TOWARDS SMART VENTILATION

FLANDERS INNOVATION & ENTREPRENEURSHIP

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Intro: Wrap up "Towards Smart Ventilation in Mid-sized Buildings"

Hilde Breesch

KU LEUVEN · UNIVERSITEIT GENT · Universiteit Antwerpen · TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY · Buildwise

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Industrial advisory board

Design → Development → Manufacturing → Installation → Maintenance

- boydens engineering, hysopt, SWECO, Atic, Ansys, AUTODESK, TAKE AIR
- TROX TECHNIK (The art of handling air), ventiline products, Lindab, itho daalderop (Climate for life), menerga (a systemair company), RENSON
- international, Vlaamse Confederatie Bouw (Bouw, energie & milieu), AIRX (Air experts), BOUWUNIE (unie van het kmo-bouwbedrijf), Techlink, ventibel, Ventilair Group, NAV.:

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Starting point

- Smart ventilation system (AIVC)
  - Able to continually adjust itself to provide IAQ while minimizing energy use, discomfort, noise
  - Responsive to e.g. occupancy, outdoor thermal and air quality
  - Can provide info about e.g. IAQ, energy use, need for maintenance

↕

- Current practice in design of ventilation systems
  - Driven by minimum requirements of individual indicators
  - In mid-sized buildings: very conservative and inefficient
  - Existing methods dependent on brainpower of engineer

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Research aim and goals

- **Aim** = determine performance-based method for smart ventilation design driven by optimization during whole life-cycle
- **Specific goals**
  - Define performance **sub-indicators** for **indirect metrics**
  - Aggregate all sub-indicators into **1 general economic performance indicator**
  - **Automate and optimize** aerolic **lay-out** ventilation design
  - **improve and optimize positioning of connections** to outdoor and indoor
- **Focus**: new + renovated mid-sized buildings (Q > 1000 m³/h)
  - Schools
  - Offices
  - Care facilities (elderly homes)

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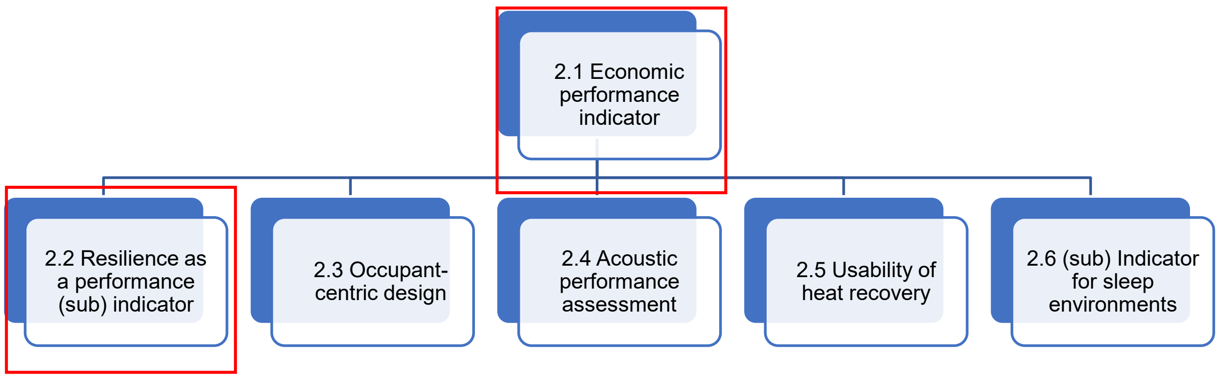
Research method

- WP2: Performance assessment



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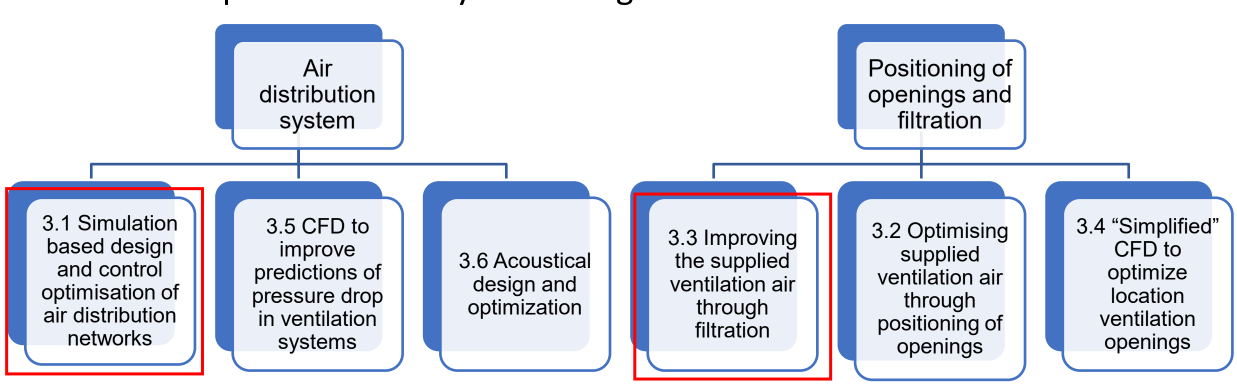
Research method

- WP3: Optimization of system design



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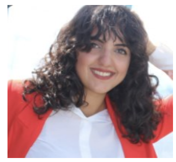
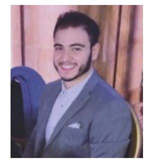
webinar
2023.12.12

Smart ventilation in non-residential buildings. How to assess? How to design?




Agenda (CET)

- 15:00 | Welcome & Intro, Hilde Breesch (KU Leuven, Belgium)
- 15:10 | An (Economic) Indicator for Assessment of Smart Ventilation Systems, Klaas De Jonge (Ghent University, Belgium)
- 15:25 | Quantitative Assessment Framework of IAQ Resilience in Buildings, Douaa Al-Assaad (KU Leuven, Belgium)
- 15:40 | Simulation Based Design of Smart Ventilation Systems, Zakarya Kabbara (University of Antwerp, Belgium)
- 15:55 | Improving the Supplied Ventilation Air Quality through Filtration, Joris Van Herreweghe (Buildwise, Belgium)
- 16:10 | Questions and answers
- 16:30 | End of the webinar

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DEPARTMENT OF ARCHITECTURE AND URBAN PLANNING
BUILDING PHYSICS RESEARCH GROUP

AN (ECONOMIC) INDICATOR FOR ASSESSMENT OF SMART VENTILATION SYSTEMS

Klaas De Jonge, Dr. Ir-Arch [12/12/2023]

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A VERY BRIEF NON-EXHAUSTIVE HISTORY

IAQ 》 Perceived Comfort 》 Outdoor Air / Ventilation / Airflow rates/Person

O. Fanger

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A VERY BRIEF NON-EXHAUSTIVE HISTORY

Ventilation rates obtained $\overset{?}{\neq}$ Good IAQ

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A VERY BRIEF NON-EXHAUSTIVE HISTORY

Ventilation rates obtained = Ventilation system works as designed

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INDOOR AIR QUALITY

IAQ ❯

- Health
- Sick-Building Syndrome
- Comfort: Bio-effluents, Hygric
- Work Performance
- Sleep Quality

IAQ-management strategies ❯

- Acoustic
- Energy Use
- Comfort: Thermal
- Investment cost
- Resilience

❯ What is optimal design?

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Health
Sick-Building Syndrome
Comfort: Bio-effluents, Hygric
Work Performance
Sleep Quality
Acoustic
Energy Use
Comfort: Thermal
Investment cost
Resilience

What is optimal design?

Cost-Function
for design optimization

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COST-FUNCTION

Dr. Louis Cony

Cony, Louis, and Jelle Laverge. "A Methodology to Assess Economical Impacts of Poor IAQ in Office Buildings from DALY and SBS Induced Costs." CLIMA 2022 Conference, May 20, 2022. https://doi.org/10.34641/clima.2022.297.

Cost-function?

€

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Health ⟹ €
Sick-Building Syndrome ⟹ €
Comfort: Bio-effluents, Hygric ⟹ €
Work Performance ⟹ €
Sleep Quality ⟹ €
Acoustic ⟹ €
Energy Use ⟹ €
Comfort: Thermal ⟹ €
Investment cost ⟹ €
Resilience ⟹ €

€

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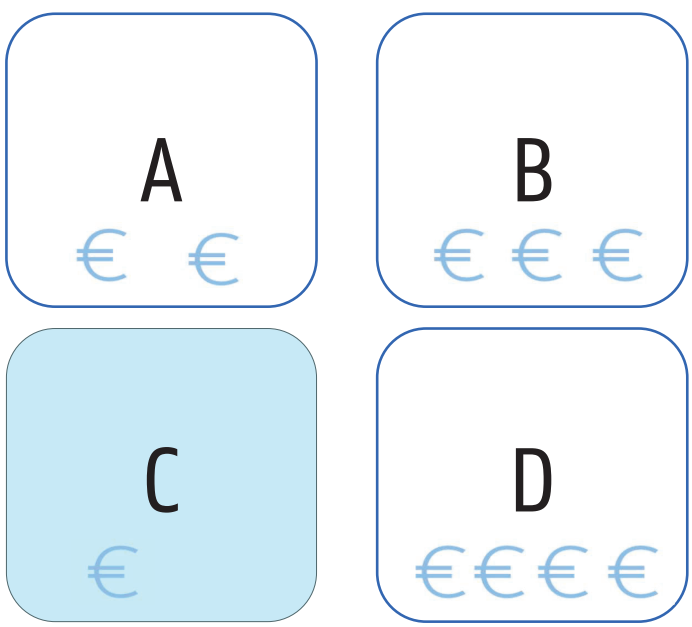

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OFFICE BUILDING

Health
Sick-Building Syndrome
Comfort: Bio-effluents, Hygric
Work Performance
Sleep Quality
Acoustic
Energy Use
Comfort: Thermal
Investment cost
Resilience

Influences

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$$IAQ_{Cost} = \sum_{i}^{p} Daly_i \times Daly\ cost_i + SBS_{cost}$$

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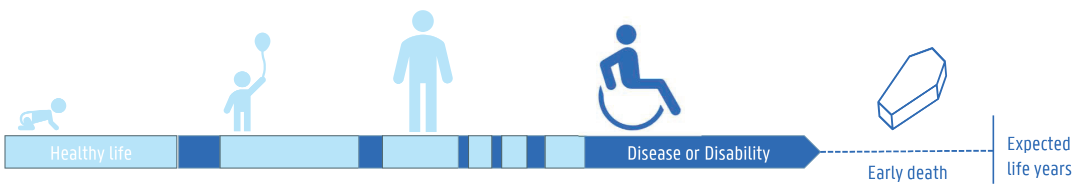
HEALTH

$$IAQ_{Cost} = \sum_i^p Daly_i \times Daly\ cost_i + SBS_{cost}$$

Disability-Adjusted Life years (lost) = Metric of harm



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HEALTH

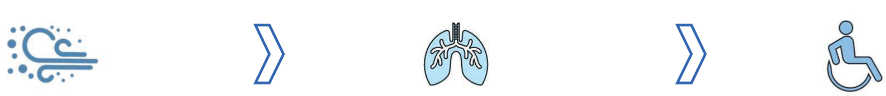
$$IAQ_{Cost} = \sum_i^p Daly_i \times Daly\ cost_i + SBS_{cost}$$

Disability-Adjusted Life years (lost) = Metric of harm

Pollutant exposure concentration

Incidence of a health outcome

DALY



EXAMPLE

PM2.5 exposure

Chronic Bronchitis

Not able to do active sports & Early death

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HEALTH

$$IAQ_{Cost} = \sum_{i}^{p} Daly_i \times Daly\ cost_i + SBS_{cost}$$

5 main categories:

- Mortality and life cost
- Medical costs
- Productivity cost
- ~~Research, prevention and regulation costs~~
- ~~Willingness to pay~~

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HEALTH

$$IAQ_{Cost} = \sum_{i}^{p} Daly_i \times Daly\ cost_i + SBS_{cost}$$

$$= LY_{cost} + H_{cost_i} + P_{cost}$$

5 main categories:

- Mortality and life cost (LY_{cost})
- Medical costs
- Productivity cost
- ~~Research, prevention and regulation costs~~
- ~~Willingness to pay~~

In a previous socio-economical study, life year (LY) cost was estimated around € 115 000 per year per person.

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HEALTH

$$IAQ_{Cost} = \sum_{i}^{p} Daly_i \times Daly\ cost_i + SBS_{cost}$$

$$= LY_{cost} + H_{cost_i} + P_{cost}$$

5 main categories:

- Mortality and life cost
- Medical costs (H_{cost_i})
- Productivity cost
- ~~Research, prevention and regulation costs~~
- ~~Willingness to pay~~

Medical costs vary from one pollutant to another as the diseases induced are also different.

Pollutant	Medical cost (€)
Benzene	46 000
Trichloroethylene	70 971
Radon	25 526
PM	10 402
CO	1 085
Others (if unknown)	40 000

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HEALTH

$$IAQ_{Cost} = \sum_{i}^{p} Daly_i \times Daly\ cost_i + SBS_{cost}$$

$$= LY_{cost} + H_{cost_i} + P_{cost}$$

5 main categories:

- Mortality and life cost
- Medical costs
- Productivity cost (P_{cost})
- ~~Research, prevention and regulation costs~~
- ~~Willingness to pay~~

Average national productivity is estimated around **€ 145 000 per year per person** but can be recalculated for each building, based on the average productivity of the concerned company.

*We consider that the proportion of productivity loss is equal to the life quality loss
(e.g, a person suffering a disease that induces a 20% life quality lost, would have a 20% productivity loss).

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$$IAQ_{Cost} = \sum_{i}^{p} Daly_i \times Daly\ cost_i + SBS_{cost}$$

Sick-Building Syndrome

= Mild, temporary acute effects of (bad) IAQ that cause concentration disturbance and productivity loss while at work.

≠ Severe health effects

Combining concepts of:

"Percentage of Occupants Presenting 1 or 2 SBS symptoms – **POP1 & POP2**"

"Indoor Air Pollution Index - **IAPI**" & "Indoor Discomfort Index – **IDI**"

$$= P_{cost} \times P_{loss}(0.83 + 2.83IAPI + 0.83IDI) \times \frac{2}{5}$$

Subjective data of employees (questionnaires)

⇩⇧ CAN BE MODELLED

CO, CO2, Acetaldehyde, Acrolein, Benzene, Formaldehyde, Styrene, Tetrachloroethylene, Toluene, Trichloroethylene, xylene, and Particulate Matters (PMs).

Temperature and Relative Humidity (RH)

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Main reference:

Cony, Louis, and Jelle Laverge. "A Methodology to Assess Economical Impacts of Poor IAQ in Office Buildings from DALY and SBS Induced Costs." *CLIMA 2022 Conference*, May 20, 2022. https://doi.org/10.34641/clima.2022.297.

Acknowledgements

Dr. Louis Cony

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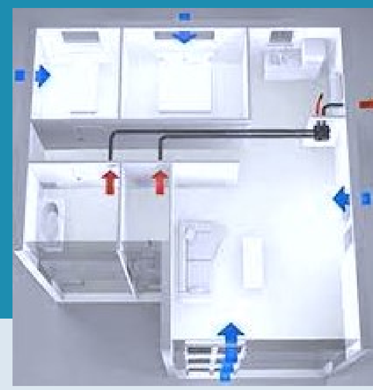
Indoor air Quality (IAQ) resilience performance of Smart ventilation: Quantitative assessment framework



Douaa Al Assaad, douaa.al-assaad@kuleuven.be

Building Physics and Sustainable design group

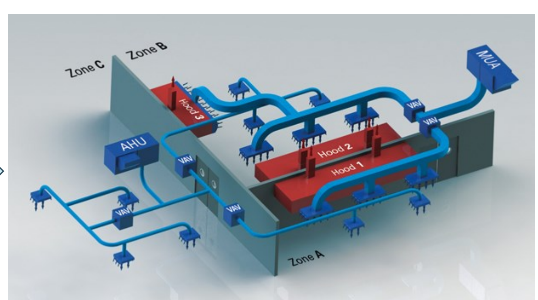
Campus Gent

KU Leuven, Belgium

What is resilience performance?

Expected indoor/outdoor conditions

Good breathable air quality
Energy efficient



Unexpected disturbance Or "shock"

Reduced system performance: Indoor space shifts drastically from its **IAQ design conditions**

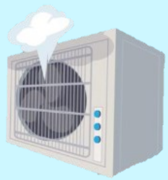
(-) Accumulation of contaminants

(-) Acute exposure during short duration

System needs to be resilient

Disruptive Events

Mechanical disruptions



Partial or complete disruption in the operation of the ventilation system (e.g., fan failure, power outages, fouling filters)

Internal disruptions

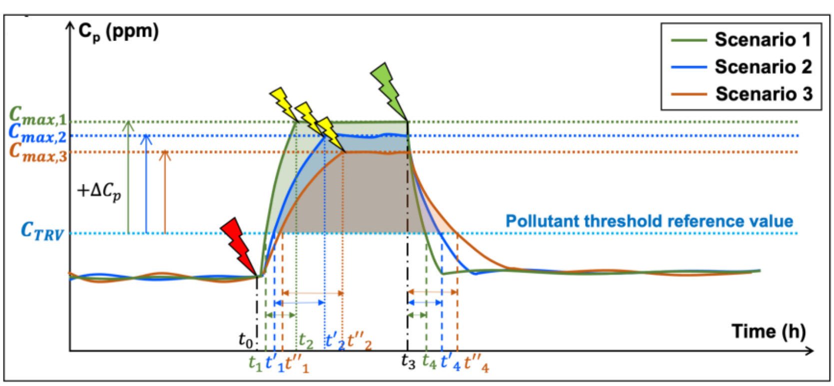
Occurs inside the space due to excessive indoor pollution event (e.g.,excess occupants beyond capacity of AHU)

External disruptions

Occurs outside the building envelope due to excessive outdoor pollution (e.g., outdoor fire, traffic jams)

Introduction | Resilience score | Case study | Conclusions

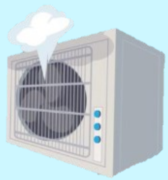
Resilience performance aspects



- Absorptivity
- Recovery
- Degree of impact

Quantification of disruptive events: the degree of shock

Mechanical disruptions



$$doMS = \underbrace{\frac{\dot{Q}_{a,r} - \dot{Q}_{a}}{\dot{Q}_{a,r}}}_{Severity} \times \underbrace{\frac{t_s}{t_{occ}}}_{Duration}$$

degree of mechanical shock (**doMS**)

Internal disruptions

$$doIS_s = \underbrace{\frac{ER_s - ER_{s,exp}}{ER_{s,exp}}}_{Severity} \times \underbrace{\frac{t_s}{t_{occ}}}_{Duration}$$

degree of internal shock (**doIS**)

External disruptions

$$doOS_s = \underbrace{\frac{C_{s,oa} - C_{s,oa\ exp}}{C_{s,oa\ exp}}}_{Severity} \times \underbrace{\frac{t_s}{t_{occ}}}_{Duration}$$

degree of outdoor shock (**doOS**)

Introduction | Resilience score | Case study | Conclusions

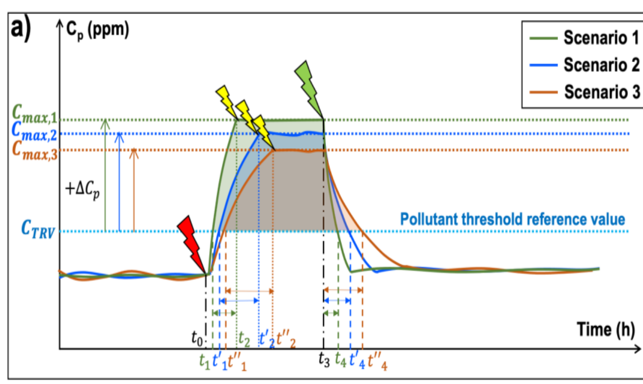
Quantification of resilience aspects

Absorptivity $\varepsilon_{abs} = \frac{\Delta t_{abs}}{t_{occ}}$

Slower absorptivity time is desired

Recovery $\varepsilon_{rec} = 1 - \frac{\Delta t_{rec}}{t_{occ}}$

Faster recovery time is desired

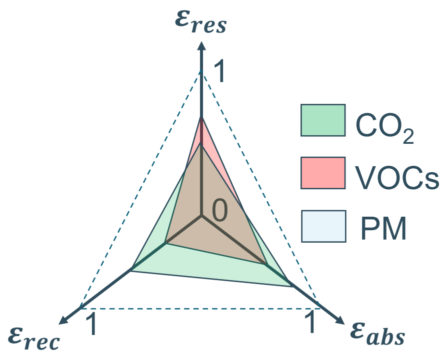


Resilience effectiveness

$$\varepsilon_{res} = \frac{ppm.hours_{ref} - ppm.hours_{system\ under\ shock}}{ppm.hours_{ref} - ppm.hours_{system\ normal\ operation}}$$

Higher effectiveness desired

The total resilience score



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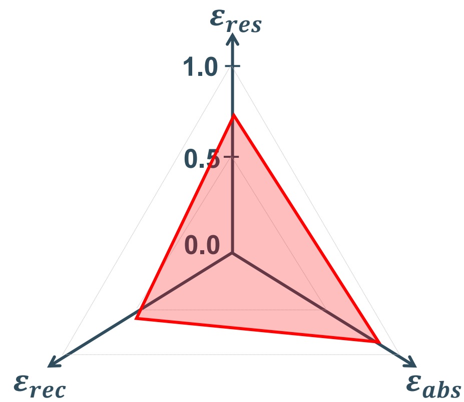


$$RS_{zone} = \frac{5}{13}\left(RS_{CO_2} + \sum \omega_i RS_i\right)$$

i = 1 to N (number of Hazardous air pollutants) **0 < RS < 1**

The total resilience score: Determining the weighting factors

Qualitative approach

- **C**arcinogenic
- **M**utagenic
- **R**eprotoxic effects
- **E**ndocrine disruptions

1 (High evidence) to 5 (No evidence)

VOCs (Formaldehydes, acrolein, aldehydes usually found in classrooms) rank as CMRE2/ PM fine and coarse rank as CMRE1

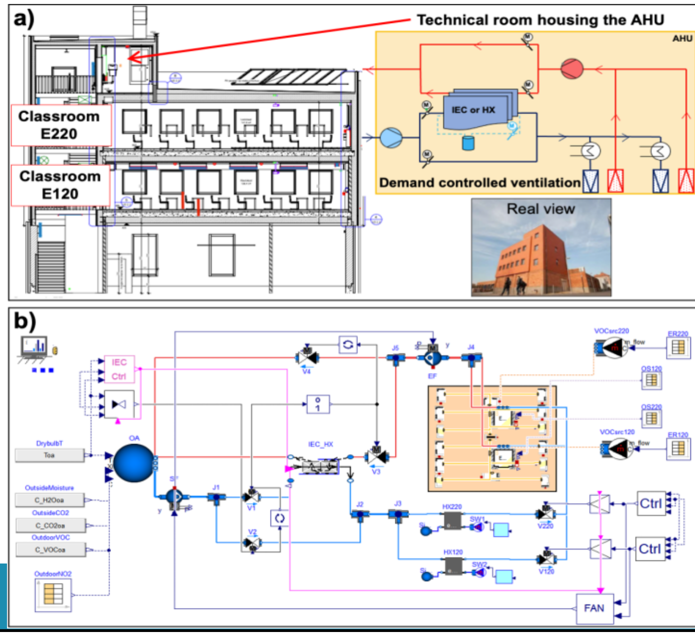
Quantitative approach: HQ: Hazard Quotient

$$HQ = \frac{Mean\ exposure\ concentration}{TRV\ (threshold\ values)}$$

$$\mathrm{HQ_{mean}} \text{ or } \mathrm{HQ}_{P95} > 1$$

8 Sérafin, Guillaume, Patrice Blondeau, and Corinne Mandin. "Indoor air pollutant health prioritization in office buildings." *Indoor Air* 31.3 (2021): 646-659.

Case study



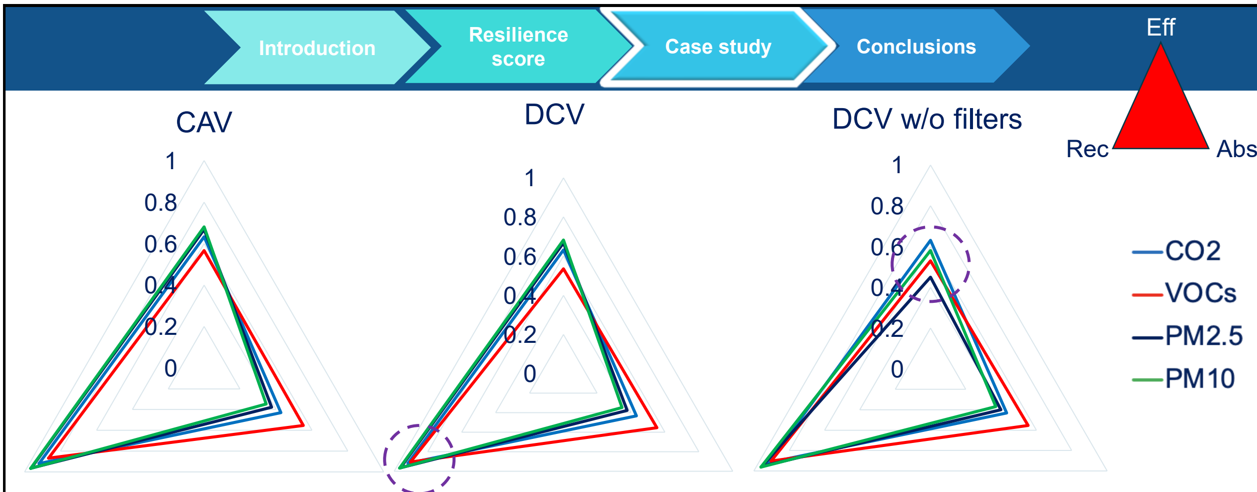
Model in Modelica, Dymola

Scenarios

Demand controlled balanced mechanical ventilation (DCV)
Constant air volume system (CAV)
DCV without filters

Mechanical shock (doMS: 0 to 1)
Internal shock (doIS: 0 to 1)
Outdoor shock (doOS: 0 to 1)

Contaminants: CO_2, VOCs, $PM_{2.5}$, PM_{10}



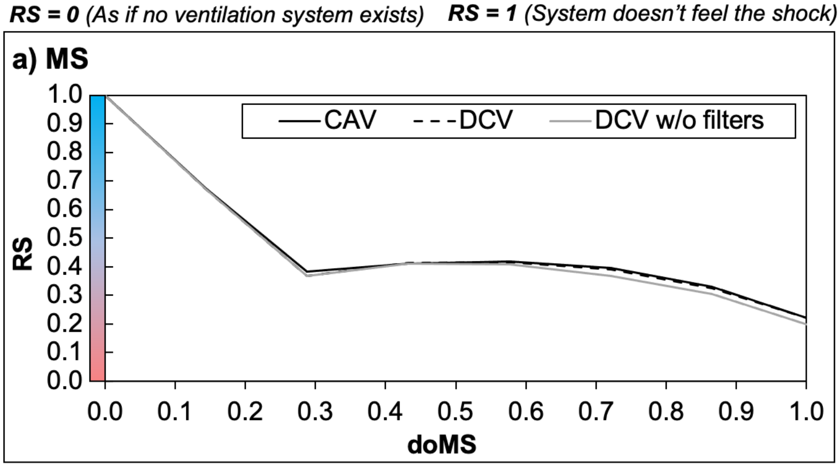
CO_2 : Same Absorbtivity, Recovery and Effectiveness

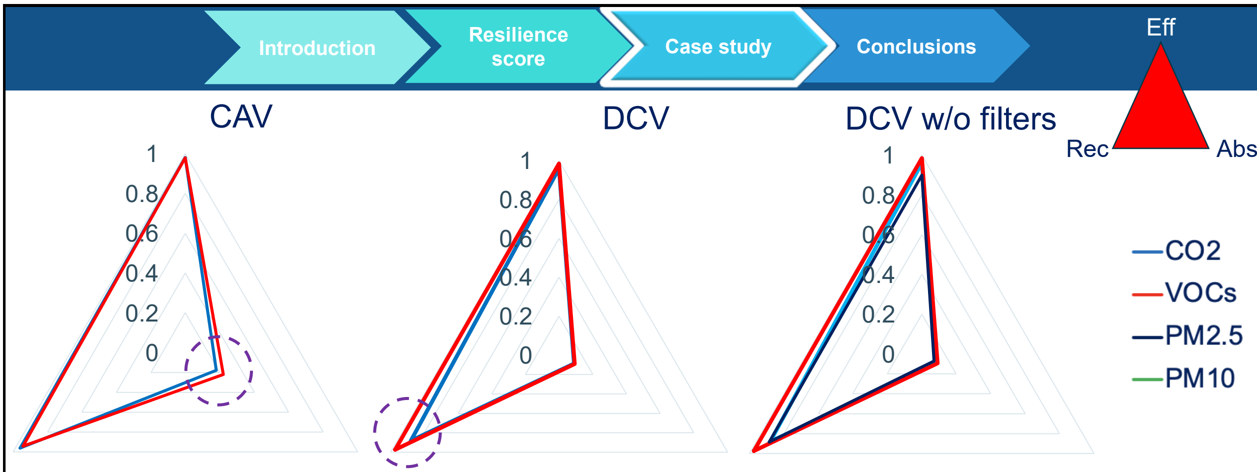
VOCs: Same Absorptivity but DCV has better recovery and CAV has better effectiveness

PM: Same Absorbtivity, Recovery and Effectiveness. DCV w/o filters has significantly lower effectiveness

Resilience score (RS): Mechanical shock (MS)

***RS = 0** (As if no ventilation system exists)* ***RS = 1** (System doesn't feel the shock)*





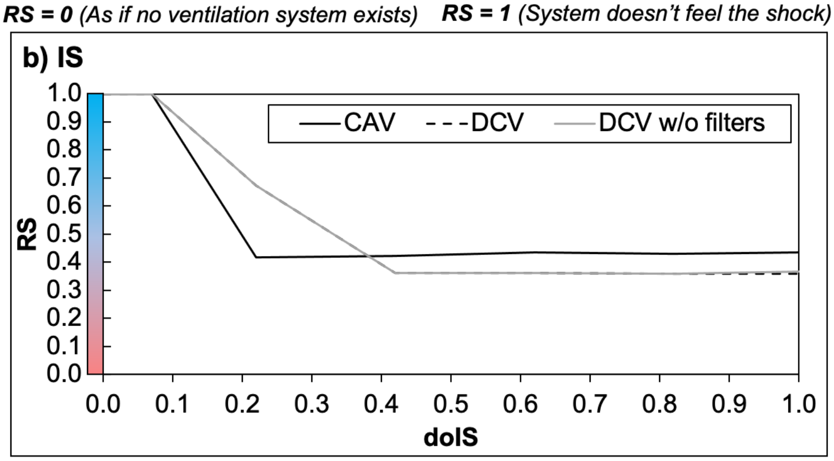
CO_2 : Same Effectiveness, but CAV has slower gradual absorbtivity and faster recovery

VOCs: Same Effectiveness (very high in both), CAV has significantly slower absorptivity, DCV has slightly faster recovery

PM: Only challenged at high shock intensities and for the case of DCV w/o filters

Resilience score (RS): Indoor shock (IS)

RS = 0 *(As if no ventilation system exists)* ***RS = 1*** *(System doesn't feel the shock)*



Conclusions

- **Resilience score** for **IAQ resilience** assessment was developed
- **Smart** vs **Conventional** ventilation **IAQ resilience** during **disruptive events**:
  - Mechanical shocks: Smart **=** Conventional
  - Internal shocks: Smart **<** Conventional
  - Outdoor shocks: Smart **>** Conventional
- **Filters**: No pronounced effect in the case of Mechanical and Internal shocks but more so in Outdoor shocks
- Framework should be tested for more case studies (residential, offices) and more systems (mechanical extract, natural ventilation, personalized systems, other smart control strategies, etc.)

Thank you for listening

Next speaker:

Zakarya Kabbara
Antwerp University, Belgium

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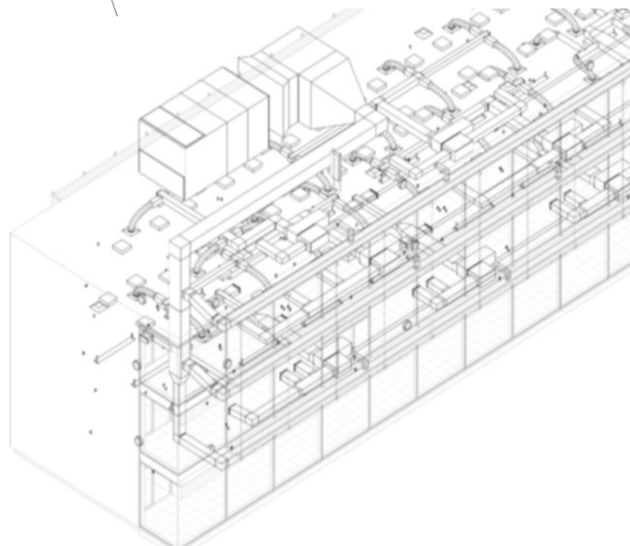
Simulation-based design of smart centralized ventilation systems

Easing design engineers' challenges and generating optimized designs



Zakarya Kabbara (EMIB-research group, University of Antwerp)

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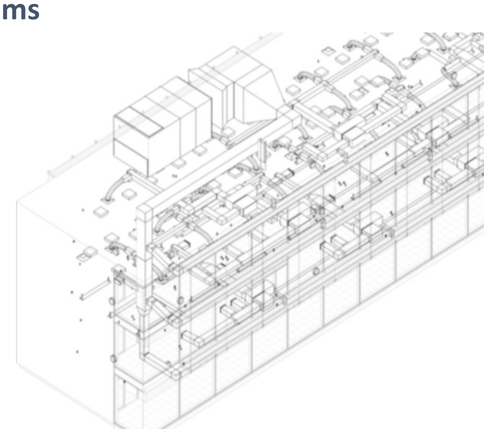
Design challenges of centralized air distribution systems

- Cost efficiency
- Energy-efficiency
- Acoustical comfort
- Hygrothermal comfort
- Healthy IAQ
- Aesthetic - Architecture limitations
- …

All these have to be achieved within a limited budget and time



Simulation-based design method for informed decision making

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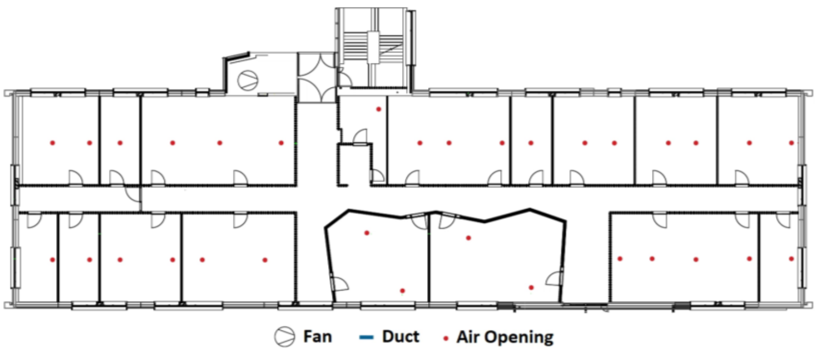
Aimed simulation-based design method:

For a random floor plan:

Automatically generate optimized ductwork configuration (= layout + sizing)

Min. LCC: Ductwork material and installation costs and fan energy costs



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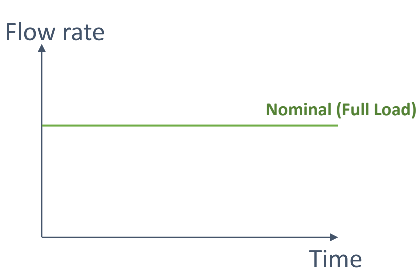
Aimed simulation-based design method:

For a random floor plan:

Generate ductwork configuration (= layout + sizing) with minimum life cycle cost

Design inputs:

- Nom. Flows + Demand profiles (smart systems)



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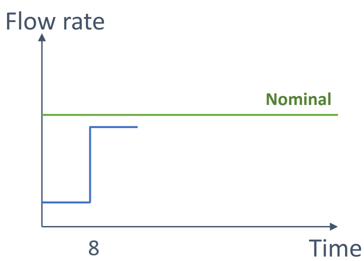

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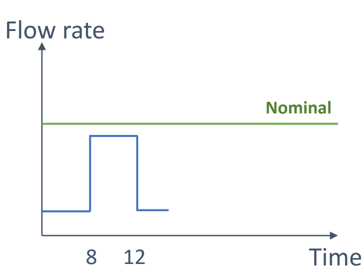

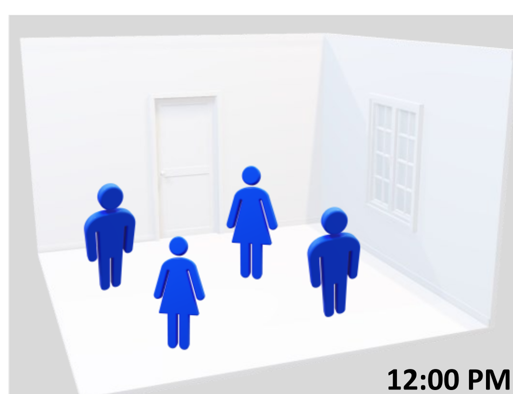

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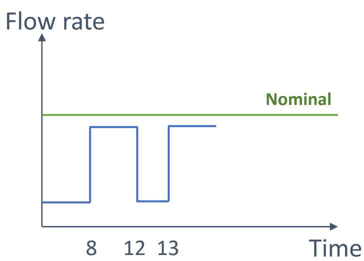

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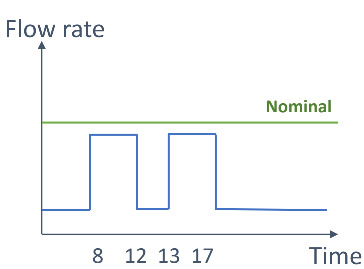
Aimed simulation-based design method:

For a random floor plan:
Generate ductwork configuration (= layout + sizing) with minimum life cycle cost

Design inputs:

- Nom. Flows + Demand profiles (smart systems)



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Aimed simulation-based design method:

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Generate ductwork configuration (= layout + sizing) with minimum life cycle cost

Design inputs:

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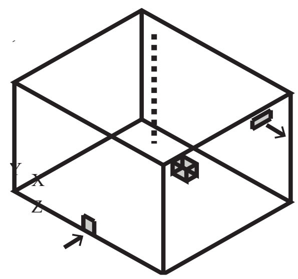
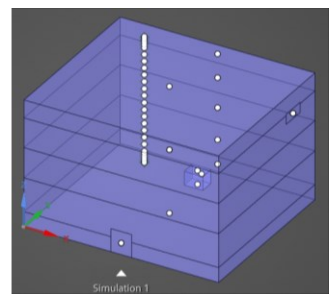
- **Location of air openings**





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Boundary conditions:

Hard boundary conditions

- Maximum velocity
- Maximum duct dimensions

Soft boundary condition

- Pressure-balancing

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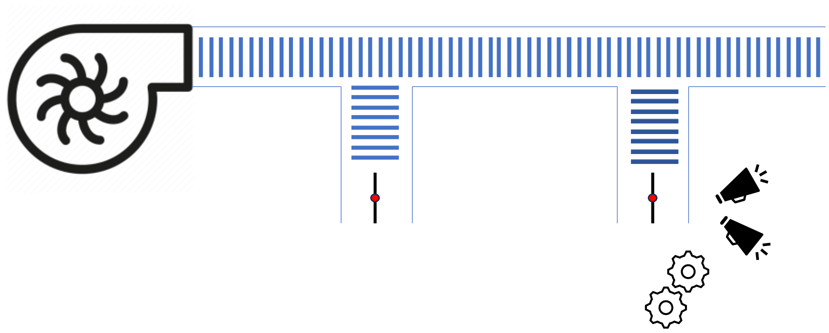

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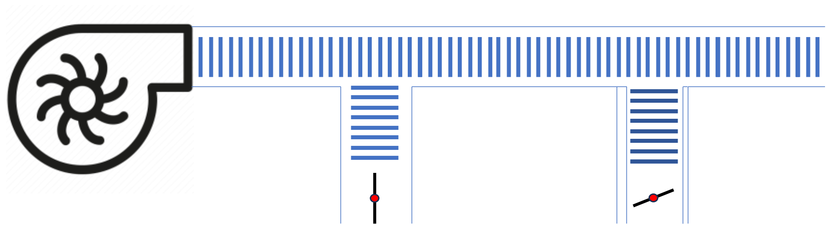

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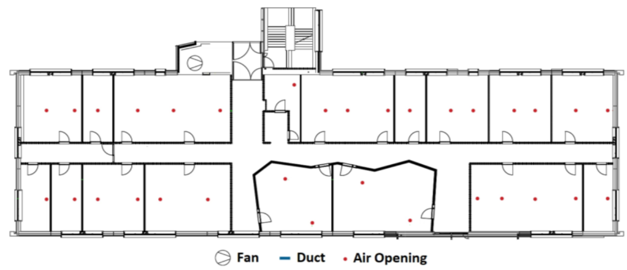
Design method outputs

Existing design



Optimized design

- 18.5 % reduction in material & installation costs
- 10% reduction in fan energy costs
- 15% reduction in LCC
- 25% more balanced designs

Zakarya Kabbara, Sandy Jorens, Houssam Matbouli, Jitse Van Thillo, Ivan Verhaert,
Heuristic optimization for designing centralized air distribution systems in non-residential buildings,
Energy and Buildings,Volume 292,2023,113161,ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2023.113161.

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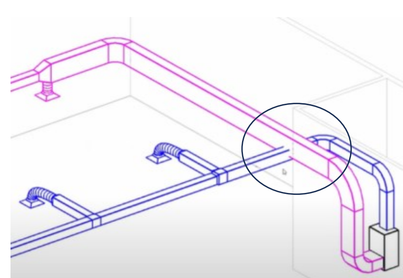
A glimpse into our future work

- Method’s valorization
- Implementation of the method in BIM software (i.e., Revit)
- Method’s expansion:
  - Simultaneous supply and extraction
  - Retrofitting/renovating applications



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Thank you for your attention!

Zakarya Kabbara, Sandy Jorens, Houssam Matbouli, Jitse Van Thillo, Ivan Verhaert,
Heuristic optimization for designing centralized air distribution systems in non-residential buildings,
Energy and Buildings, Volume 292,2023,113161, ISSN 0378-7788,
https://doi.org/10.1016/j.enbuild.2023.113161.

Zakarya Kabbara, Sandy Jorens, Ehsan Ahmadian, Ivan Verhaert,
Improving HVAC ductwork designs while considering fittings at an early stage,
Building and Environment, Volume 237, 2023, 110272, ISSN 0360-1323,
https://doi.org/10.1016/j.buildenv.2023.110272.

Zakarya Kabbara, Arne Dijckmans, Sandy Jorens, Jitse Van Thillo, Ivan Verhaert,
A performance-based acoustical design strategy for centralized air distribution networks,
IBPSA, Building Simulation, 2023, Shanghai, China

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Buildwise
Is the new WTCB/CSTC/BBRI

Improving the supplied ventilation air through filtration

Joris Van Herreweghe
Laboratory for Microbiology and Microparticles

KU LEUVEN · UNIVERSITEIT GENT · Universiteit Antwerpen · TU/e EINDHOVEN UNIVERSITY OF TECHNOLOGY · Buildwise

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TOWARDS SMART V≋NTILATION

FLANDERS INNOVATION & ENTREPRENEURSHIP

Overview

1. Why air filtration?
2. Brief overview of air filter classification
3. Research findings on filters for small residential systems
4. Translational research to midsized systems (cSBO)

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TOWARDS SMART VENTILATION

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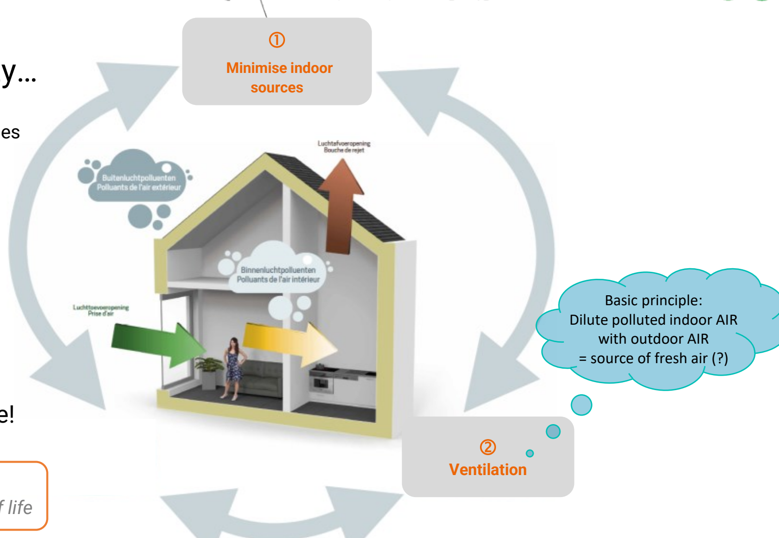
Road to a good Indoor Air Quality…

- **Outdoor Air Quality** improved in last decades
- ! Some pollutants **remain problematic** ($PM_{2.5}$, ozone, NO_2)

Of EU urban population are exposed to [$PM_{2.5}$] > WHO guidelines

- **Health impact** of poor Air Quality is huge!

Belgium: 8340 deaths = 86.000 years of life
↔ *Traffic in Belgium: 597 deaths = 40.800 years of life*



General Context: Indoor Air Quality

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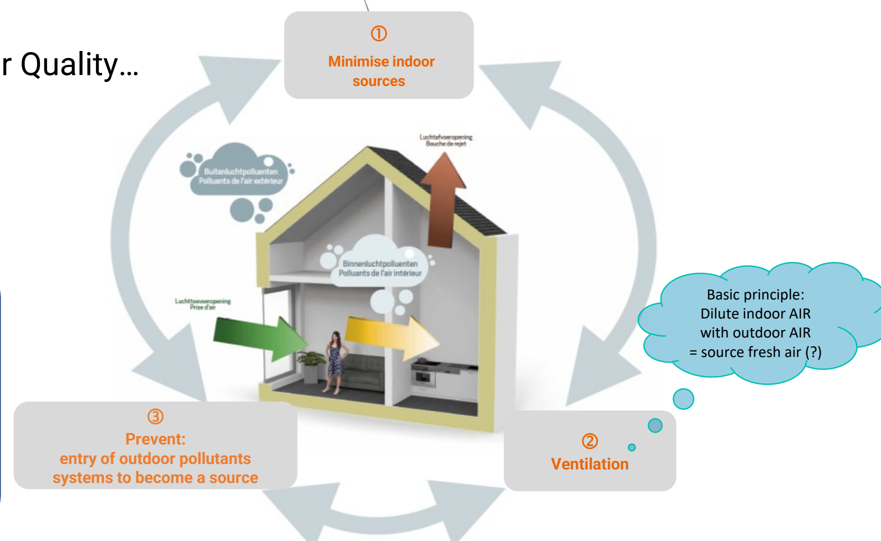

Out2In (residential)

!Pollutants do enter

! Improvement possible:
- F7-e$PM_{2.5}$ bag filter
- ESP

? Applicable in AHU (cSBO)

General Context: Filtration

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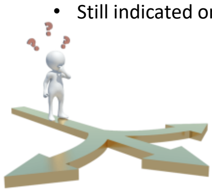
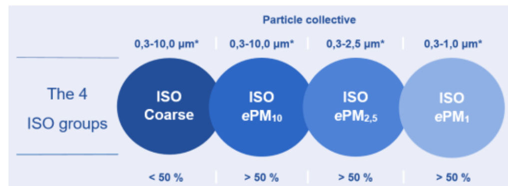
General air filters: classification

NBN EN779:2012 (replaced)	→	NBN EN ISO 16890:2017

- Classes = Eff. for particules of 0.4µm
- Classification
  G = Coarse (Grossier) G1, G2, **G3, G4**
  M = Medium **M5**, M6
  F = Fine **F7**, F8, **F9**
- 9 classes of filtres **(5 often used)**
- Still indicated on datasheets



- Classification in 4 groups (0.3-10µm)

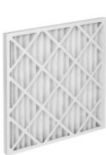


- Classification within a group (/5%)
  49 classes of filtres! (coarse 5-95%, others 50-95%)
- Labelling according to ISO standard mandatory since **july 2018**

☞ Fundamental differences (test procedure & classification)
= no 1:1 relation between EN 779 and ISO 16890 classification
☞ The same EN779 filter can be classified differently: F7 = ePM2.5 (65-95%) or ePM1 (50-65%)

Same class, different type…

Iso Coarse 60% (G4)



Folded panel Bag

ePM1 55%/ ePM2.7 70% (F7)


Folded panel Bag

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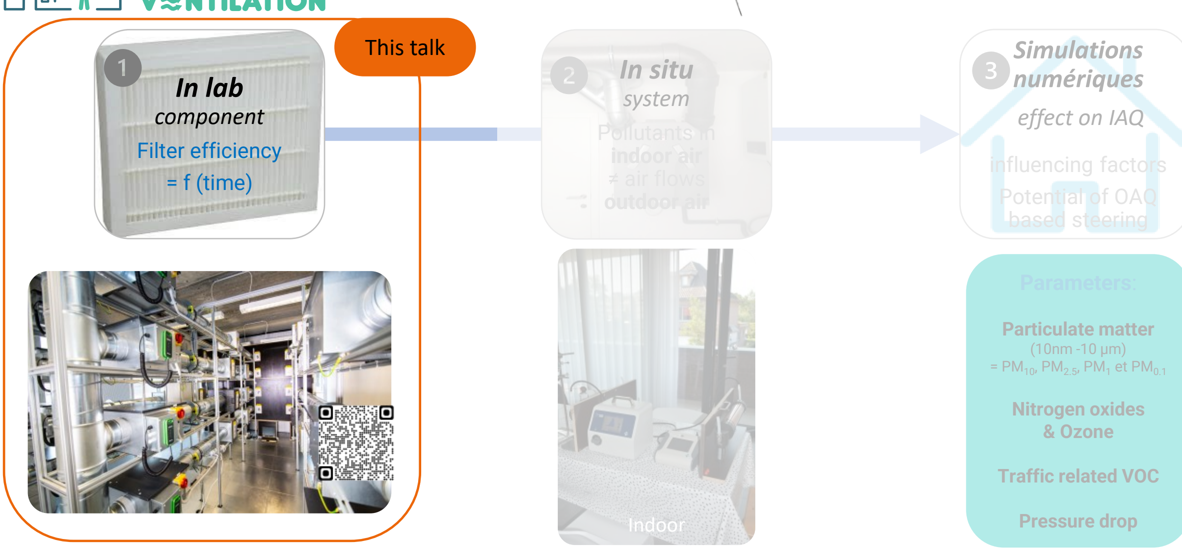

Existing knowledge: Out2In with focus on single family residential systems Approach

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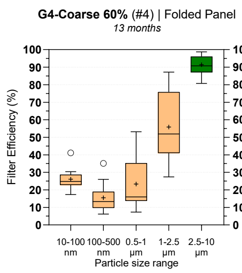
Coarse filters
= system protection

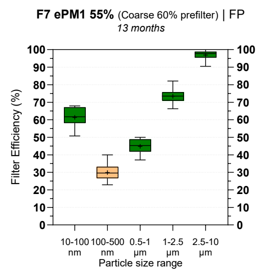
- ≥ Coarse 50-60% (G4)
- no improvement SUP Air Quality (except for pollen > 10µm)



Fine filters
= $PM_{2.5}$

- ≥ ePM1 55% (F7) folded panel + Coarse or ePM2.5 70% (F7) bag filter alone

= [PM2.5] in SUP< WHO (5µg/m³) given [outdoor] @ BXL



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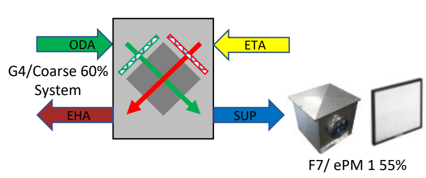
Fine filters: 2 options with equal efficiency

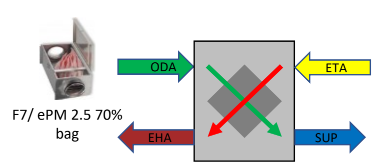
Interesting solution
Protection &
Improvement in 1

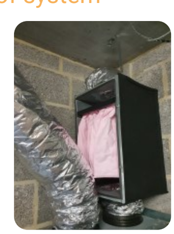
Option 1:
Coarse 60% (G4) + ePM1 55% (F7) folded panel



Coarse prefilter needed
ΔP $_{28}$ 51 ^{193} Pa

Option 2:
ePM2.5 (F7) bag type alone in front of system





No prefilter needed
Lower pressure drop over 13mths runtime: ΔP $_{25}$ 31 ^{38} Pa

Midsize system = x times tested filters in a frame

Equal performance?, Points of attention?

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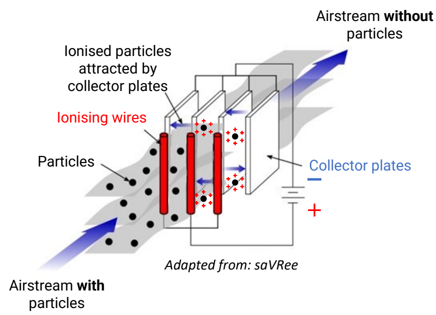
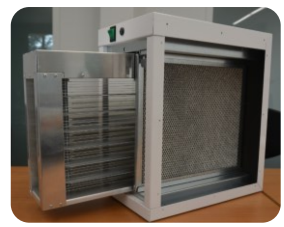
Electrostatic precipitator = Ioniser + collector





Existing knowledge: Out2In with focus on single family residential systems Main conclusions

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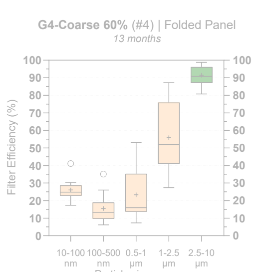
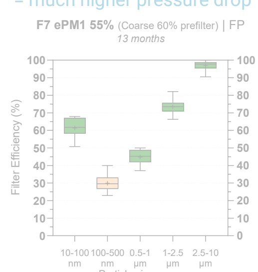


Fine filters

= $PM_{2.5}$

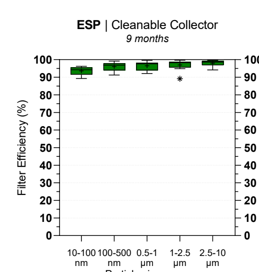
- ≥ ePM1 55% (F7) folded panel + Coarse or ePM2.5 70% (F7) bag filter alone
  = [PM2.5] in SUP< WHO (5µg/m³) given [outdoor] @ BXL
- [ePM1 80% (F9) & E10 (HEPA)]
  = much higher pressure drop



Electrostatic Precipitator

= PM_{10} + $PM_{2.5}$ + UFP

- high consistent performance for all particle sizes (10nm-10µm) (when maintained)
- very low pressure drop << F7



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In situ test of different configurations

1 M5-coarse 80%-filtre bag + F7-ePM$_1$ 55% folded panel
@ nominal air flow: 4400 m³/h

2 F7-ePM$_{2.5}$ 70% bag
@ nominal air flow: 4400 m³/h

3 F7 bag filter at different air flows
800 – 1600 - 2500 m³/h

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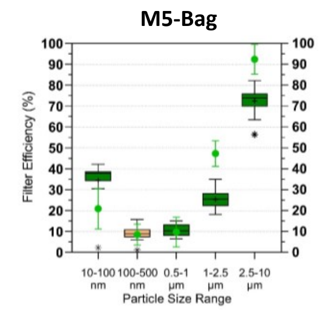
Setup 1



• M5 Bag

cSBO@3937 m^3/h
M5 0.51 m/s
F7 0.098 m/s

Out2In@150m^3/h
M5 0.052 m/s
F7 0.034 m/s

Translational research to midsized systems (cSBO)

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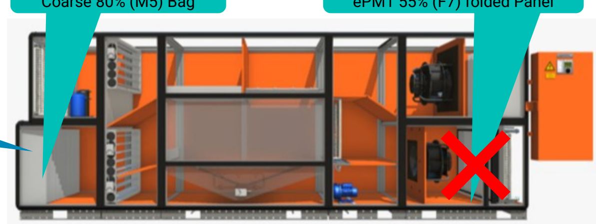
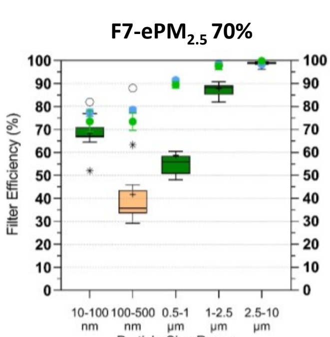
Setup 2





Filter	State	Pressure drop (Pa)		Airflow (m^3/h)
M5-coarse 80% Bag + F7-ePM_1 55% Folded Panel	New	81.3 ±2.5 Pa 27.9±2.2 Pa	∑= **109.8**±3.3 Pa	3937±26 m^3/h
F7-$ePM_{2.5}$ 70% Bag	New	**95.5 Pa** *(new)* **99.9**±1.7 Pa *(2 months in use)*		3937±30 m^3/h

Translational research to midsized systems (cSBO)

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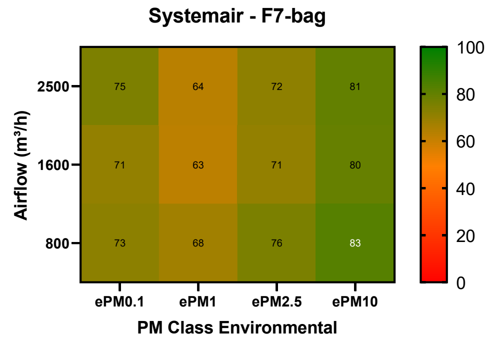
Setup 3



Test @ different air flows

➢ No significant difference in eff.

Translational research to midsized systems (cSBO)

Conclusion et recommandations

General: consistency between results of both projects
= recommandations Out2In, *based on long-term follow-up measurements,*
can be transposed to AHU

Filters

- Class, type, place: possible to install different setups in AHU itself
  (coarse + fine FP or fine bag)
- Installation: ! Structural stability of the filter
  ! Connection between filter and its housing and between filters!
  ! Bag filters: bags in vertical position
  + be careful during installation
- Replacement: follow-up of ΔP by BMS = targeted filter replacement(↔ residential)
- Potential of ESP: needed space is available within the AHU

Filters:
Van Herreweghe *et al.* (2022) Real-life ventilation filter performance: final results of an in-depth study