Performance assessment framework for smart ventilation systems

Hilde Breesch (KU Leuven, Belgium)

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

Aim and goals

- **Aim** = determine performance-based framework for smart ventilation design driven by optimisation 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 optimise** aerolic **lay-out** ventilation design
  - **improve and optimise positioning of connections** to outdoor and indoor
- **Focus**: new + renovated mid-sized buildings (Q > 1000 m^3/h)
  - Multi-family residential
  - Schools
  - Offices
  - Care facilities (elderly homes)

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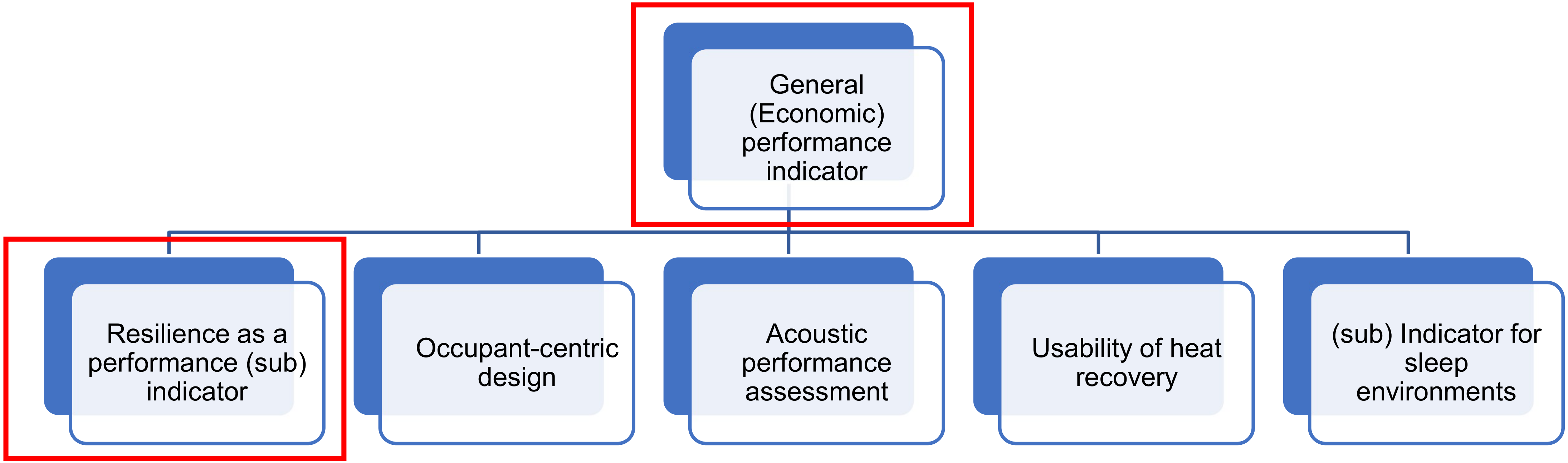
Research method

- Performance assessment



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Research method

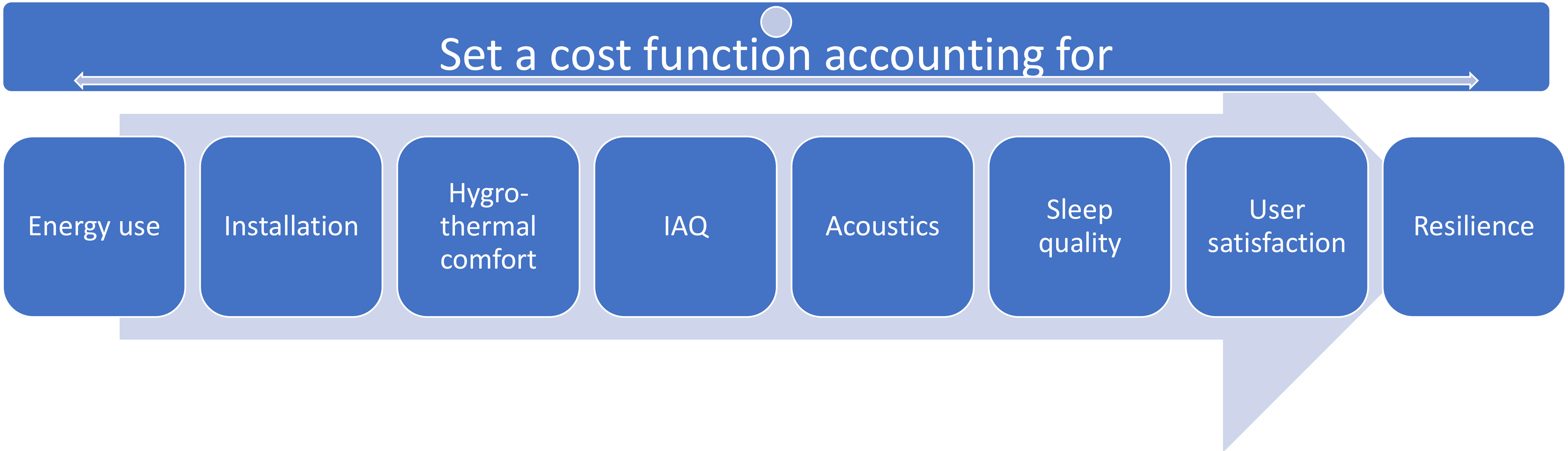
- Optimisation of system design

- Air distribution system
  - Simulation based design and control optimisation of air distribution networks
  - CFD to improve predictions of pressure drop in ventilation systems
  - Acoustical design and optimization
- Positioning of openings and filtration
  - Improving the supplied ventilation air through filtration
  - Optimising supplied ventilation air through positioning of openings
  - “Simplified” CFD to optimize location ventilation openings

Overview

- Introduction
- Performance assesment framework
  - General performance indicator (Cony and Laverge, Ghent University)
  - Resilience
- Optimisation of system design
  - Principle
  - Case study
- Conclusions

Performance assessment framework



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Performance assessment framework

- Material
- Maintenance
- Operational
- Installation

Hard costs

- Health
- Productivity loss
- Learning disturbance

Soft costs

Hygro-thermal comfort

Hygro-thermal comfort cost

- Hours of thermal discomfort can be calculated from initial simulation
- 2nd simulation with ideal setpoint T° and infinite hot/cold power

→ $Hygrothermal\ comfort\ cost\ = \Delta E_{need} X\ PPD$

  - ΔE_{need}: extra energy need during discomfort hours (electrical cost)
  - PPD: Percentage of person disatisfied

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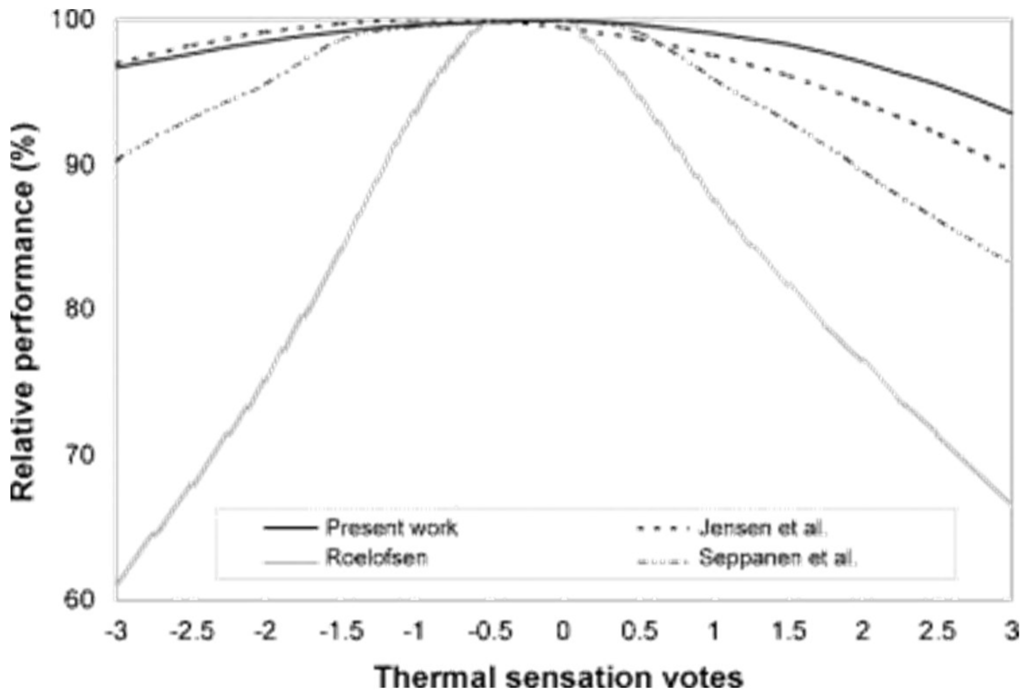
User satisfaction

User satisfaction cost

- Cost= productivity loss*productivity



Lan, Li, Pawel Wargocki, and Zhiwei Lian. 2011.

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Disability Adjusted Life Year (DALY) = Metric of harm

Rationale:

Mortality does not give a complete picture of the burden of disease borne by individuals in different populations. The overall burden of disease is assessed using the disability-adjusted life year (DALY), a time-based measure that combines years of life lost due to premature mortality (YLLs) and years of life lost due to time lived in states of less than full health, or years of healthy life lost due to disability (YLDs). One DALY represents the loss of the equivalent of one year of full health. Using DALYs, the burden of diseases that cause premature death but little disability (such as drowning or measles) can be compared to that of diseases that do not cause death but do cause disability (such as cataract causing blindness).

Definition:

One DALY represents the loss of the equivalent of one year of full health.
DALYs for a disease or health condition are the sum of the years of life lost to due to premature mortality (YLLs) and the years lived with a disability (YLDs) due to prevalent cases of the disease or health condition in a population.

https://www.who.int/data/gho/indicator-metadata-registry/imr-details/158

World Health Organisation, “WHO methods and data sources for global burden of disease estimates 2000-2019.” 2020.

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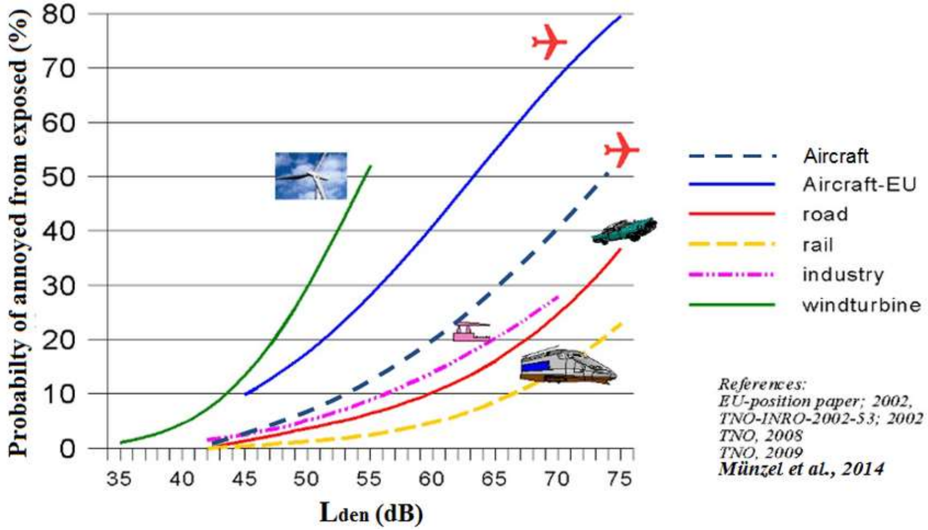
Acoustics

Acoustical cost

- $Noise_{Cost} = DALY_{noise} \times DALY\ cost \quad + Productivity\ loss$
- $DALY\ cost_i = life\ year\ cost + Productivity\ cost + health\ cost$
- $DALY_{noise}$ creation:
  - Diseases induced
  - Life impact of disease
  - Probability of disease occurrence **due to acoustic disturbance**
- Productivity loss estimation :
  - % of people Highly Annoyed by noise disturbance
  - % of productivity decrease



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Indoor Air Quality

IAQ cost

- $IAQ_{Cost} = \sum_i^p DALY_i \times DALY\ cost_i + SBS_{cost}$
  - DALY : Disability adjusted life years lost
  - SBS: sick building syndrome
- $DALY\ cost_i = life\ year\ cost + Productivity\ cost + health\ cost_i$
- $SBS_{cost} = productivity\ cost \times \left(POPS2 \times productivity\ decrease + POPS \times \frac{productivity\ decrease}{2}\right) \times \frac{2}{5}$
  - POPS and POPS2: Percentage Of People with (SBS) 1 (POPS) or 2 (POPS2) Symptoms (from 1 to 3 days a week)
  - POPS and POPS2 : questionary input metrics but calculation formula exists (from indoor air pollution and indoor environmental indexes)

Pollutant	Health cost (€)
Benzene	46 000
Trichloroethylene	70 971
Radon	25 526
PM	10 402
CO	1 085

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- Introduction
- Performance assesment framework
  - General performance indicator
  - Resilience (Al-Assaad and Breesch, KU Leuven)
- Optimisation of system design
  - Optimisation method
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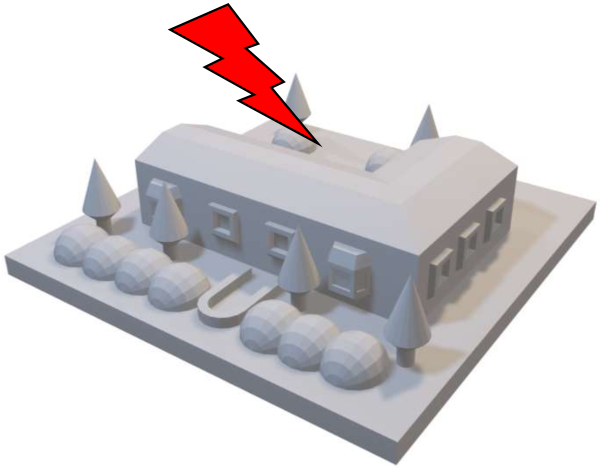
Resilience: why does it matter?

Expected indoor/outdoor conditions

Thermal comfort
Good breathable air quality
Energy efficient



Unexpected disruptive events

Building shifts drastically from its **IAQ design conditions**

(-) Accumulation of pollutants

(-) Acute exposure

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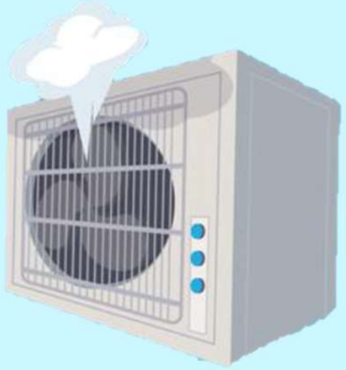
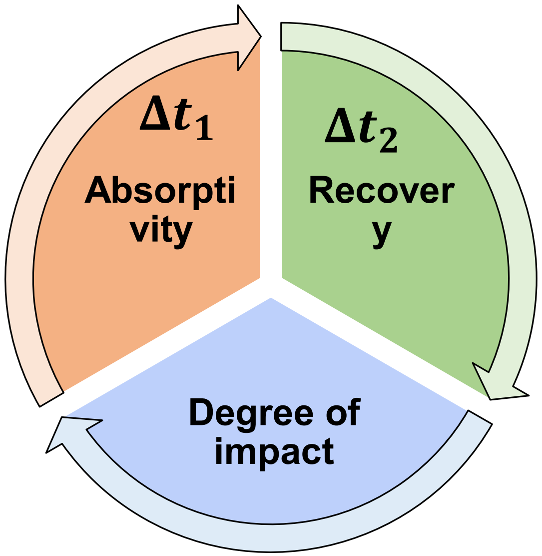
Resilience: how to assess?

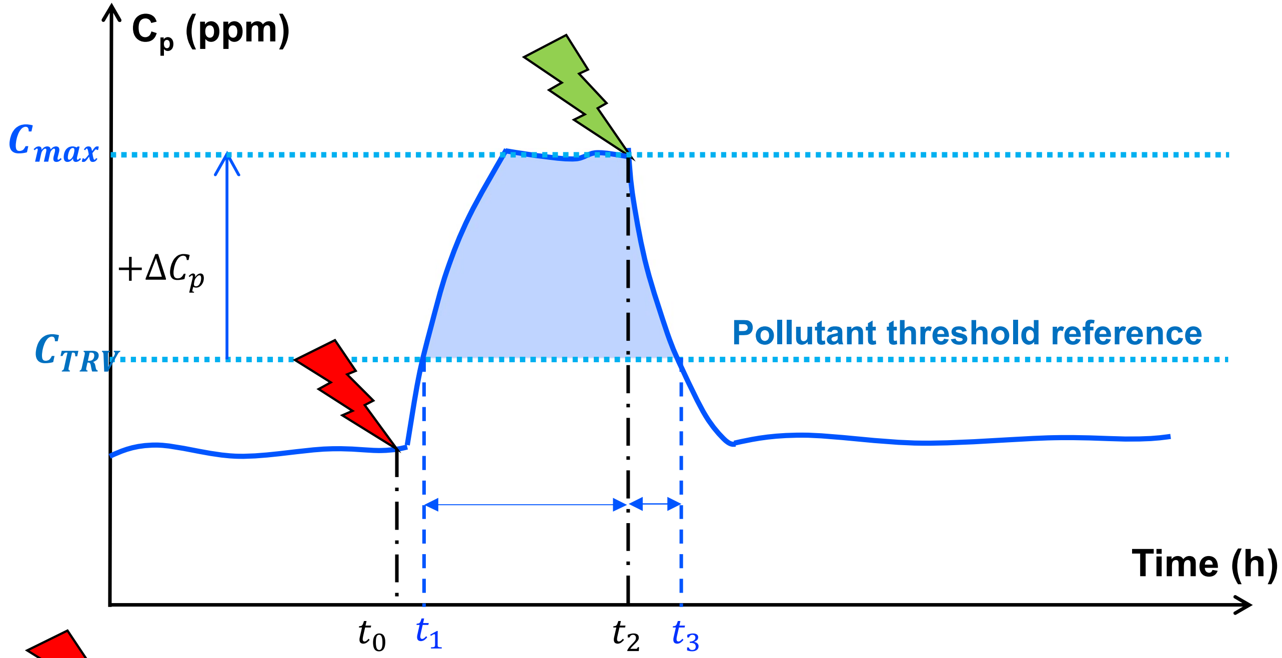
1. Identify disruptive events

Mechanical disruptions	Internal disruptions	External disruptions
		
Partial or complete disruption in the operation of the ventilation system (e.g., fan failure, power outages, fouling filters)	Occurs inside the space due to excessive indoor pollution event (e.g.,excess occupants beyond capacity of AHU)	Occurs outside the building envelope due to excessive outdoor pollution (e.g., outdoor fire, traffic jams)

Resilience: how to assess?

2. Quantify the aspects of resilience





Shock occurrence (t_0)

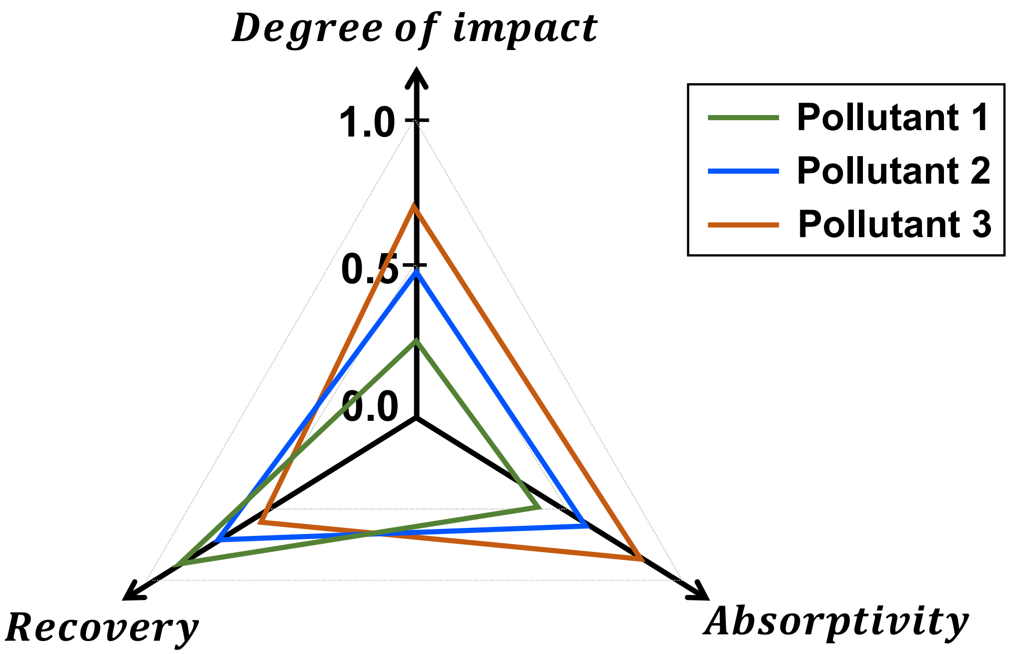
$\Delta t_{abs} = t_2 - t_1$: **Absorptivity time**

End of shock effects (t_2)

$\Delta t_{rec} = t_3 - t_2$: **Recovery time**

Resilience: how to assess?

3. Resilience score (RS)



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Optimization problem: objective

For a random floorplan: find ductwork configuration (= layout + sizing) with minimum life-cycle cost

minimize ('soft' costs & 'hard' costs)

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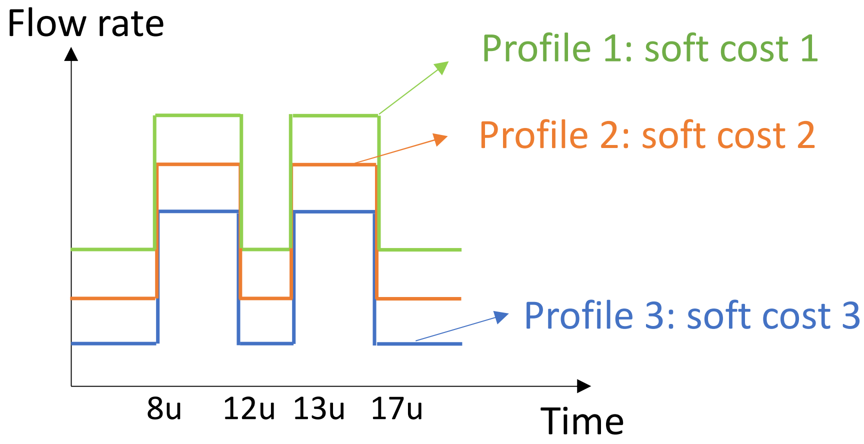
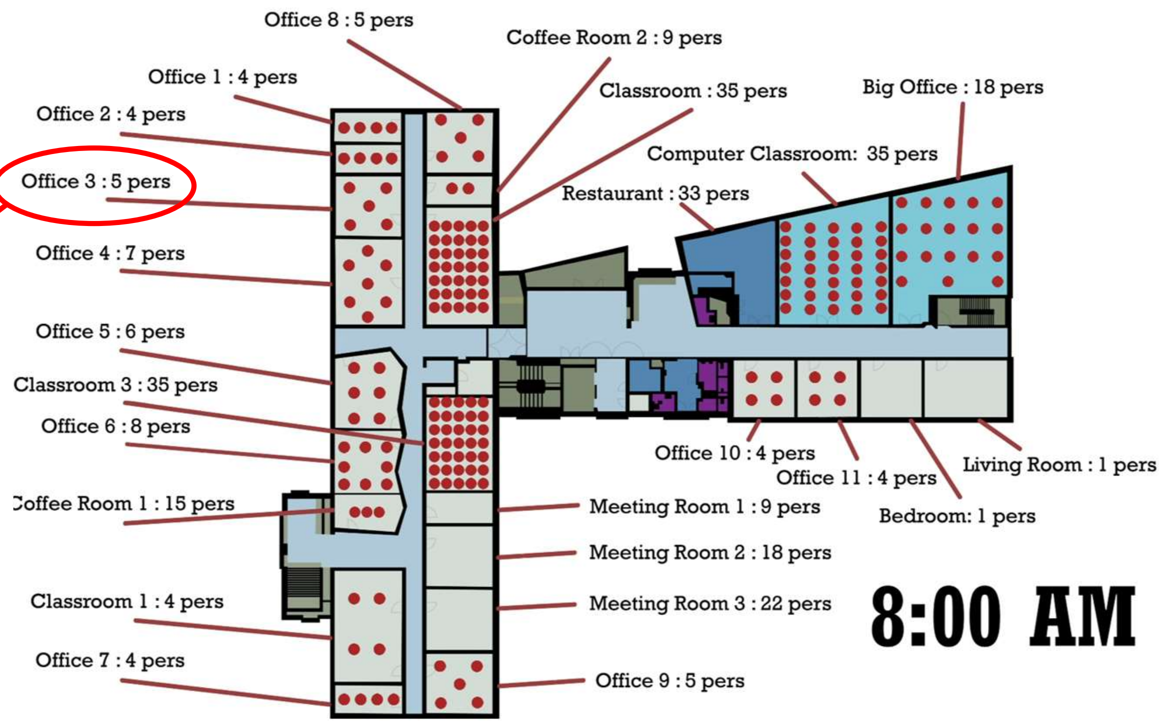
Input optimization method

- Floorplan
- Input profiles

  → based on demand profiles/room





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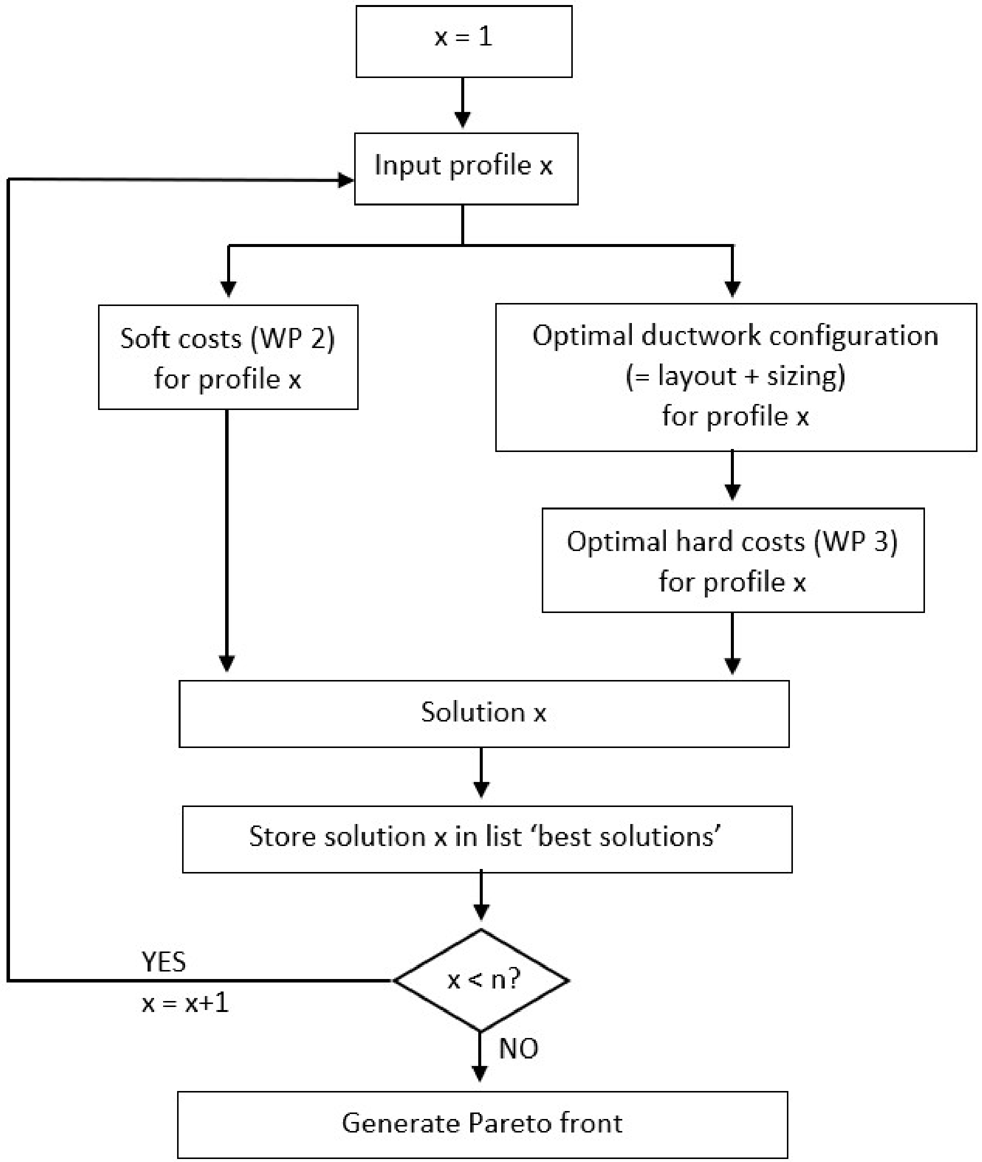
Optimization method



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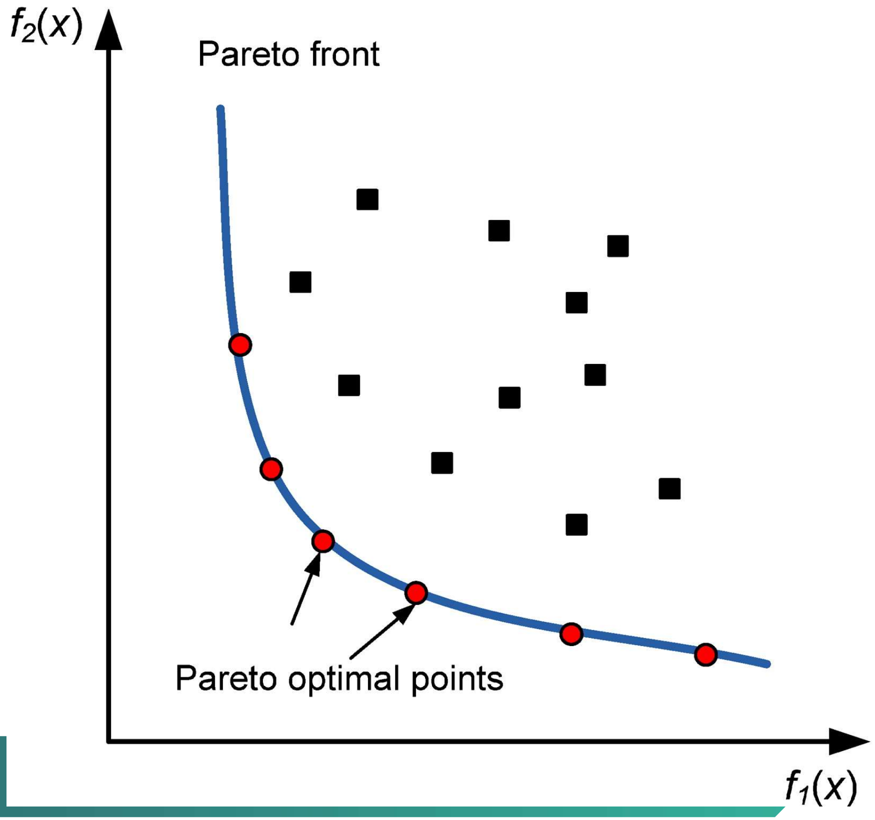
Output optimisation algorithm

Soft costs and hard costs: not the same order of magnitude

- **Pareto front** instead of 1 optimized solution:

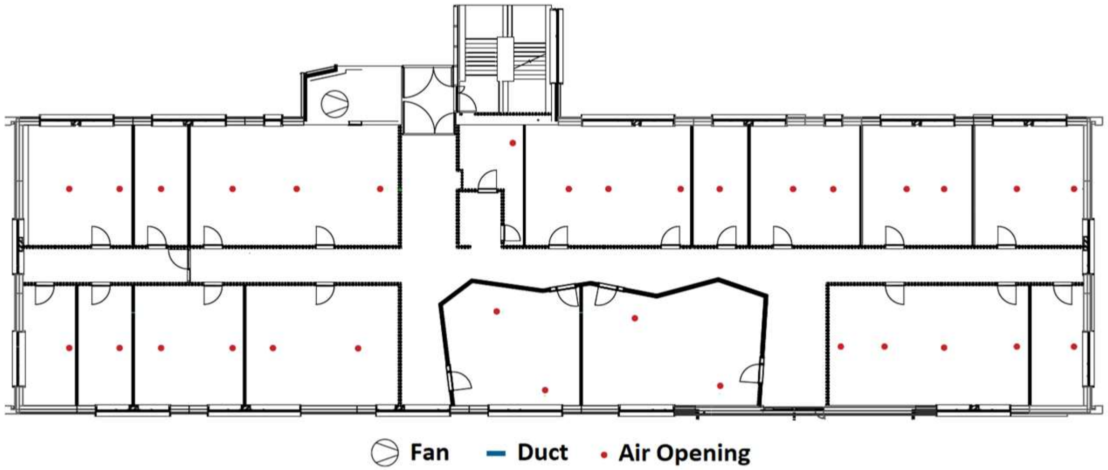
  user can select solution according to preference



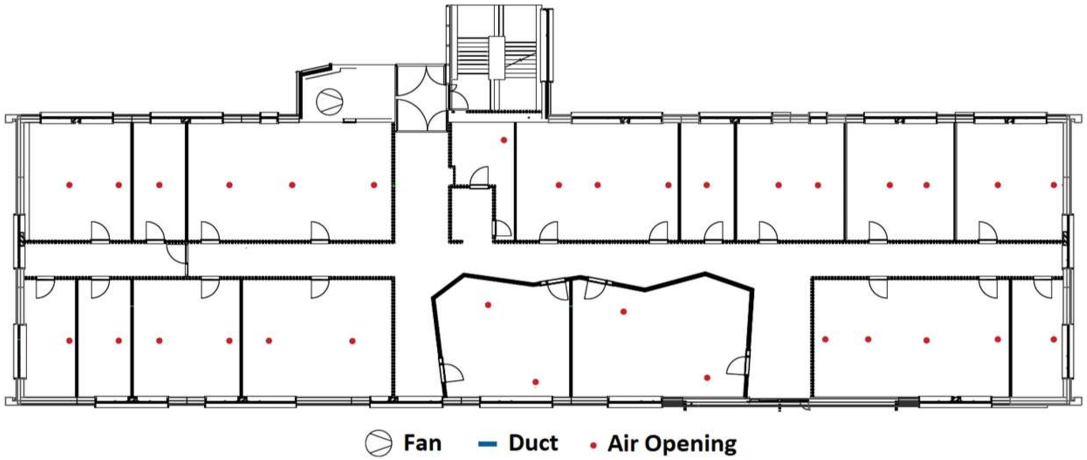
Case study: University of Antwerp: Building Z

Case study

Potential design method



Existing design



Optimized design

Total hard costs: 15% lower

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Conclusions

- Need for design guideance for smart ventilation systems
- Performance assessment framework for smart ventilation defined
- System optimisation design method developed

Various building types

- **Offices** → Original formulation
- **Residential buildings** → Productivity cost replaced by extra energy (electical Wh) cost to reach minimum productivity loss
- **Retirement house** → $$Retirement\ house_{Cost} = \frac{Residential_{cost} \times N_{retired} + Office_{cost} \times N_{workers}}{N_{retired} + N_{workers}}$$
- **Hotels** → $$Hotel_{Cost} = \frac{Residential_{cost} \times N_{customers} + Office_{cost} \times N_{workers}}{N_{customers} + N_{workers}}$$
- **Schools** → $$School_{Cost} = \frac{Student_{cost} \times N_{students} + Office_{cost} \times N_{workers}}{N_{students} + N_{workers}}$$

  → $Student_{cost}$: Actually encountering difficulties to estimate learning disturbance cost

Sleep quality cost

Assumptions

- Many factors influence sleep quality
- Litterature may have divergent opinions
- Sleep quality is hard to quantify from environmental parameters only

→ Improving sleep quality only from ventilation related parameters is complex

→ Detection of bad environment for sleep quality is possible

all bad conditions gathered → probability of sleep disturbance is 1

$$Sleep\ quality = \frac{1}{K_{tot}} \sum_{1}^{n} \frac{k_i w_i}{n}$$

Sq ≤ 0 →good

0 < Sq ≤ 1 → probably bad

Sq ≥ 1 → bad for sure

Good/ Probably good — Neutral/ Uncertain — Bad/ Probably bad — Bad for sure

-1 — 0 — 1 — 2n-1

	Coefficient	Good (-1)	Neutral (0)	Probably bad (1)	Bad (2n-1=3)
T (°C)	0,0447		17-28	<17 or >28	
H° (%)	0,0447		40-60	<40 or >60	
CO2 (ppm)	0,0351		750-1150	1150-2600	2600
Noise (dB)	0,0319			35	

From assessment to health cost

- Translation, from sleep disturbance issue to DALY
    - Equivalent of DALY lost per issue
    - Probability of issue with & without sleep disturbance
    - Cost induced/issue