690 %	No
Outdoor $PM_{2.5}$	50 minutes	1 hour 47 minutes	+ 114 %	No

Results & Discussion

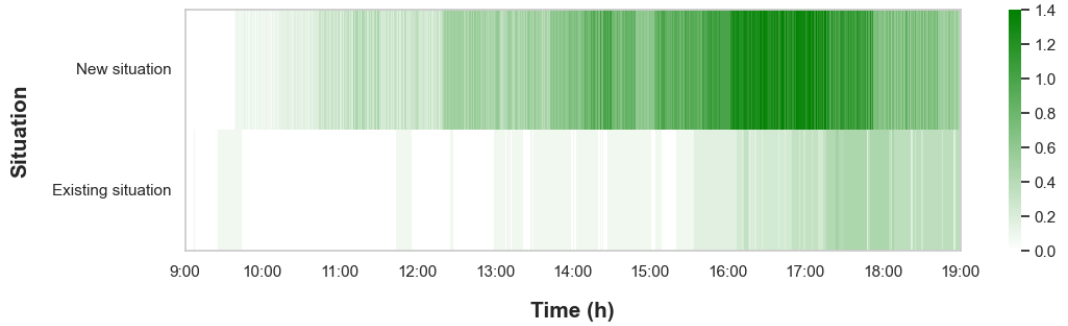
Comparison

Parameter	Exceedance existing situation [mean per workday]	Exceedance new situation [mean per workday]	Ratio	Improvement
Indoor temperature	2 hours 19 minutes	52 minutes	- 63 %	Yes
Indoor relative humidity	1 hour 43 minutes	-	-	Yes
Indoor CO_2	1 hour 53 minutes	38 minutes	- 66 %	Yes
Indoor $PM_{2.5}$	10 minutes	1 hour 19 minutes	+ 690 %	No
Outdoor $PM_{2.5}$	50 minutes	1 hour 47 minutes	+ 114 %	No
Indoor PM_{10}	-	19 minutes	-	No
Outdoor PM_{10}	49 minutes	1 hour 12 minutes	+ 47 %	No

Results & Discussion

Comparison

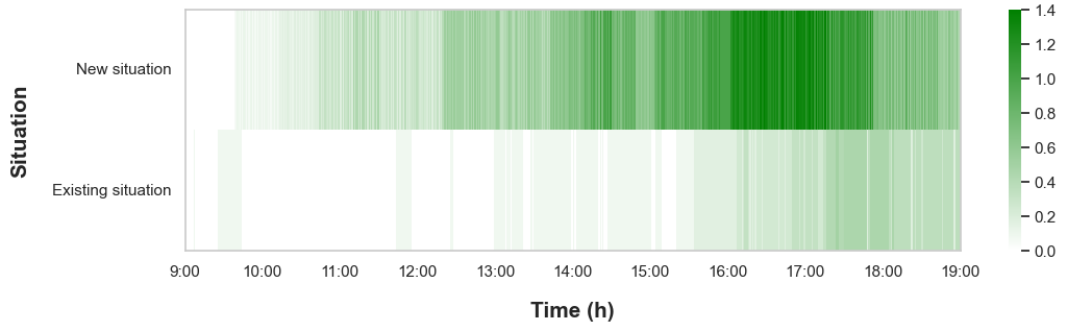
Parameter	Exceedance existing situation [mean per workday]	Exceedance new situation [mean per workday]	Ratio	Improvement
Indoor temperature	2 hours 19 minutes	52 minutes	- 63 %	Yes
Indoor relative humidity	1 hour 43 minutes	-	-	Yes
Indoor CO_2	1 hour 53 minutes	38 minutes	- 66 %	Yes
Indoor $PM_{2.5}$	10 minutes	1 hour 19 minutes	+ 690 %	No
Outdoor $PM_{2.5}$	50 minutes	1 hour 47 minutes	+ 114 %	No
Indoor PM_{10}	-	19 minutes	-	No
Outdoor PM_{10}	49 minutes	1 hour 12 minutes	+ 47 %	No
Window opening time	48 minutes	4 hours 39 minutes	+ 481 %	-



Results & Discussion

Comparison

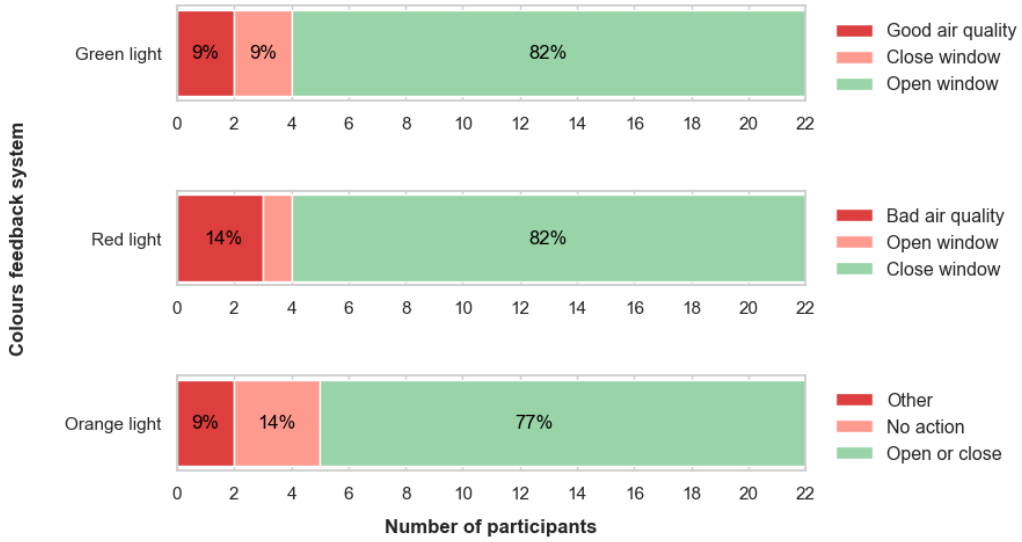
Parameter	Exceedance existing situation [mean per workday]	Exceedance new situation [mean per workday]	Ratio	Improvement
Indoor temperature	2 hours 19 minutes	52 minutes	- 63 %	Yes
Indoor relative humidity	1 hour 43 minutes	-	-	Yes
Indoor CO_2	1 hour 53 minutes	38 minutes	- 66 %	Yes
Indoor $PM_{2.5}$	10 minutes	1 hour 19 minutes	+ 690 %	No
Outdoor $PM_{2.5}$	50 minutes	1 hour 47 minutes	+ 114 %	No
Indoor PM_{10}	-	19 minutes	-	No
Outdoor PM_{10}	49 minutes	1 hour 12 minutes	+ 47 %	No
Window opening time	48 minutes	4 hours 39 minutes	+ 481 %	-
Ineffective window opening time	**2 hours 51 minutes**	**1 hour 17 minutes**	**- 55 %**	**Yes**



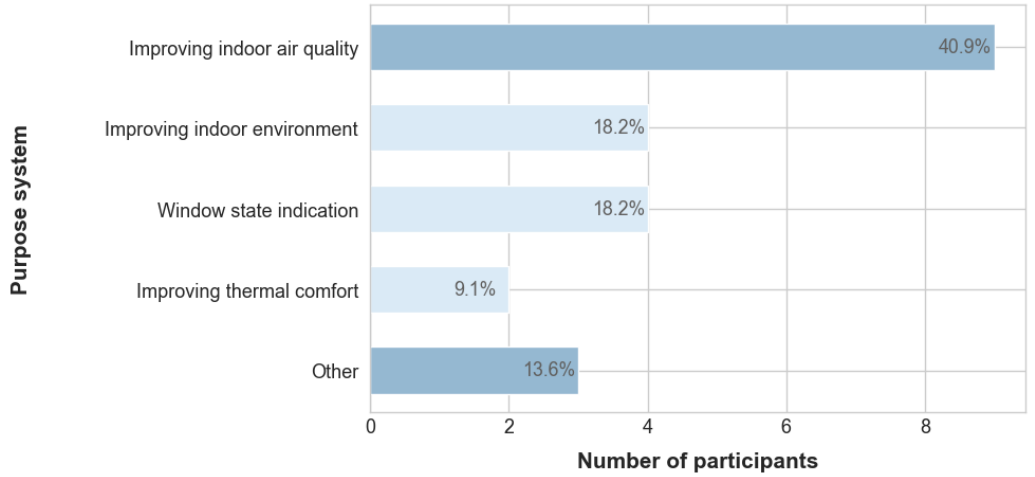
Results & Discussion

Comparison

Understanding of the window feedback light colours:



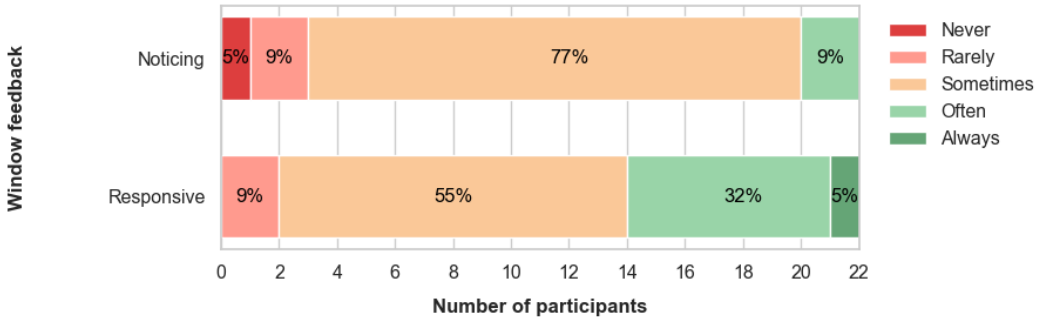
Purpose of window feedback system:



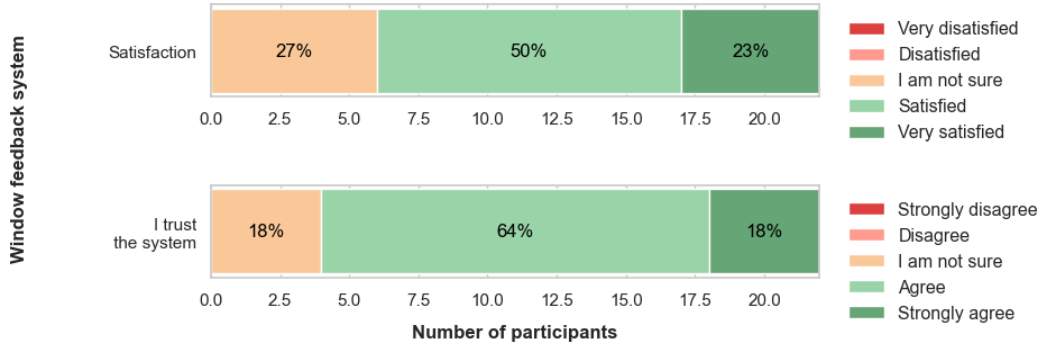
Results & Discussion

Comparison

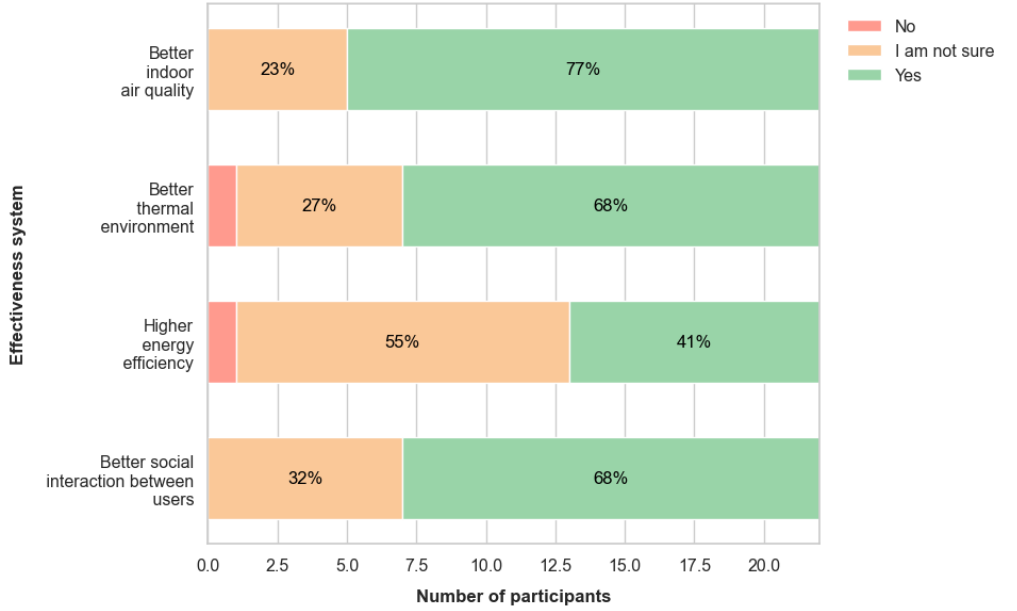
Noticing and responsive to window feedback:



Trust and satisfaction of window feedback:



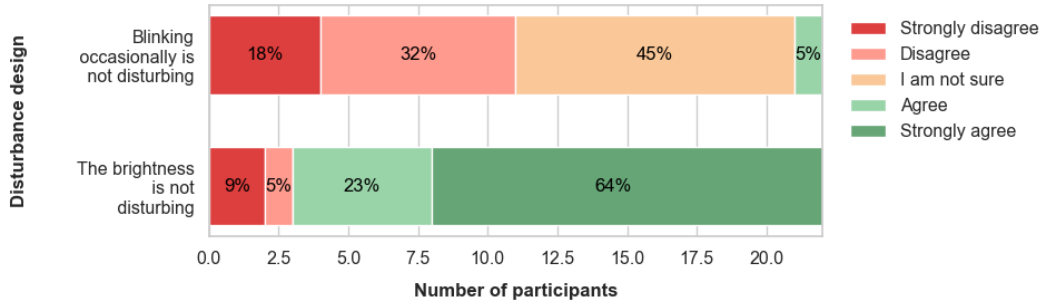
Contribution of window feedback:



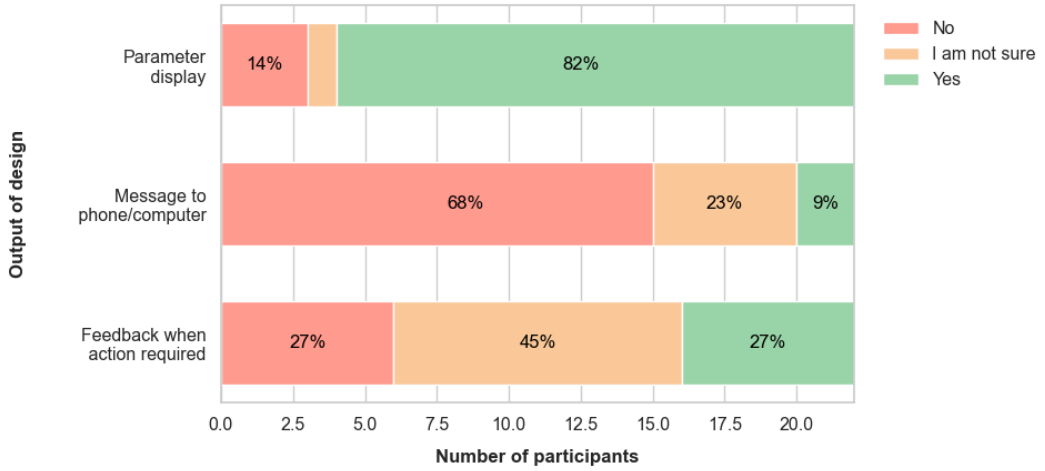
Results & Discussion

Comparison

Blinking and brightness of window feedback system:



Output of window feedback system:



Conclusion

1. The window feedback system does contribute to a better environment

2. Design guidelines:
    - Include mean radiant temperature, outdoor noise and solar radiation in algorithm
    - Reconsider the importance of the outdoor air quality
    - Include a parameter display
    - Avoid blinking lights and messages to phones/computers
    - Reconsider meaning of the lights.

QUESTIONS