Planning of Fluid Systems Towards Energy-Efficiency by Mathematical Optimization

Prof. Ulf LORENZ – **University of Siegen (Germany)**

9 - 11 April 2025, Antibes Juan-les-Pins (France)

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Prof. Dr. Ulf Lorenz

Planning of fluid systems towards energy-efficiency by mathematical optimization

FAN 2025
joint work with Peter Pelz, Julius Breuer, Thorten Ederer

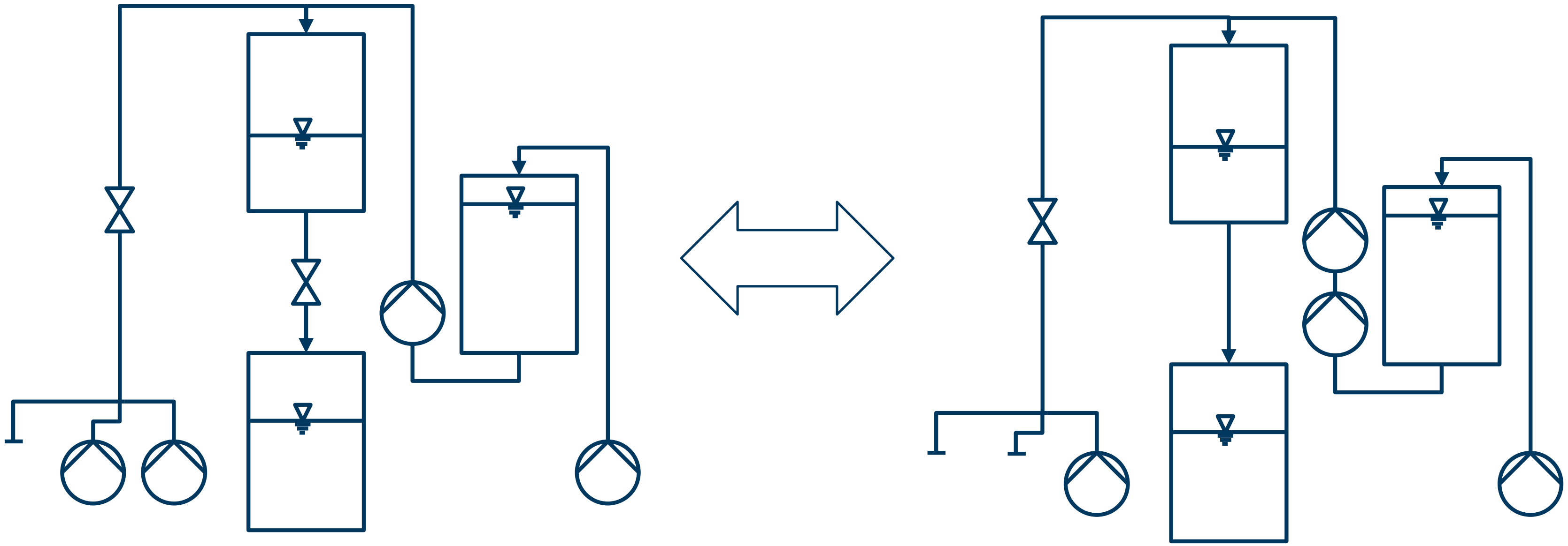
Overview

- The Beginning: Different Views on Design Processes
- An Illustrating Example --- the Design of a Booster Station ---
- Noise Control in Fan Systems
- What are we Really Doing? And why?

The Beginning: Different Views on Design Processes | System Design

Compare Optimization ⇔ Simulation ⇔ Experiment

- Topology
- Selection of modules
- Goals



Source: Peter Pelz, FST, TU-Darmstadt

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The Beginning: Different Views on Design Processes | Classification

	PRODUCTS			EXTENDED PRODUKTE		SYSTEMS
PROZESS-FUNCTION	FREQ. CONVERSION	ENERGY-CONVERSION ELEK. ➔ MECH.	ENERGY-CONVERSION MECH.➔ HYDR.	OVERCOME SYSTEM RESISTANCE TO SET VOLUME FLOW		COOLING, HEETING, CHEMICAL REACTIONS, …
TECHNOLOGY	FREQUENY-CONVERTER	ELEKTRIC-MOTOR	PUMP / VENTILATOR / COMPRESSOR	EXTENDED PRODUCT + LOAD SCENARIOS FC+E-M.+P.	FLOW-UNIT (BOOSTER-STATION, …)	PLANT
SAVING-OPPORTUNITIES	+	+	+	++	++	+++
RESPOSIBILITY	MOTOR MANUFACTURERS AND FC MANUFACTURERS		PUMP MANUFACTURERS			PLANER
CONTROL			Generally ISO 9001 monitoring and certification of the test fields (measuring equipment, qualification of employees, documentation). In the event of a dispute, commissioning of independent testing laboratories			SMART METERING

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The Beginning: Different Views on Design Processes | Classification

	PRODUCTS			EXTENDED PRODUKTE		SYSTEMS
PRO… FI…	FREQ. …	ENERGY- …	ENERGY- …	OVERCOME SYSTEM RESISTANCE TO …		COOLING, …
				FC+E-M.+P.		
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„*DIVIDE ET IMPERA*“ DOES NOT LEAD TO ENERGY SAVINGS !

Source: Peter Pelz, FST, TU-Darmstadt

The Beginning: Different Views on Design Processes

Classic Engineering combines Human Creativity with hard facts from Physics and Mathematics.

„Classic Engineering has cultivated Human Creativity.“

- Human Creativity is a central tool
- it is flanked by norms, ISO, DIN etc.

…

The Beginning: Different Views on Design Processes

Classic Engineering combines Human Creativity with hard facts from Physics and Mathematics.

„Classic Engineering has cultivated Human Creativity.“

- Human Creativity is a central tool
- it is flanked by norms, ISO, DIN etc.

vs.

„Mathematitions and Computer Scientists try to compensate or even overcome human creativity with the help of algorithms.“

The Beginning: Different Views on Design Processes

Let them do!

What a shame!

What a bullshit!

Let them do!

What a shame!

What a bullshit!

Let them do!

What a shame!

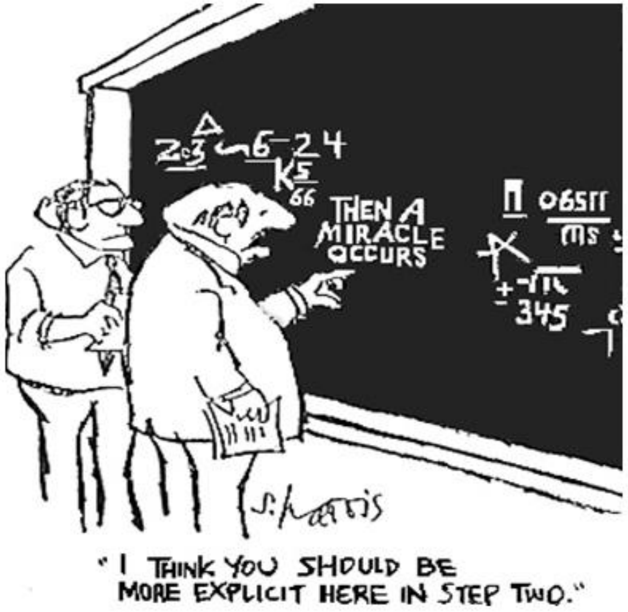
What a bullshit!

The Beginning: Different Views on Design Processes

… however there stay some difficulties with system design.

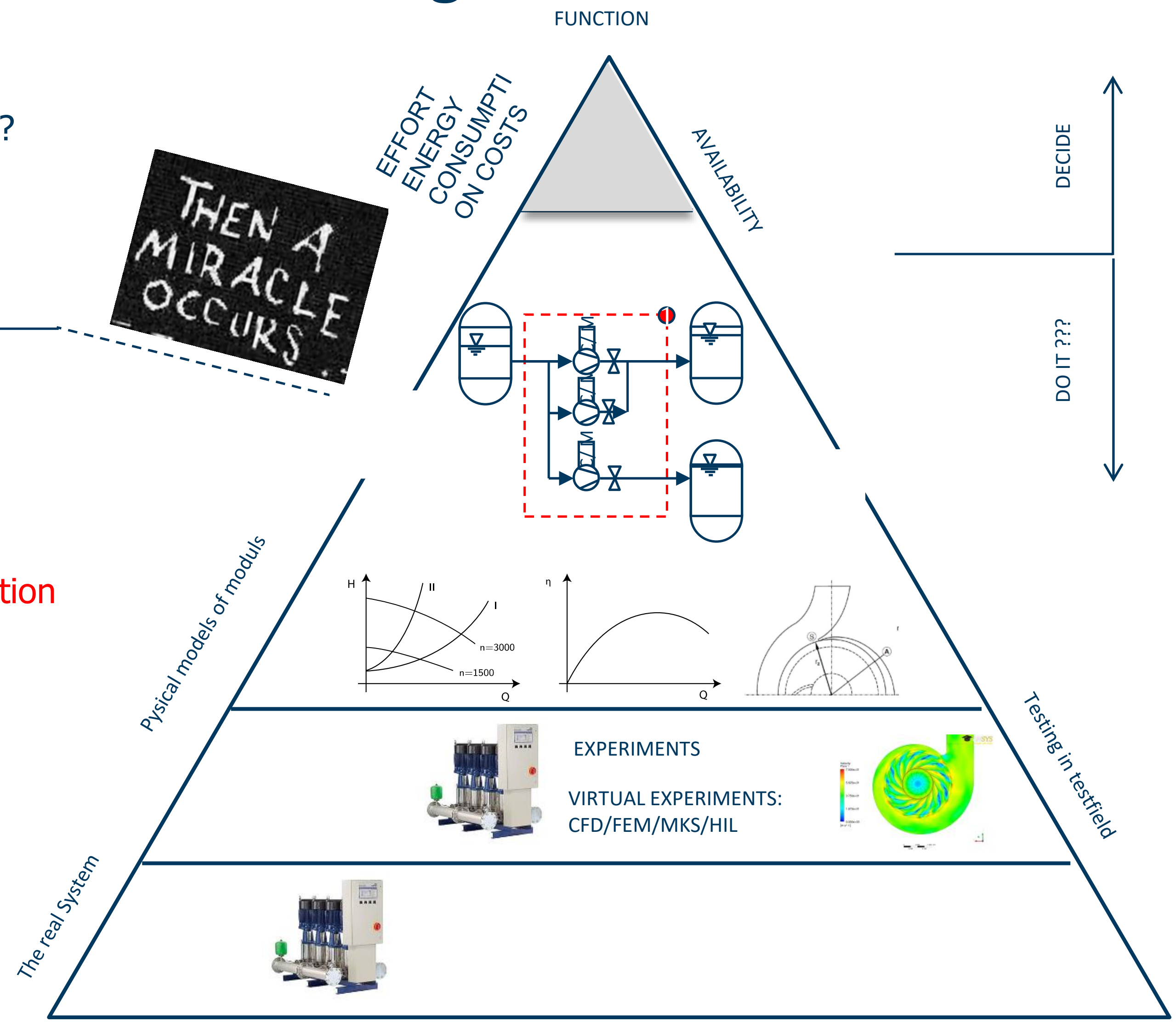
1. No Reference is available

2. Crucial decisions via intuition



The Beginning: Different Views on Design Processes

1. What is the desired function?
2. What are additional goals?
3. Use models for moduls and perform parameter-optimization
4. Validate your creation!
5. Put it to production!



Source: Peter Pelz, FST, TU-Darmstadt

The Beginning: Different Views on Design Processes

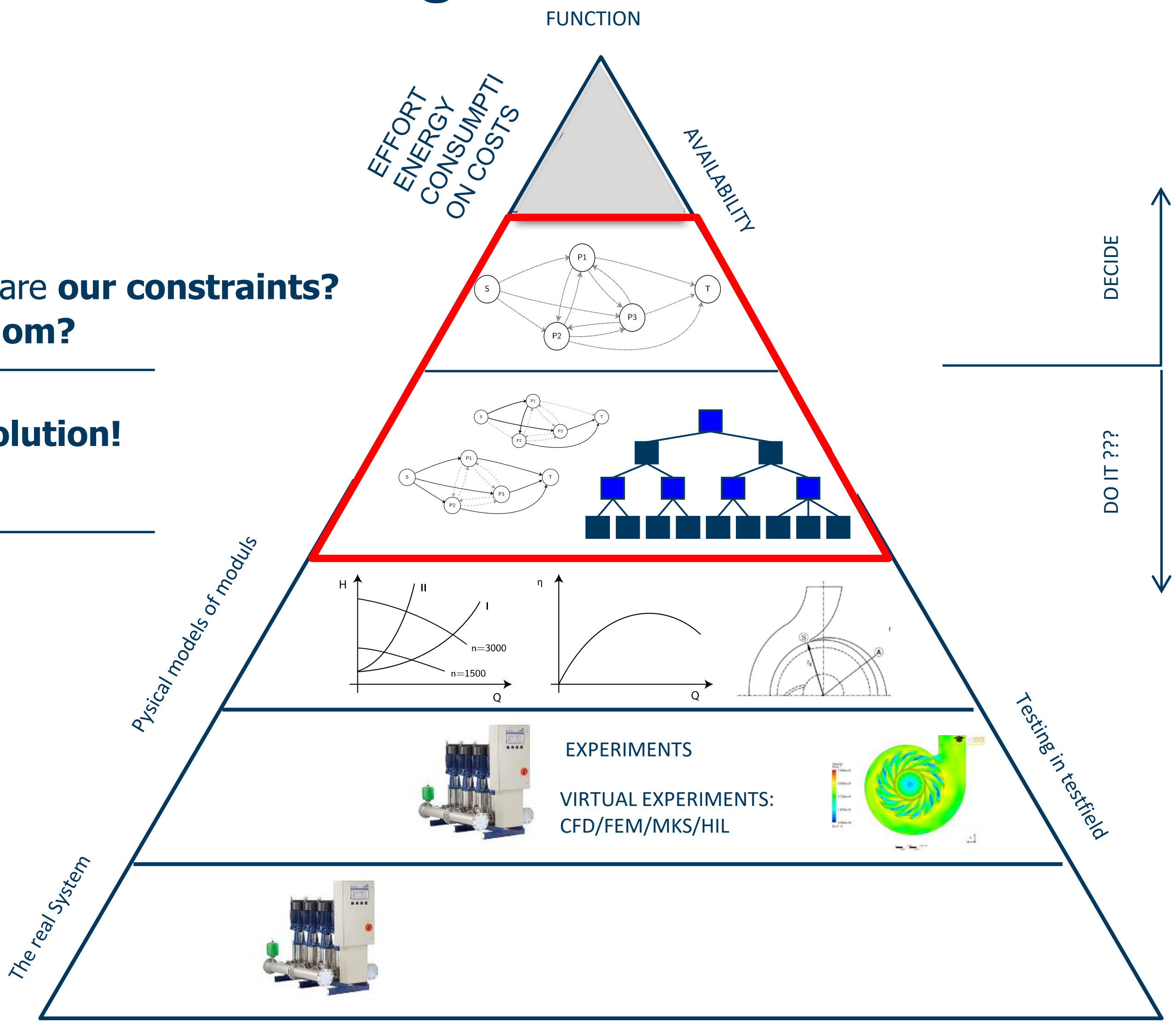
1. What is the desired function?
2. What are additional goals?
3. What is the **playing field?** What are **our constraints? What are the degrees of freedom?**

---

4. **Let an algorithm search the solution!**

---

5. Use models for moduls and perform parameter-optimization
6. Validate your creation!
7. Put it to production!



Source: Peter Pelz, FST, TU-Darmstadt

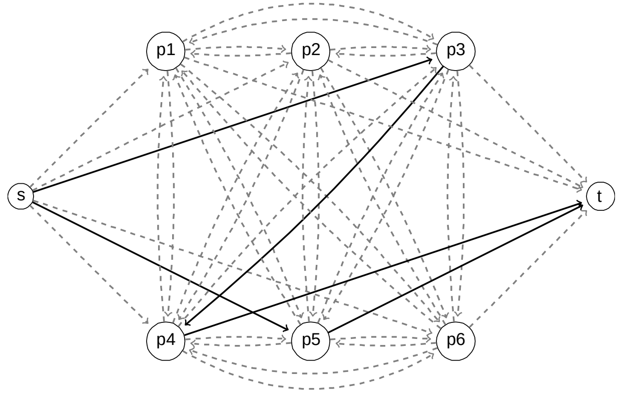
- **An Illustrating Example**

  The Design of a Booster Station

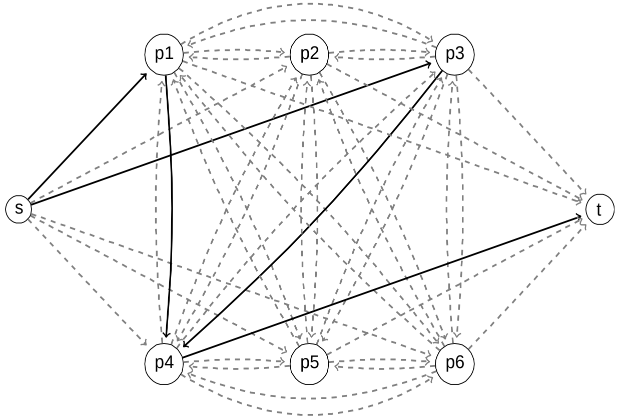
An Illustrating Example | The Design of a Booster Station

Booster Station
(Source: KSB AG)

TOPOLOGY / GRAPH 1



TOPOLOGY / GRAPH 2



An Illustrating Example | The Design of a Booster Station

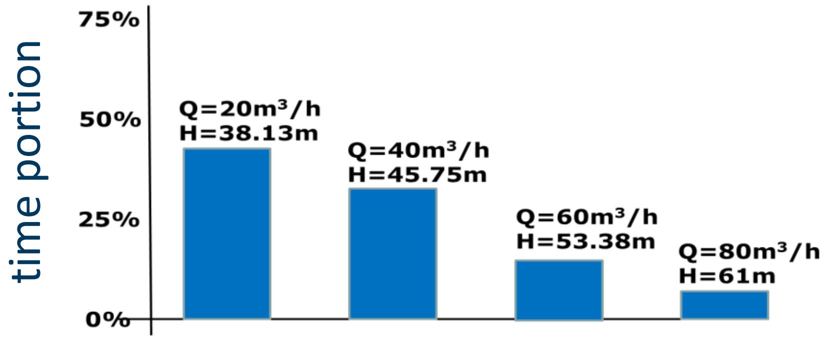
- Definition of the task:
  Which demands do we have to the booster station?

  - Transport of fluid
  - Pressure and volume flow follow some requirements, agreed between custumer and constructor.

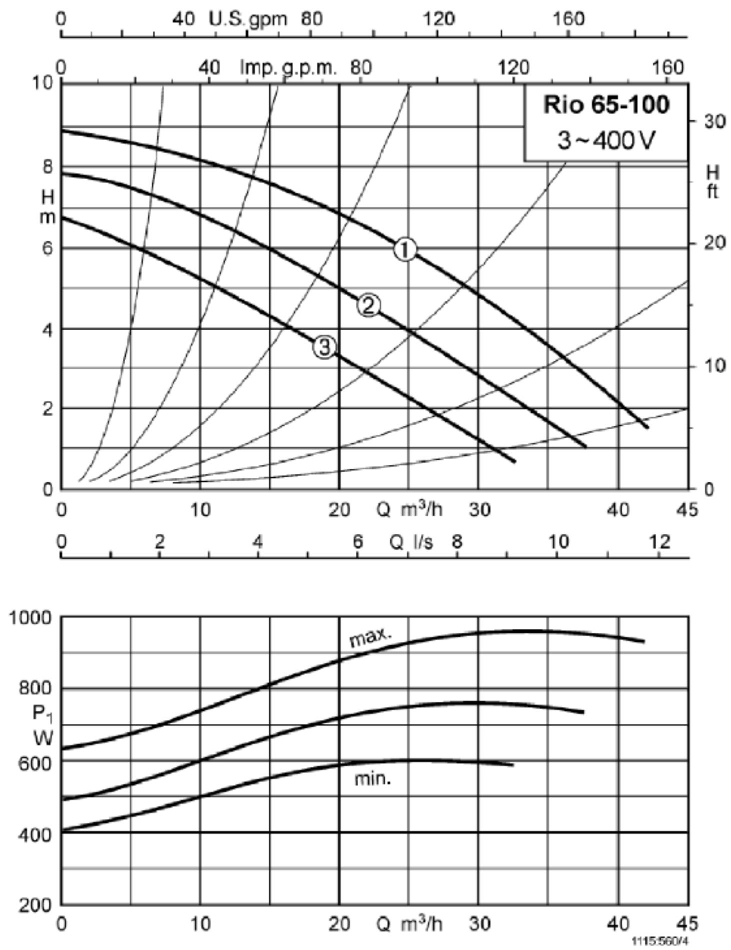
Respect the laws of fluid dynamics!

Stationary use case.

Here: A load profile with four stationary load cases.



An Illustrating Example | The Design of a Booster Station



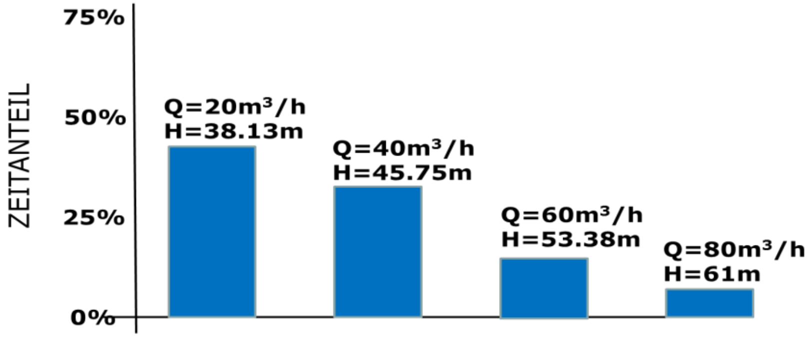
RS level 1

Q=29 m³/h

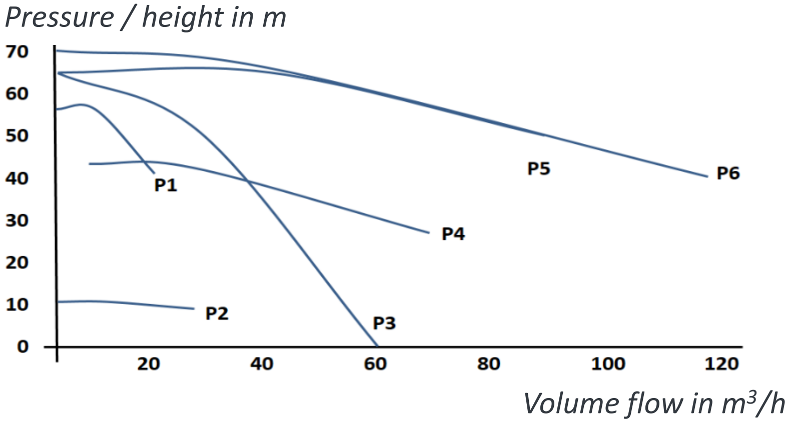
P=950 W

An Illustrating Example | The Design of a Booster Station

Load profile of customer



Components



Pumps, valves, tubes, …

An Illustrating Example | The Design of a Booster Station

Is there something towards that we want to optimize?

Minimize maximum energy consumption

Minimize the energy consumtion over the next 20 years.

No too expensive investment!

Here: minimize over investment and energy costs over 20 years

An Illustrating Example | The Design of a Booster Station

MIP MODEL FOR ALL (!) ALLOWED COMBINATIONS

$$\sum_{(i,v)\in E} q^E_{s,i,v} = q^V_{s,v} \quad \forall s \in S, v \in V : v \neq v_s$$

$$q^V_{s,v} = \sum_{(i,v)\in E} q^E_{s,i,v} \quad \forall s \in S, v \in V : v \neq v_t$$

$$h^{V-}_{s,i} - h^{V+}_{s,i} \leq 2h^{S+}_s \cdot (1 - x^E_{s,i,j}) \quad \forall s \in S, (i,j) \in E$$

$$h^{V+}_{s,i} - h^{V-}_{s,i} \leq 2h^{S+}_s \cdot (1 - x^E_{s,i,j}) \quad \forall s \in S, (i,j) \in E$$

$$h^{V+}_{s,v} + h^V_{s,v} = h^{V-}_{s,v} \quad \forall s \in S, v \in V$$

$$\sum_{(p,l)\in K^{(2D)}:(p,l+1)\in K^{(2D)}} k^z_{s,p,l} = 1 \quad \forall s \in S, p \in P^{(2D)}$$

$$k^s_{s,p,l} \leq k^z_{s,p,l} \quad \forall s \in S, (p,l) \in K^{(2D)} : (p,l+1) \in K^{(2D)}$$

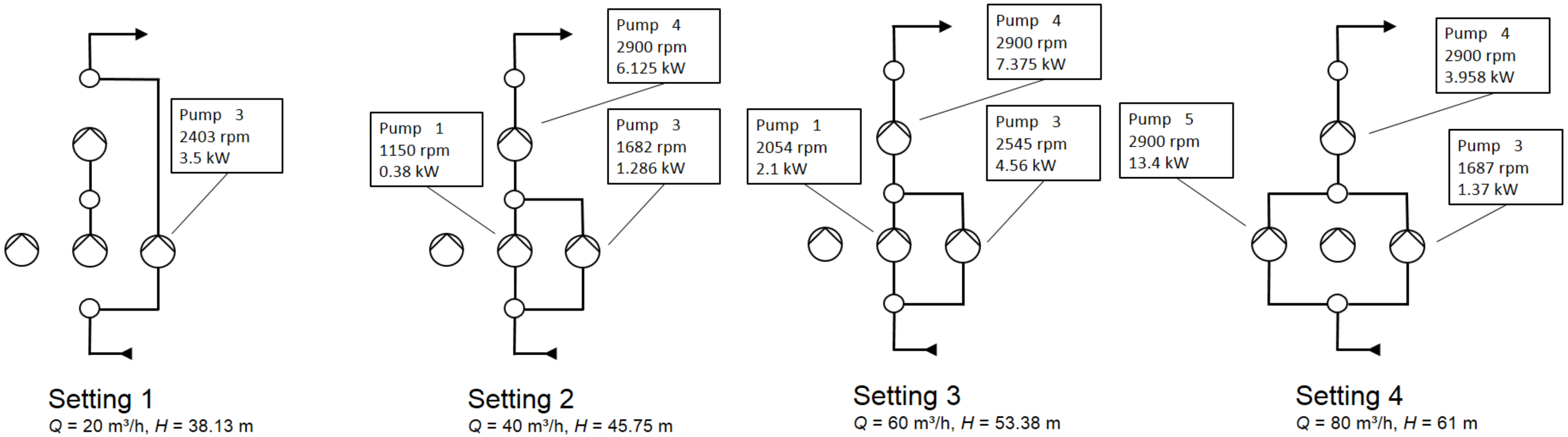
$$q^V_{s,p} = \sum_{(p,l)\in K^{(2D)}} k^q_{p,l} \cdot k^z_{s,p,l} + (k^q_{p,l+1} - k^q_{p,l}) \cdot k^s_{s,p,l} \quad \forall s \in S, p \in P^{(2D)}$$

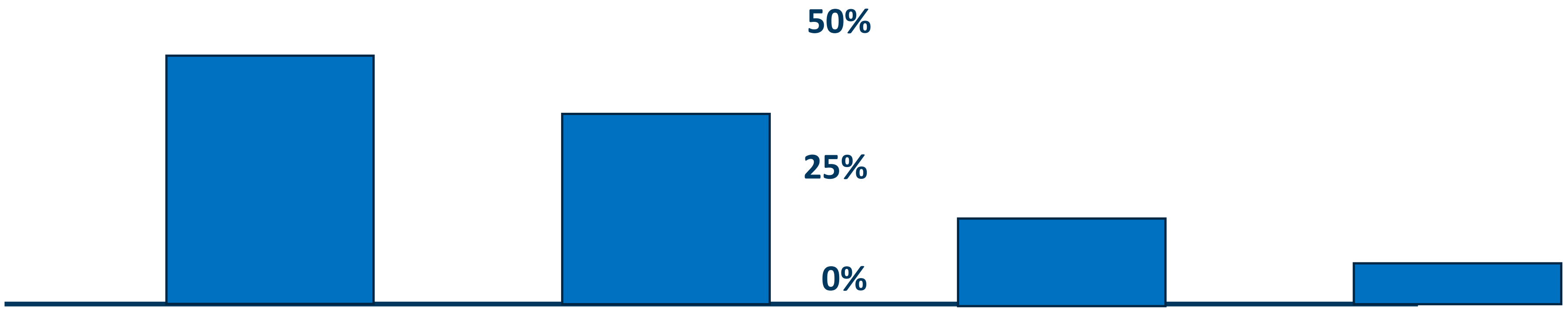
$$h^V_{s,p} = \sum_{(p,l)\in K^{(2D)}} k^h_{p,l} \cdot k^z_{s,p,l} + (k^h_{p,l+1} - k^h_{p,l}) \cdot k^s_{s,p,l} \quad \forall s \in S, p \in P^{(2D)}$$

$$p^V_{s,p} = \sum_{(p,l)\in K^{(2D)}} k^p_{p,l} \cdot k^z_{s,p,l} + (k^p_{p,l+1} - k^p_{p,l}) \cdot k^s_{s,p,l} \quad \forall s \in S, p \in P^{(2D)}$$

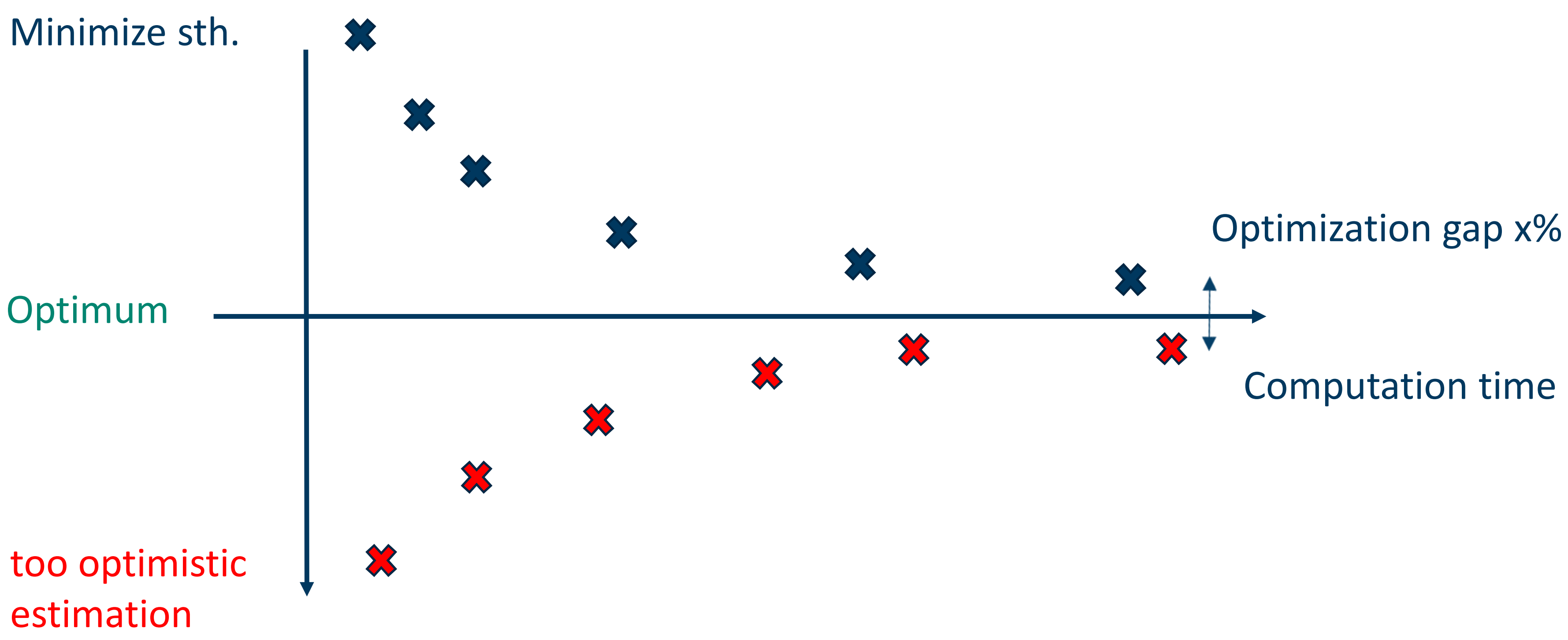
$$n^V_{s,p} = n^{(max)}_P \quad \forall s \in S, p \in P$$

An Illustrating Example | The Design of a Booster Station





An Illustrating Example | The Design of a Booster Station | Smart Algorithms for Optimization

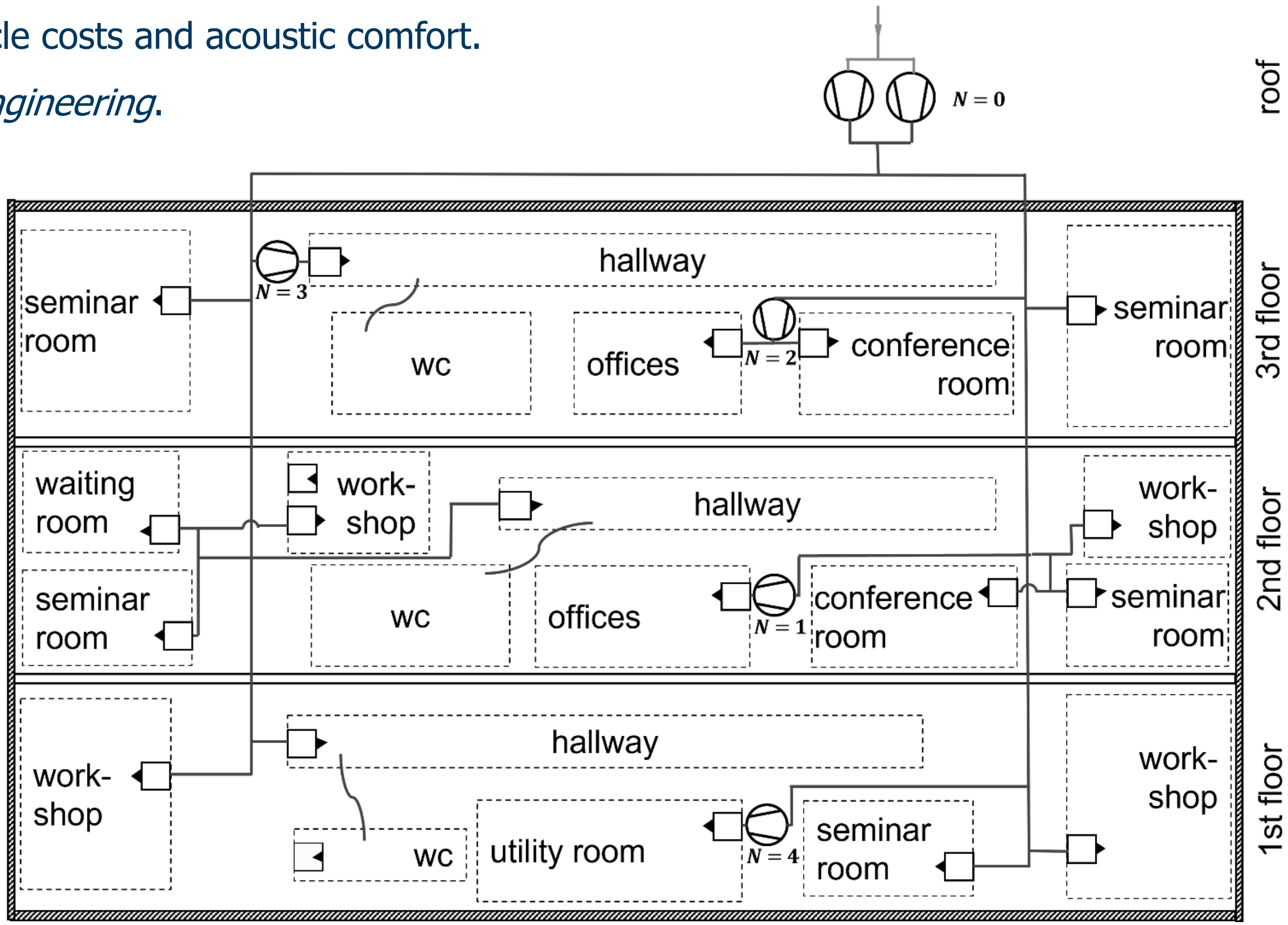


Noise Control in FAN Systems

FAN 2025

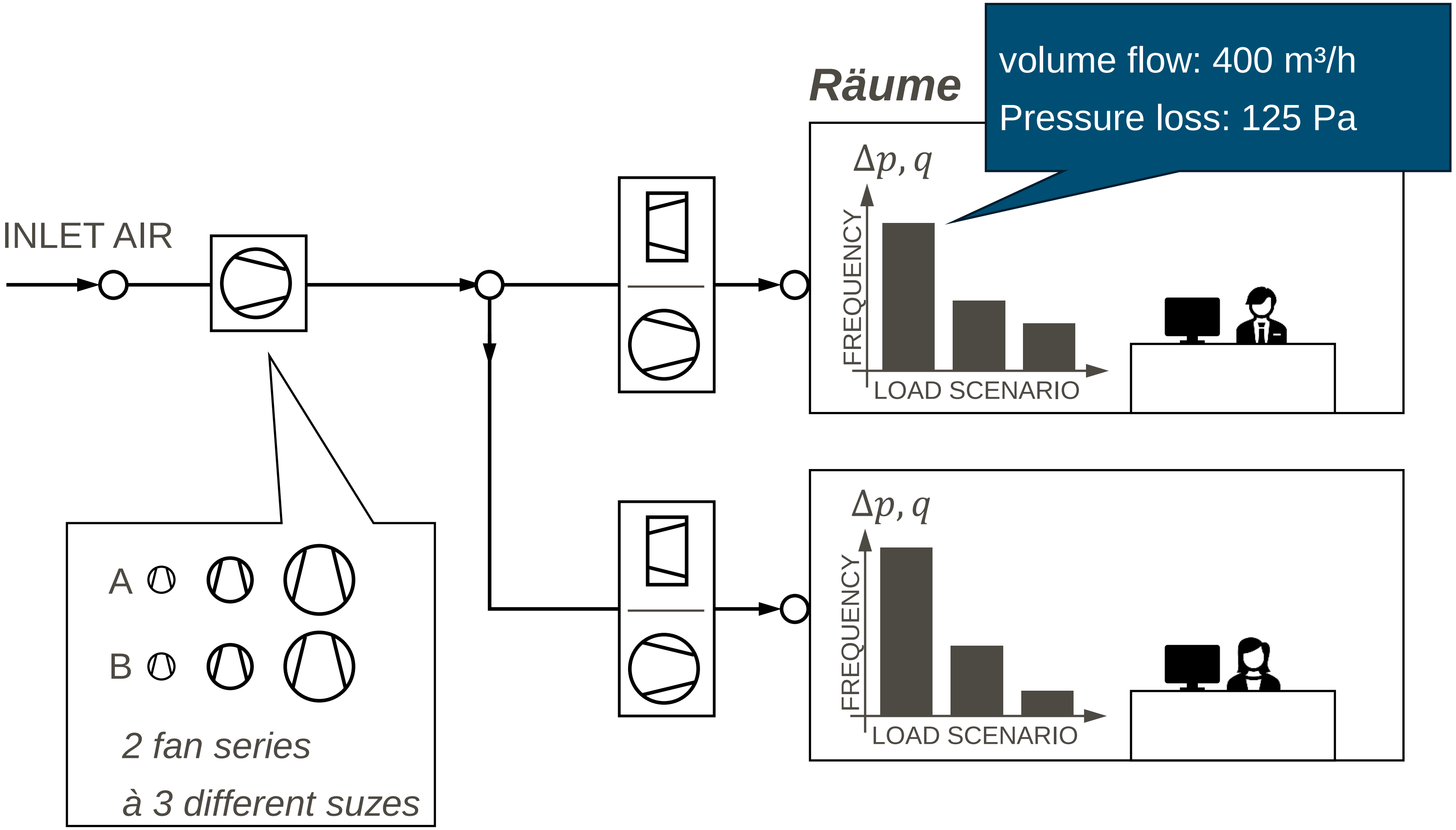
Noise Control in Fan Systems

Breuer, J. H. P., & Pelz, P. F. (2024). Algorithmic planning of ventilation systems: Optimising for life-cycle costs and acoustic comfort. *Journal of Building Engineering*.



Big thank you! to J. Breuer and P. Pelz for support with slides.

Noise Control in Fan Systems |Planning Task Air Flow

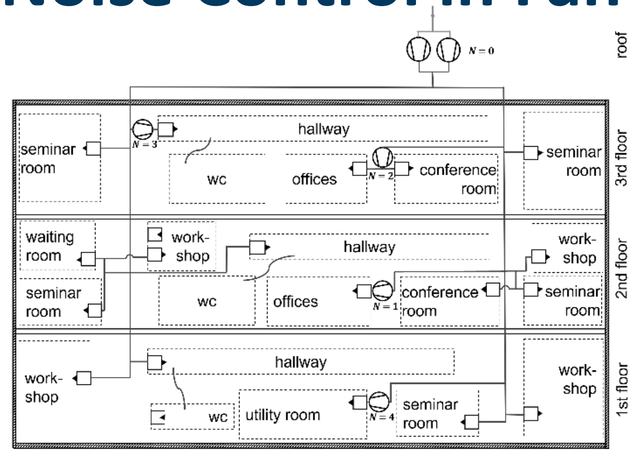


How many fans should I buy?

Where do I place them?

How can they be operated efficiently?

Noise Control in Fan Systems |Planning Task Air Flow



No. of fans to be placed:
$N \geq 13$

$M^N = 10^{13}$ decision opportunities!

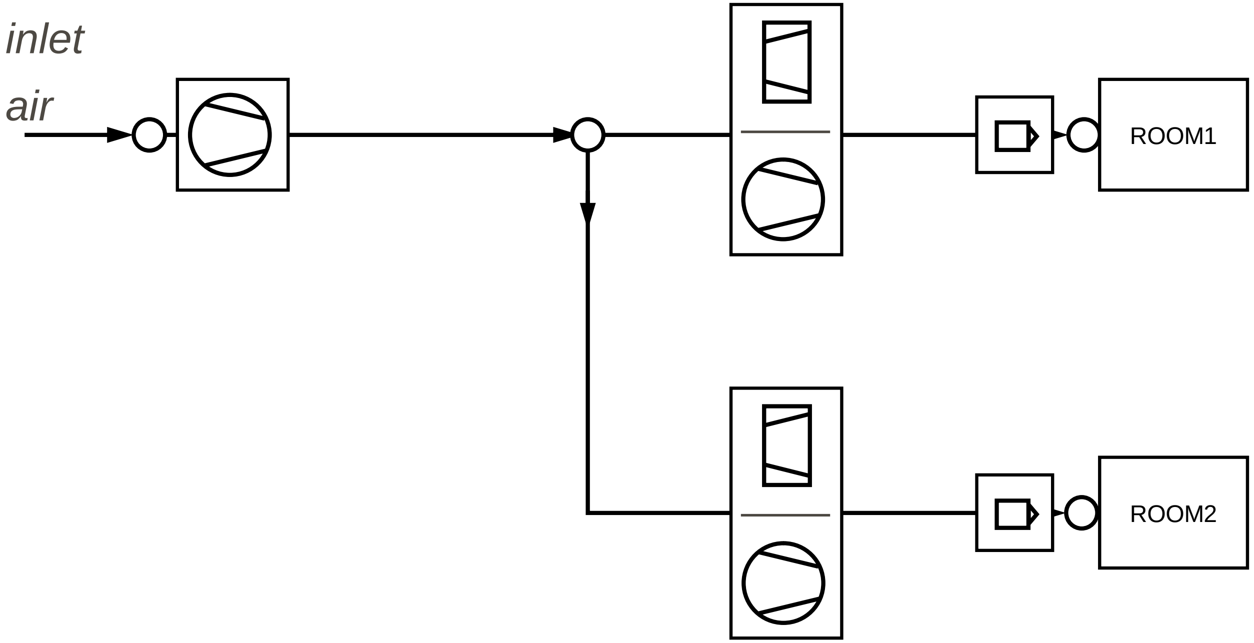
+ many others

ebm-pabst

#selectable, different fans:
$M = 10$

Typical number of freedom degrees | state space size for logistic problems:
1000 | 10^{1000}

Noise Control in Fan Systems | Planning Task Air Flow|Model



Objective

minimize life cycle costs
= investment + operational costs

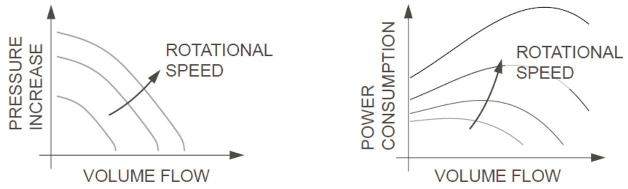
Function

supply fresh air

s.t.

- *network equations*
  (conservation of mass and energy),
- *component models (pressure increase, power consumption, purchase / activation decisions)*

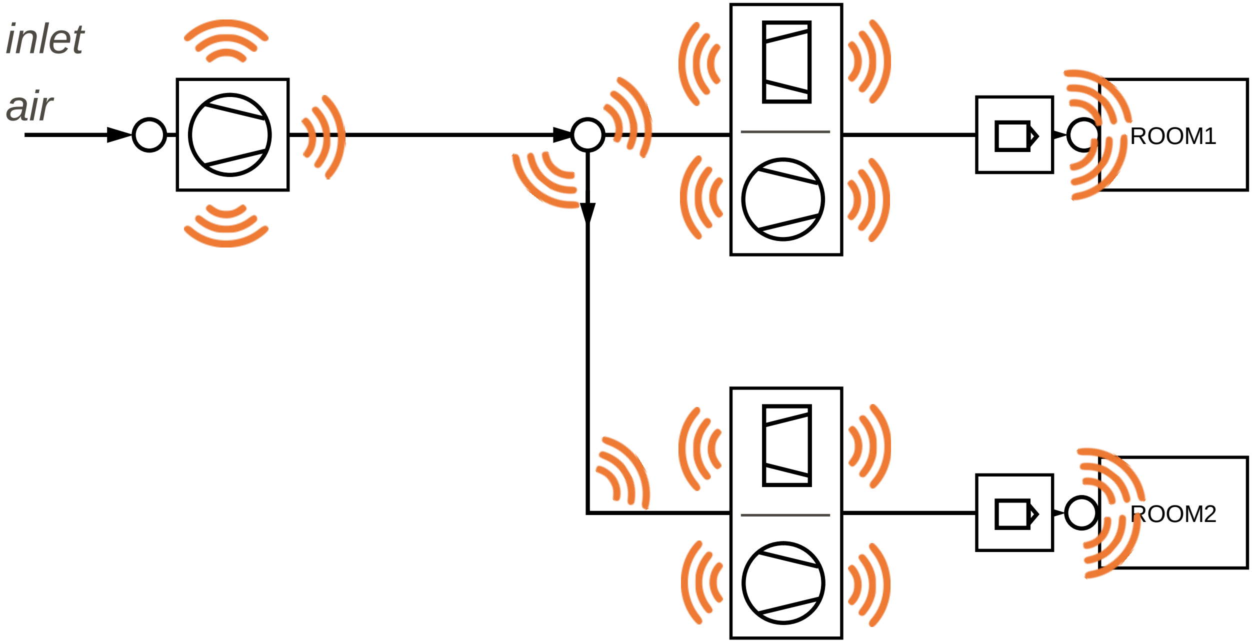
RADIAL FANS



VOLUME FLOW CONTROLLERS

arbitrary pressure loss

Noise Control in Fan Systems | Air Flow + Noise|Model



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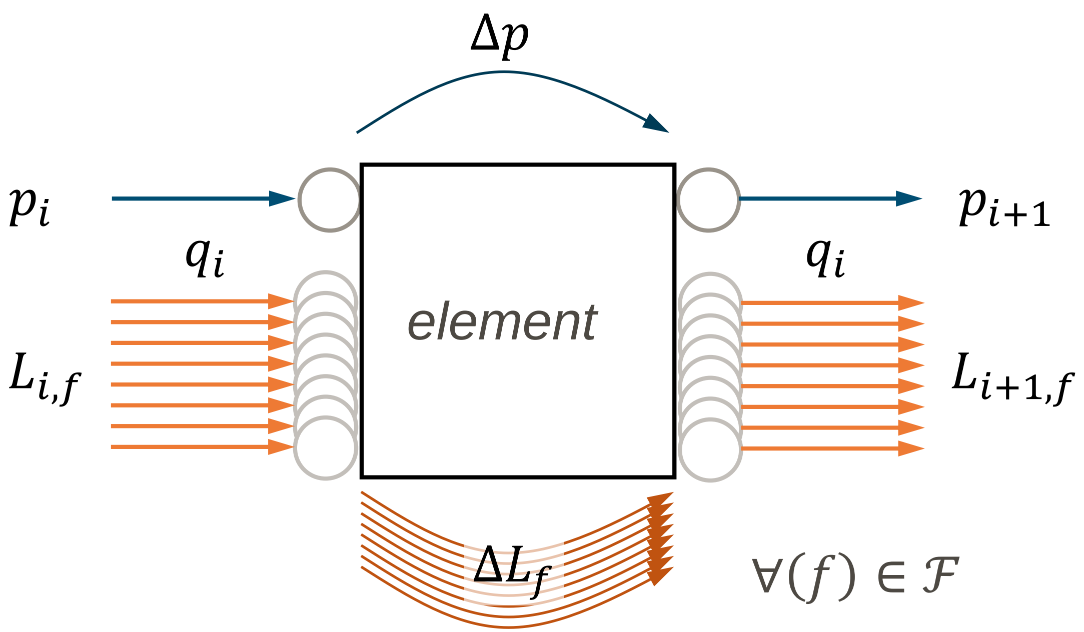
- ***NOISE LIMITS!***

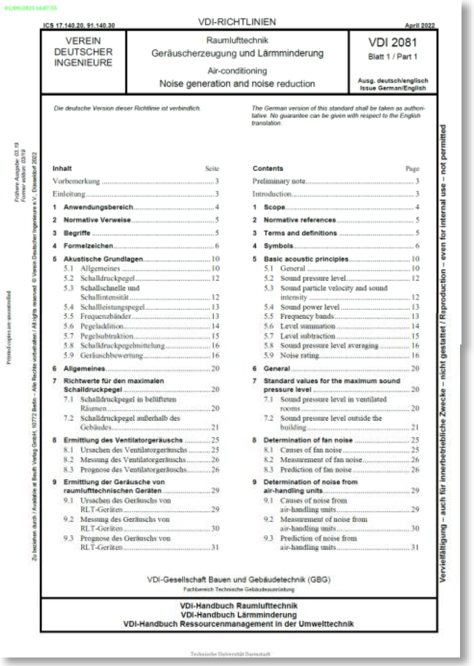
Noise Control in Fan Systems | Air Flow + Noise|Model



measure for sound: sound power level

$$L = \log_{10}\left(\frac{P}{P_{\text{ref}}}\right) \text{dB}$$

The change is frequency dependent!



ICS 17.140.20, 91.140.30 — VDI-RICHTLINIEN — April 2022

VEREIN DEUTSCHER INGENIEURE	Raumlufttechnik Geräuscherzeugung und Lärmminderung Air-conditioning Noise generation and noise reduction	VDI 2081 Blatt 1 / Part 1 Ausg. deutsch/englisch Issue German/English

Die deutsche Version dieser Richtlinie ist verbindlich.

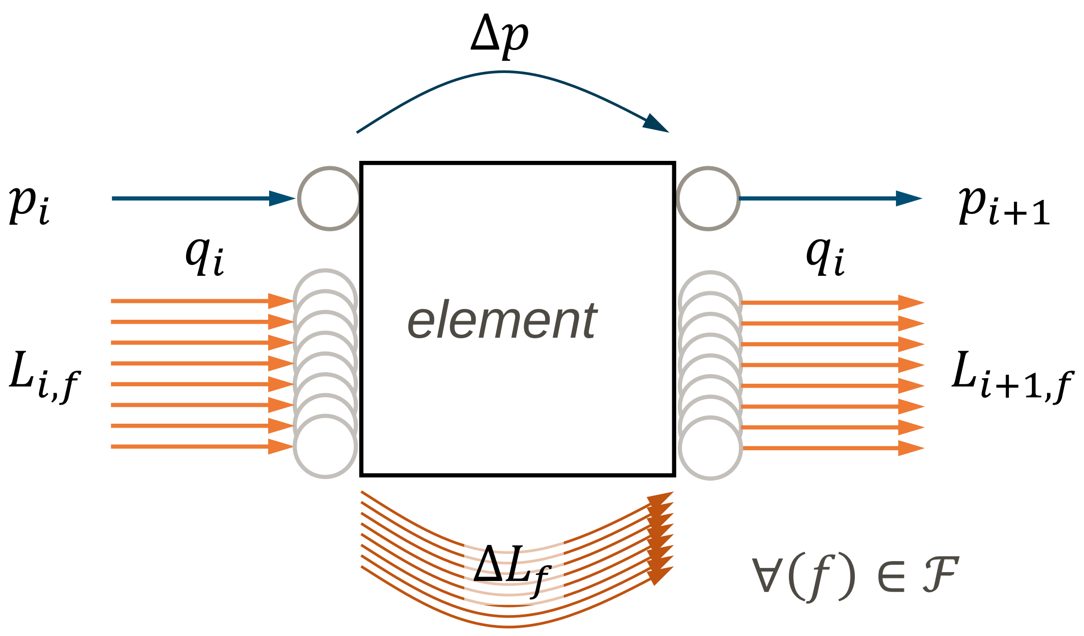
The German version of this standard shall be taken as authoritative. No guarantee can be given with respect to the English translation.

VDI-Gesellschaft Bauen und Gebäudetechnik (GBG)
Fachbereich Technische Gebäudeausrüstung

VDI-Handbuch Raumlufttechnik
VDI-Handbuch Lärmminderung
VDI-Handbuch Ressourcenmanagement in der Umwelttechnik

VDI 2081

Noise Control in Fan Systems | Air Flow + Noise|Model



$\forall(f) \in \mathcal{F}$

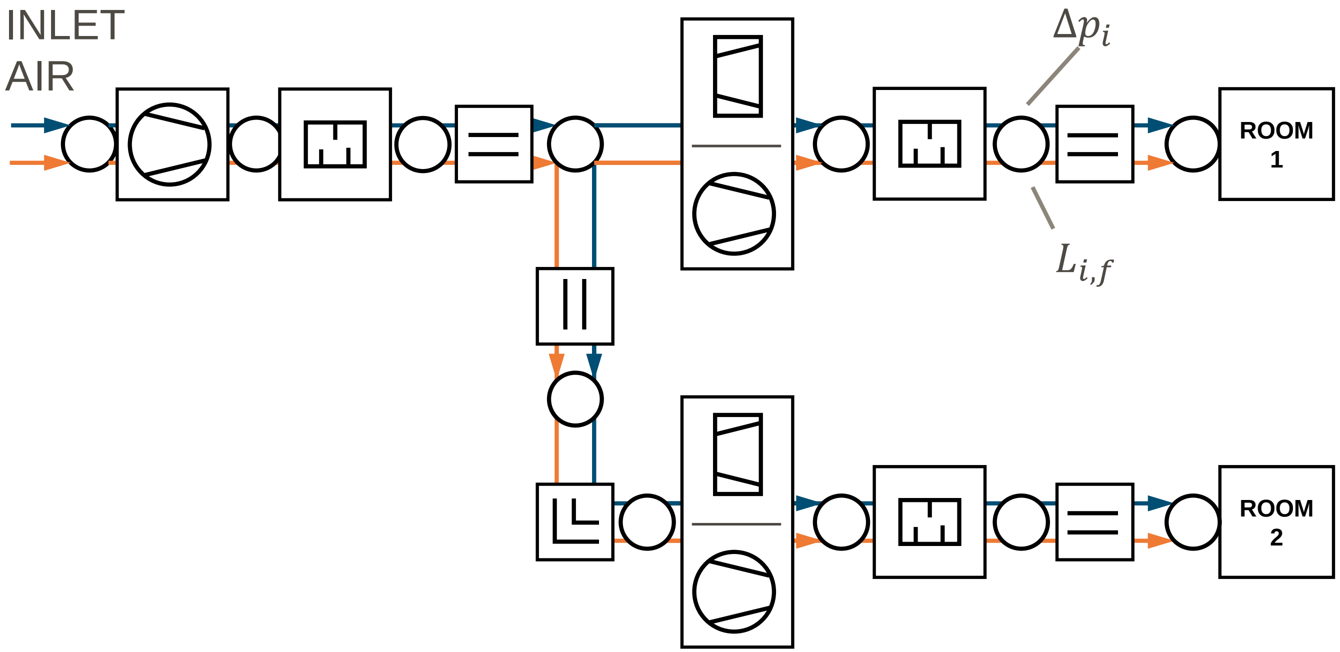
sound power level change in each element:

dampening *flow noise*

$$L_{i+1,f} = \left(L_{i,f} - D_{i,f}\right) \widetilde{\mp}\, L_{\mathrm{flow},i,f}$$

level addition

Noise Control in Fan Systems | Air Flow + Noise|Model



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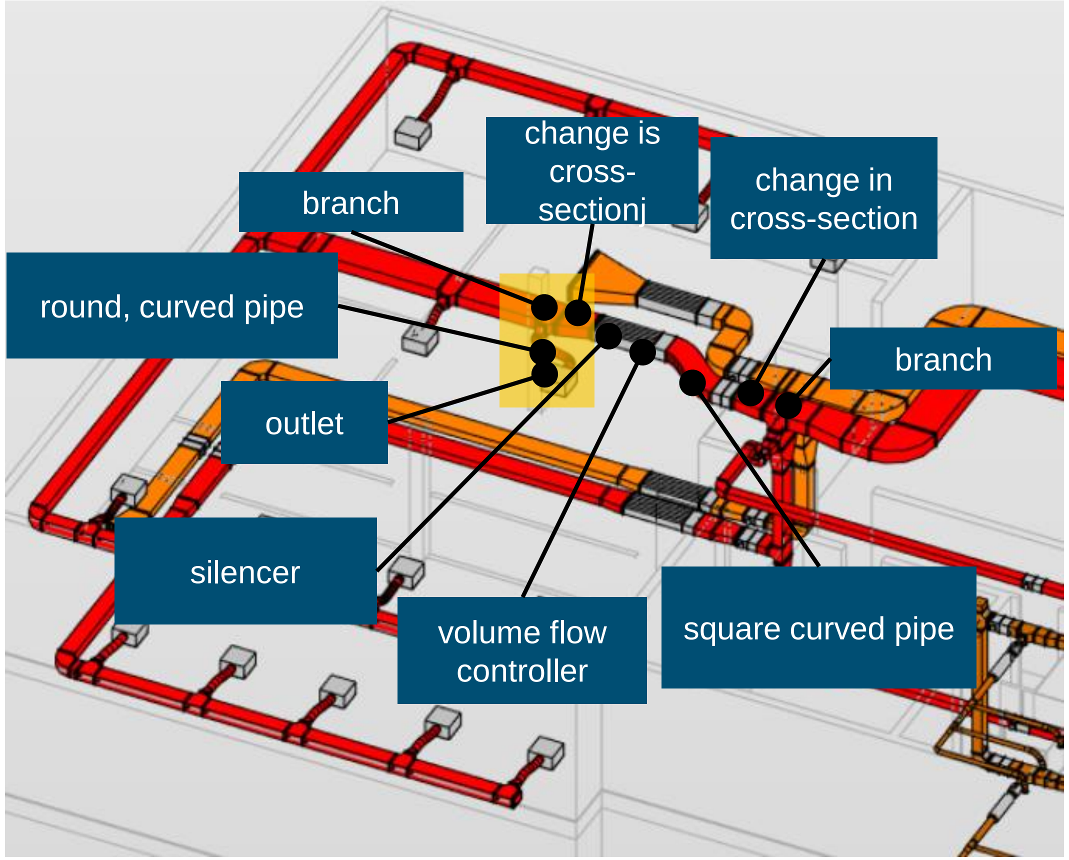
- ***NOISE LIMITS!***

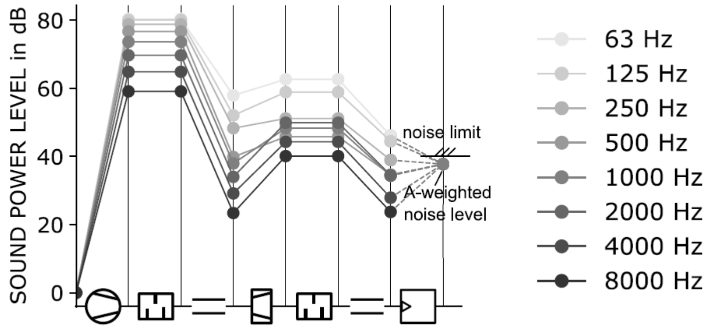
Noise Control in Fan Systems | Air Flow + Noise|Model

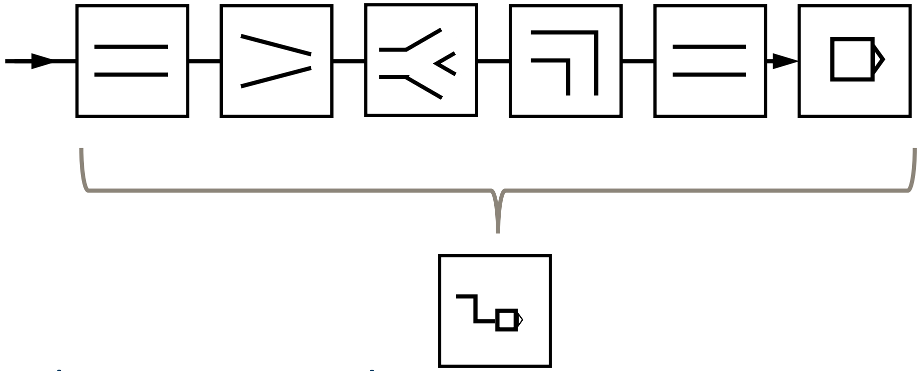


Computation following VDI 2081 / Manufacturer

→ Many **fixed parts**, whose placement are not part of optimization process.

→ Can be summarized together.





The behaviour of fixed component clusters can be precomputed.

Noise Control in Fan Systems | Air Flow + Noise|Model

Next step

- determine damping and flow noise of each component (e.g. following VDI 2081)
- Compute the resulting damping and noise levels in flow direction

$$\hat{L}_{\mathrm{flow},f,i} = L_{\mathrm{flow},f,i} - \sum_{j=i+1}^{\mathcal{B}} D_{f,j}$$

$$L_{\mathrm{flow,total},f} = \tilde{\mp} \sum_{i}^{\mathcal{B}} \hat{L}_{\mathrm{flow},f,i}$$

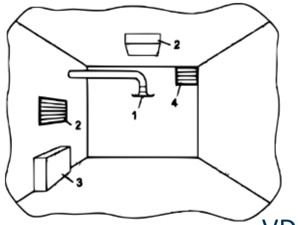
$$D_{\mathrm{total},f} = \sum_{i}^{\mathcal{B}} D_{f,i}$$

$\mathcal{B}$: set of components, sequqnced in flow direction

Volume flow controler

Wildeboer

room



VDI 2081

silencer (baffle-, pipe-)

TROX

ventilator

EBM-papst

Fixed components

KM Blechwarenfabrik

Noise Control in Fan Systems | Air Flow + Noise|Model

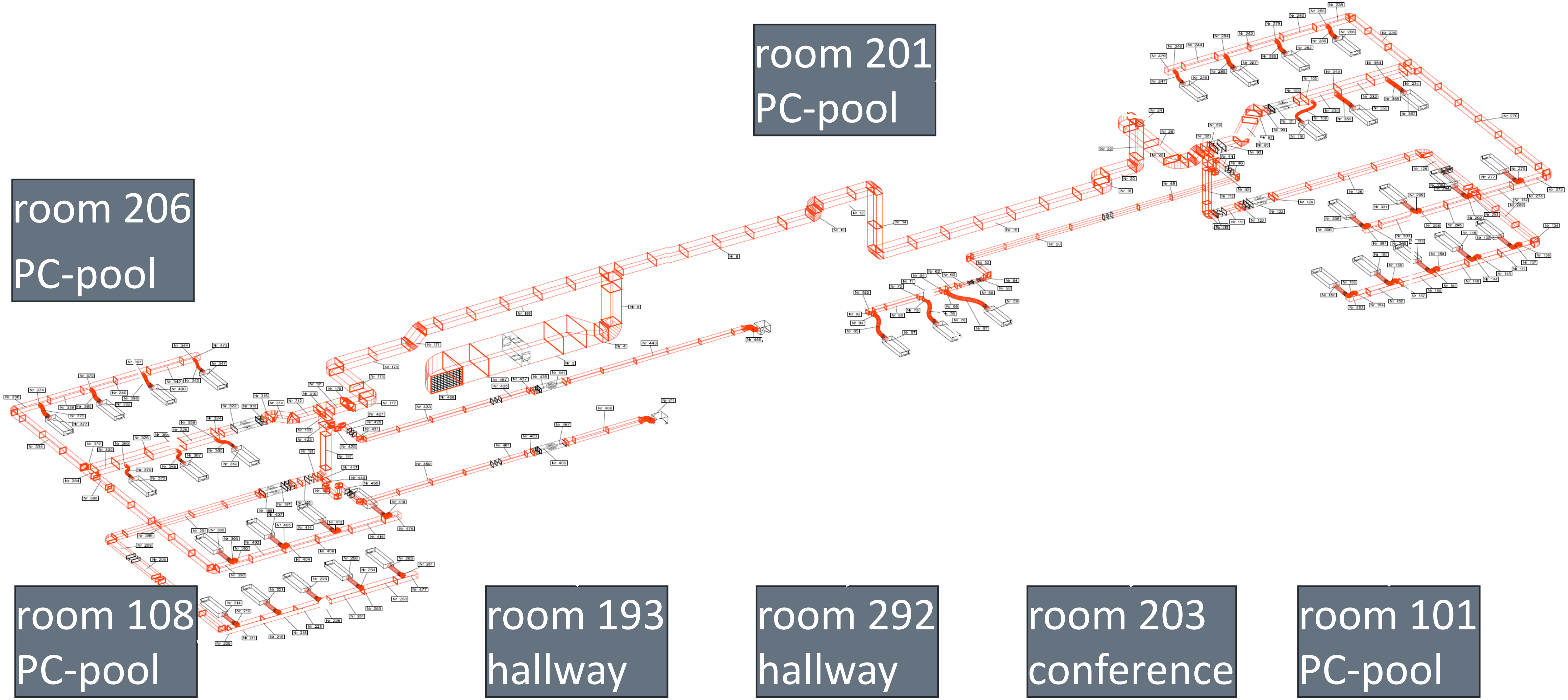
Example equations for component model for fan

Variable	*Model equation*
Pressure increase	$\Delta p(q,n,d) = \alpha_1 q^2 + \alpha_2 qn + \alpha_3 n^2$
	$P_{el}(q,n,d) = \beta_1 q^3 + \beta_2 q^2 n + \beta_3 qn^2 + \beta_4 n^3 + \beta_5$
Costs	$c = \gamma_1 d + \gamma_2 + \gamma_3(\text{sound isolation})$
Noise reduction	$D_{i,f} = 0$
Flow noise	$L_{\text{flow},i,f}(q,n,d,\Delta p) = \delta_1 n^2 + \delta_2 n + \delta_3 d + \delta_4 + 10\log_{10}(q^+ \cdot q_{\max}) + 20\log_{10}(\Delta p^+ \cdot \Delta p_{\max})$

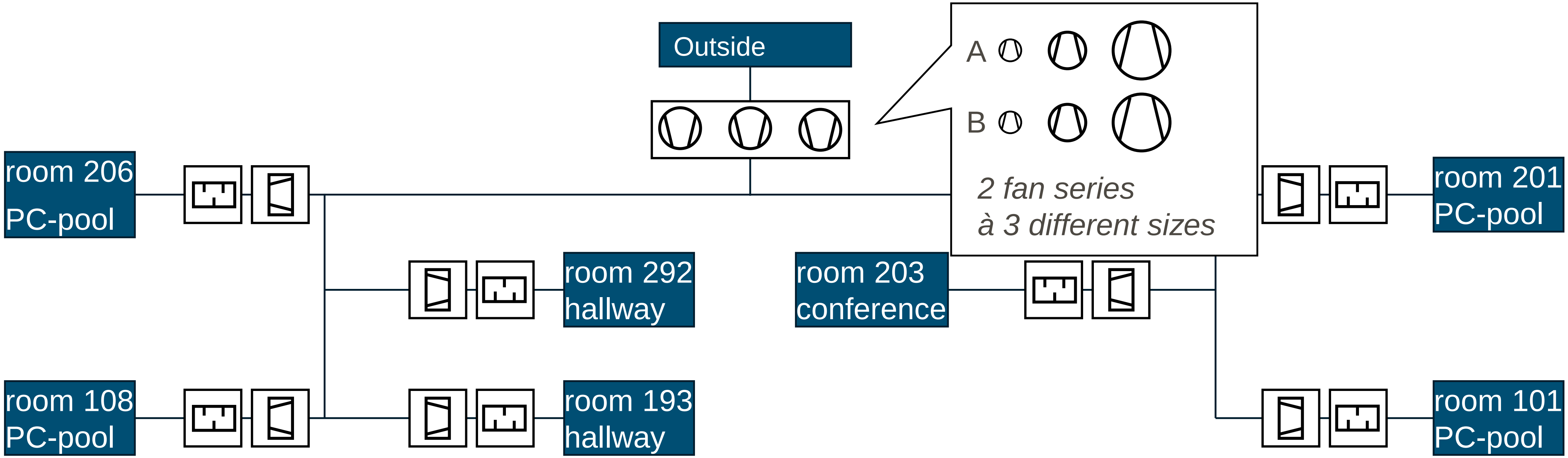
Better:

Create characteristic fields

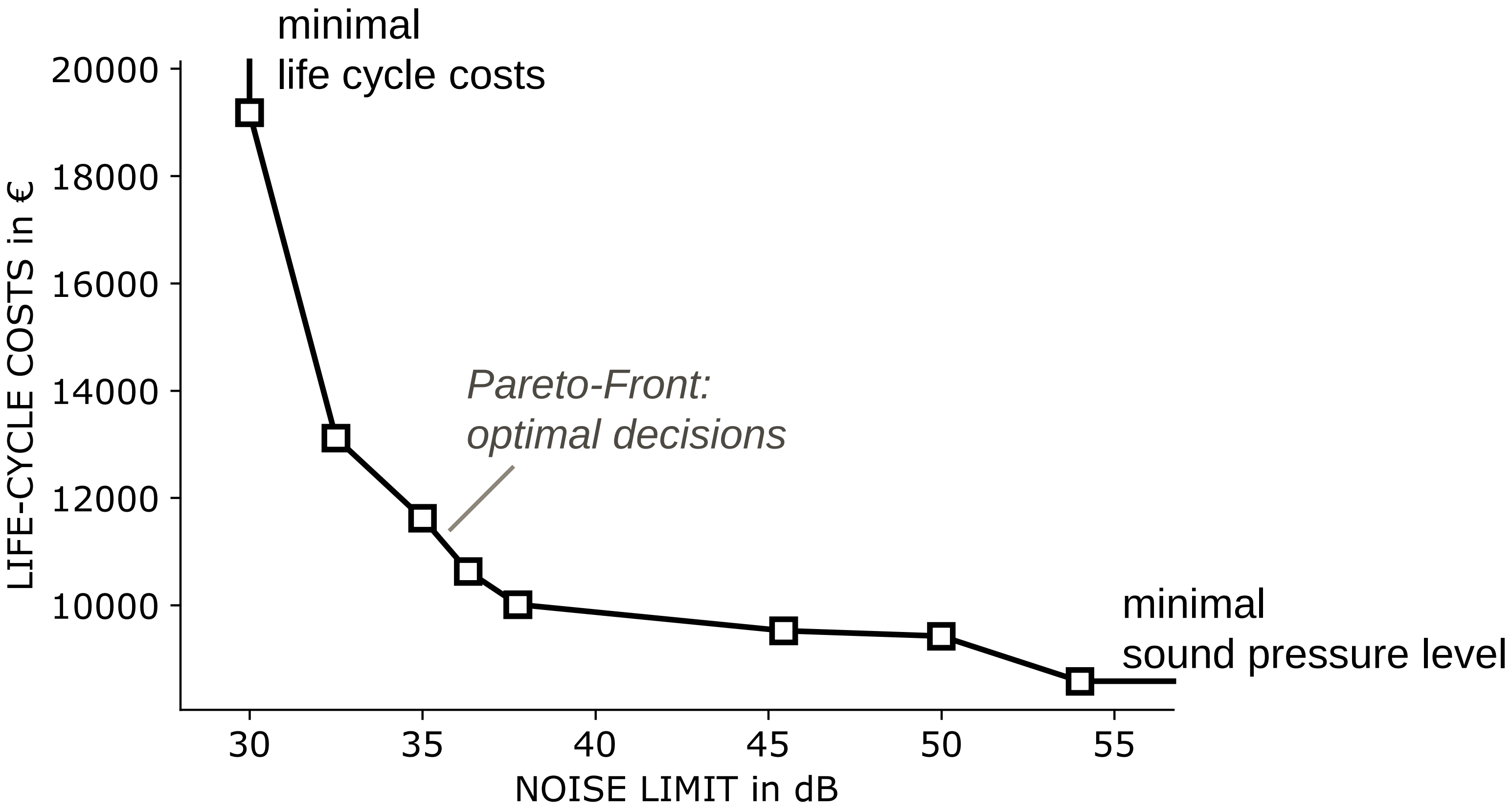
Noise Control in Fan Systems | Air Flow + Noise|Case Study



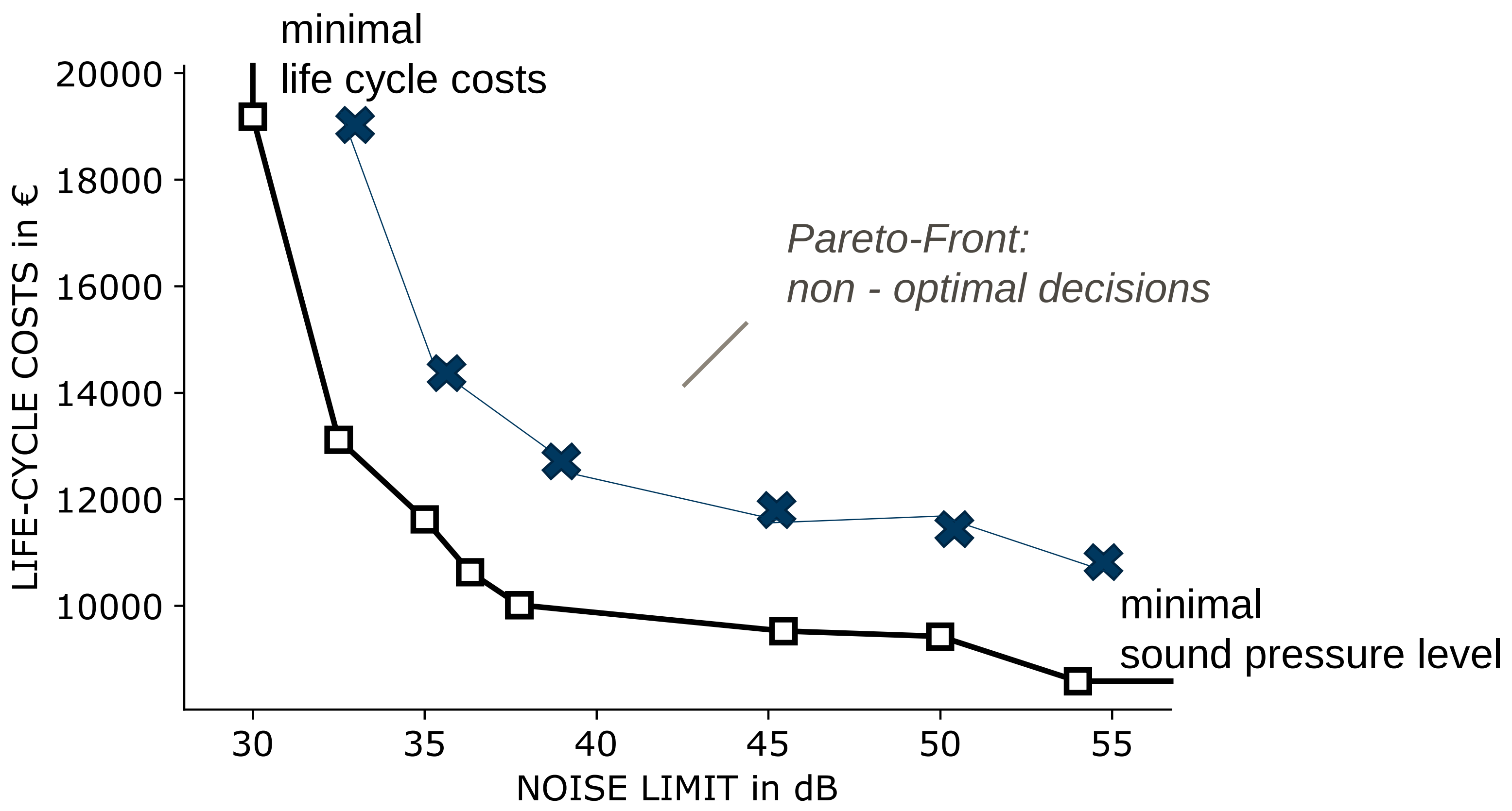
Noise Control in Fan Systems | Air Flow + Noise|Case Study



Noise Control in Fan Systems | Air Flow + Noise|Case Study



Noise Control in Fan Systems | Air Flow + Noise|Case Study

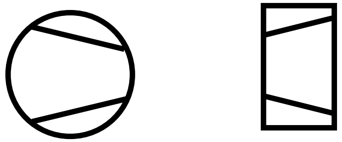


Noise Control in Fan Systems | Air Flow + Noise|Case Study

Step 1:

Choice, placement and operation

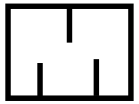
of



Step 2:

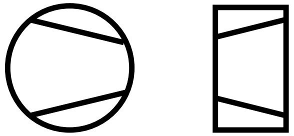
Auswahl und Platzierung

of



operations

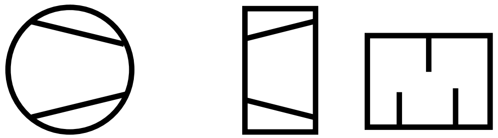
of



SEQUENTIAL

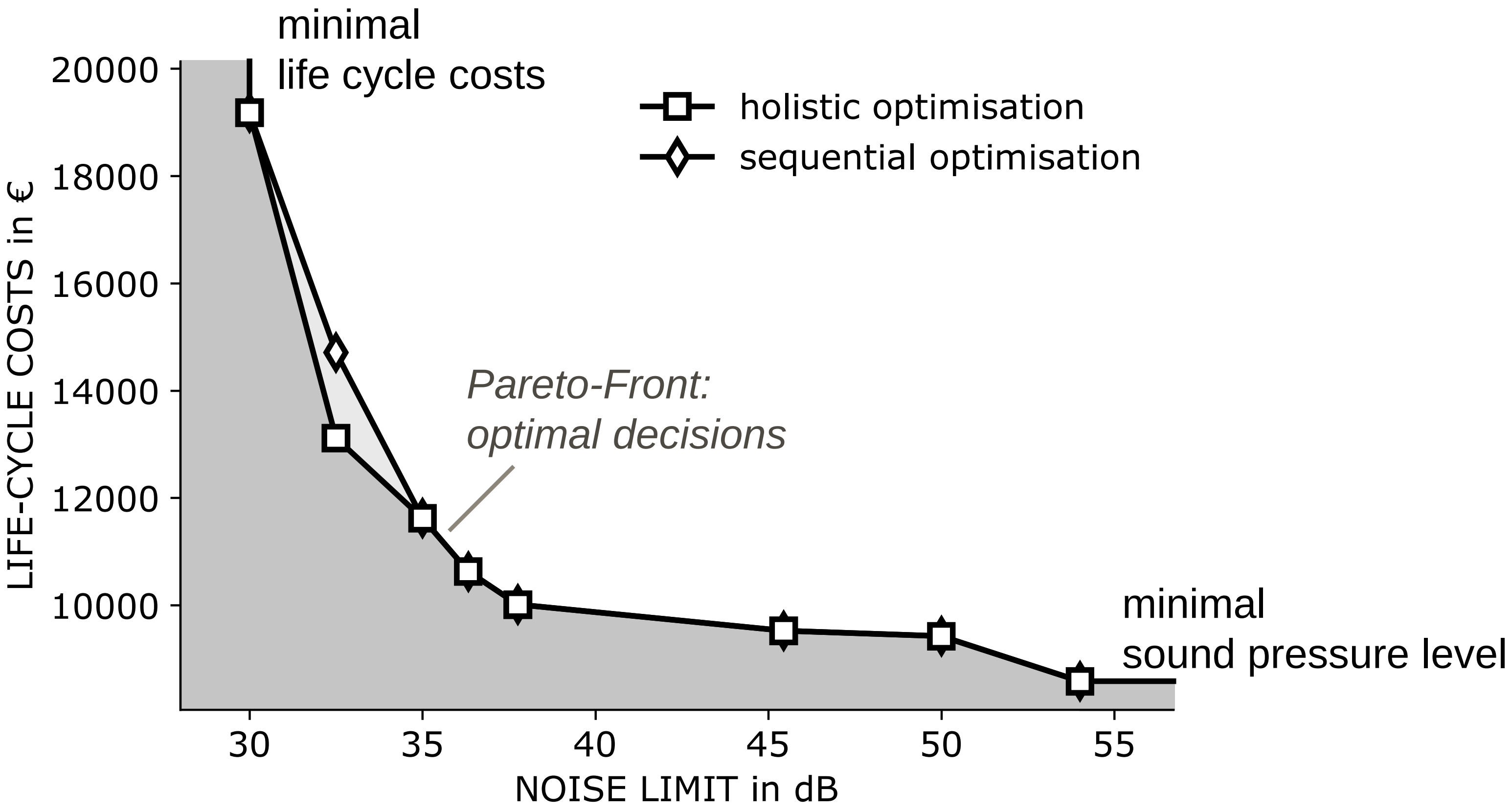
Planning in stages

In one step:
choice, placemant and operation



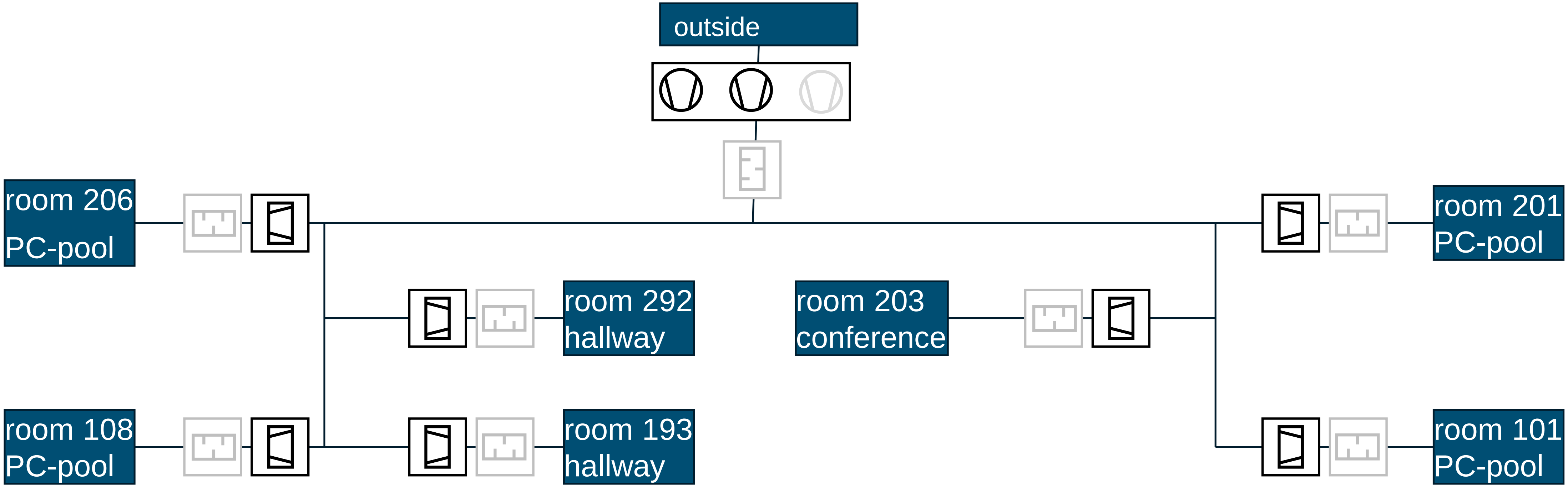
HOLISTIC

Noise Control in Fan Systems | Air Flow + Noise|Case Study



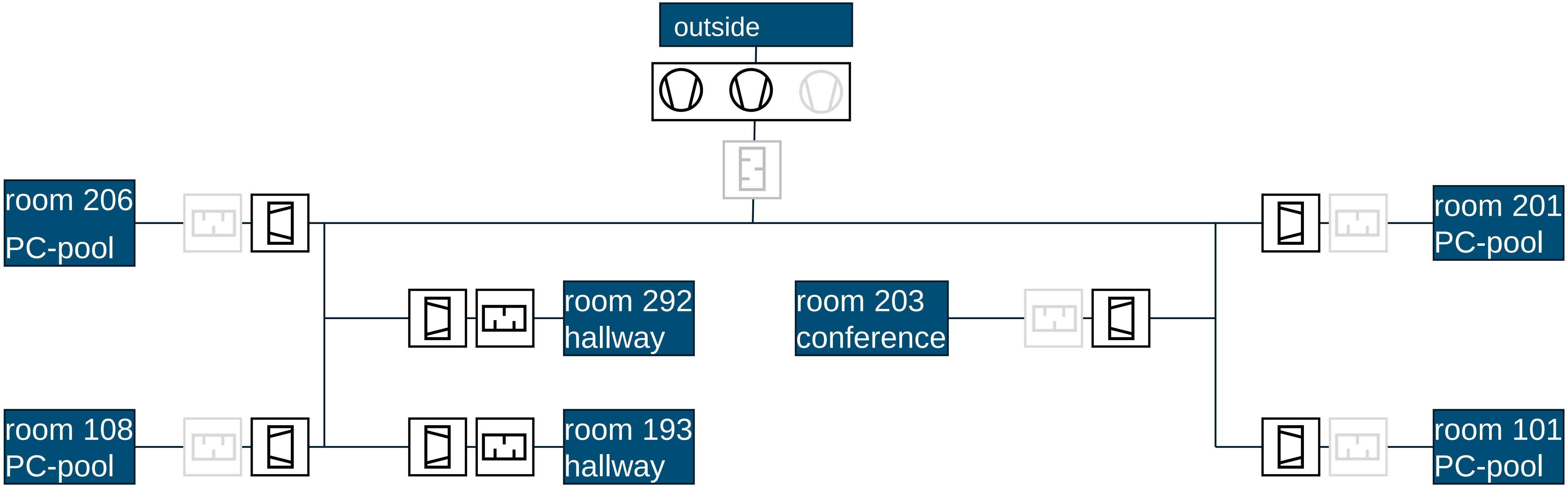
Noise Control in Fan Systems | Air Flow + Noise|Case Study

Solution without acoustics



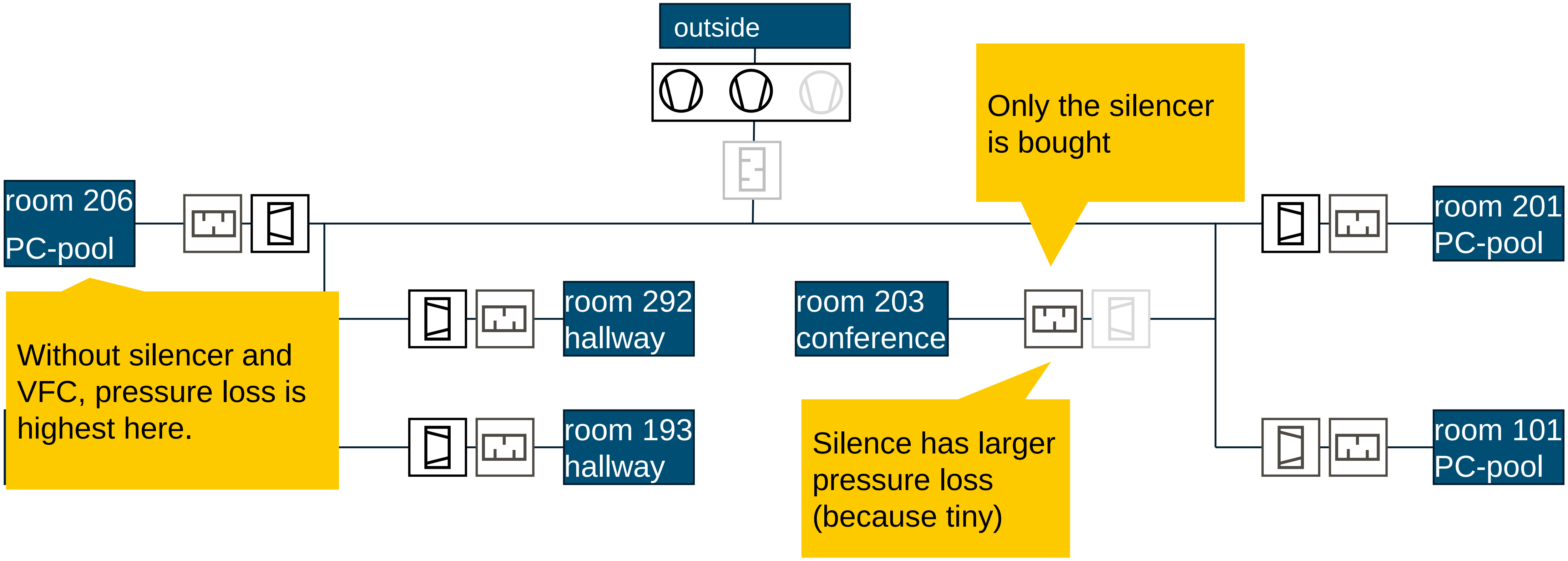
Noise Control in Fan Systems | Air Flow + Noise|Case Study

Solution with real sound pressure level



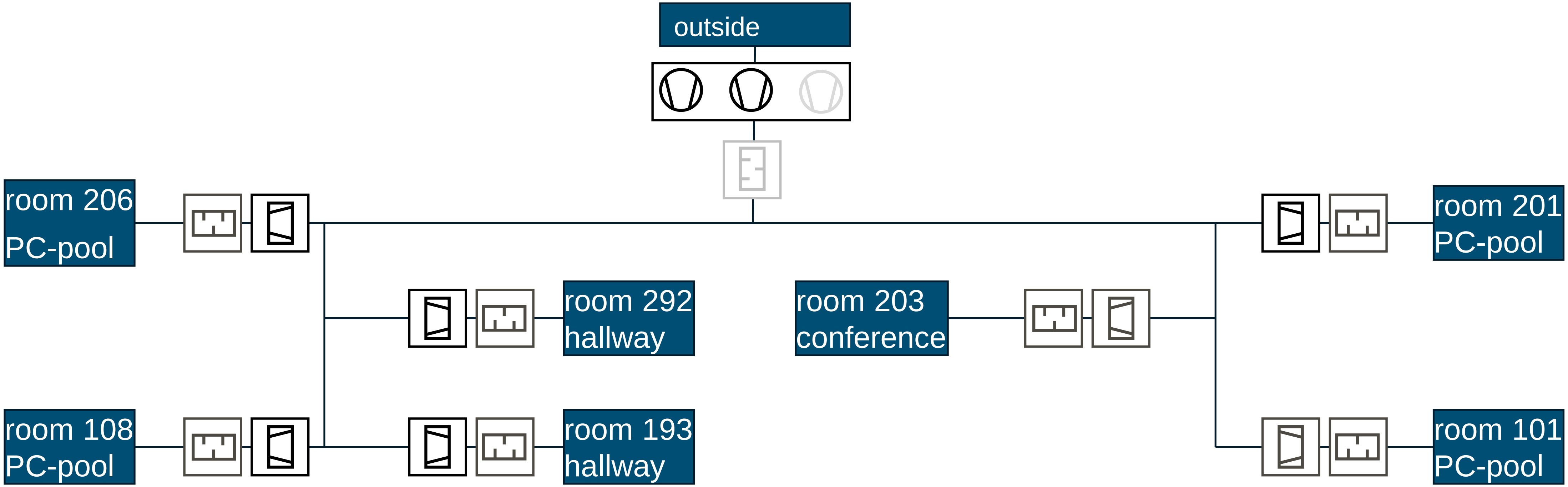
Noise Control in Fan Systems | Air Flow + Noise|Case Study

Lösung mit $L_{p,A} = 35$ dB



Noise Control in Fan Systems | Air Flow + Noise | Case Study

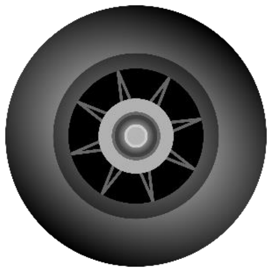
Solution with $L_{p,A} = 30$ dB



What are we Really Doing? And why?

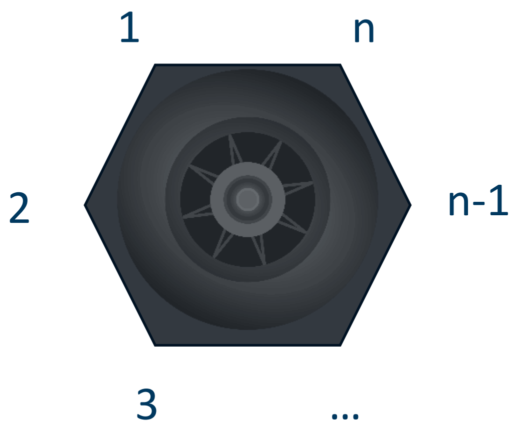
Changing Flight Height: What are we really doing? And why?

1. A **customer** wants a **wheel**.



2. **I sell him a wheel.**

3. Some „optimizer“ comes to me and says:
   „Oh no,no, no. I have doubts. I do not believe that he wants what you deliver.
   Let us formalize an optimizeation problem. Let‘s assume we have an n-gon**. We can then optimize the number of vertices for best roll-behavior!“**



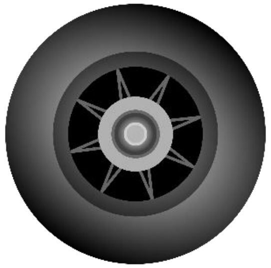
Isn‘t that a bit … stupid?

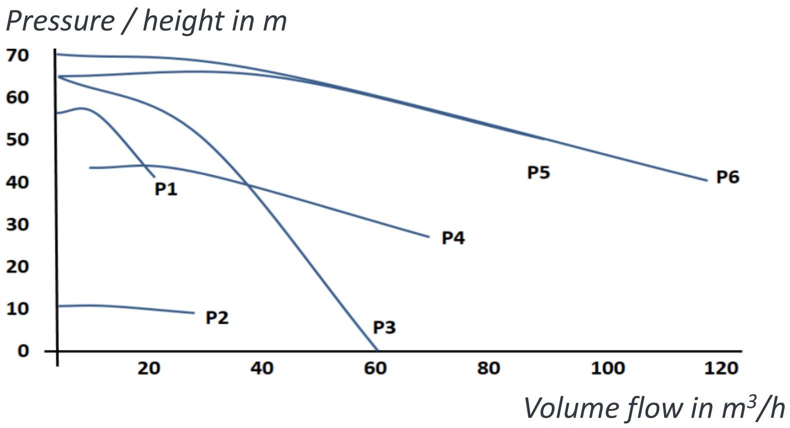
Changing Flight Height: What are we really doing? And why?

1. From certain point of view: my collegue had a point.

2. A) wheel example: stupid

2. B) booster station example: smart





Changing Flight Height: What are we really doing? And why?

1. Let us find a border line with the help of a third example.

A **brilliant engineer** and **artist** builds an **Eiffel tower**

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- ➢ World famous
- ➢ Is stable for more than 130 years

– **Algorithmic support not useful**

Selection of example:

- We are in France ☺
- Shows proximity to FEM better than fluidsystem.

Changing Flight Height: What are we really doing? And why?

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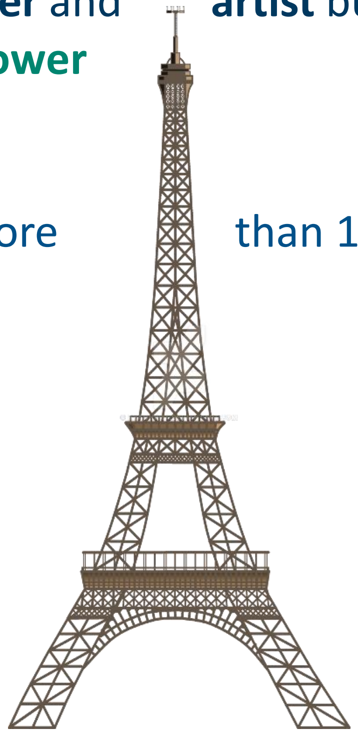

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A **bit other situation, however, may change this assessment.**

- **What if the artist is no brilliant engineer?**
- **What if the material resouces are limited, but people want or need a tower as high as possible?**
- **Or they want a comparable tower with less steel?**

Changing Flight Height: What are we really doing? And why?

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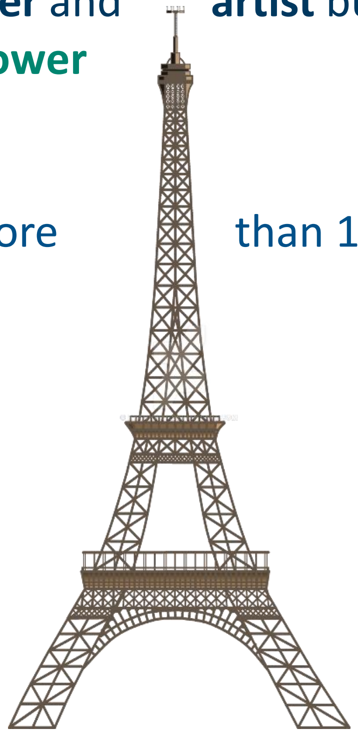

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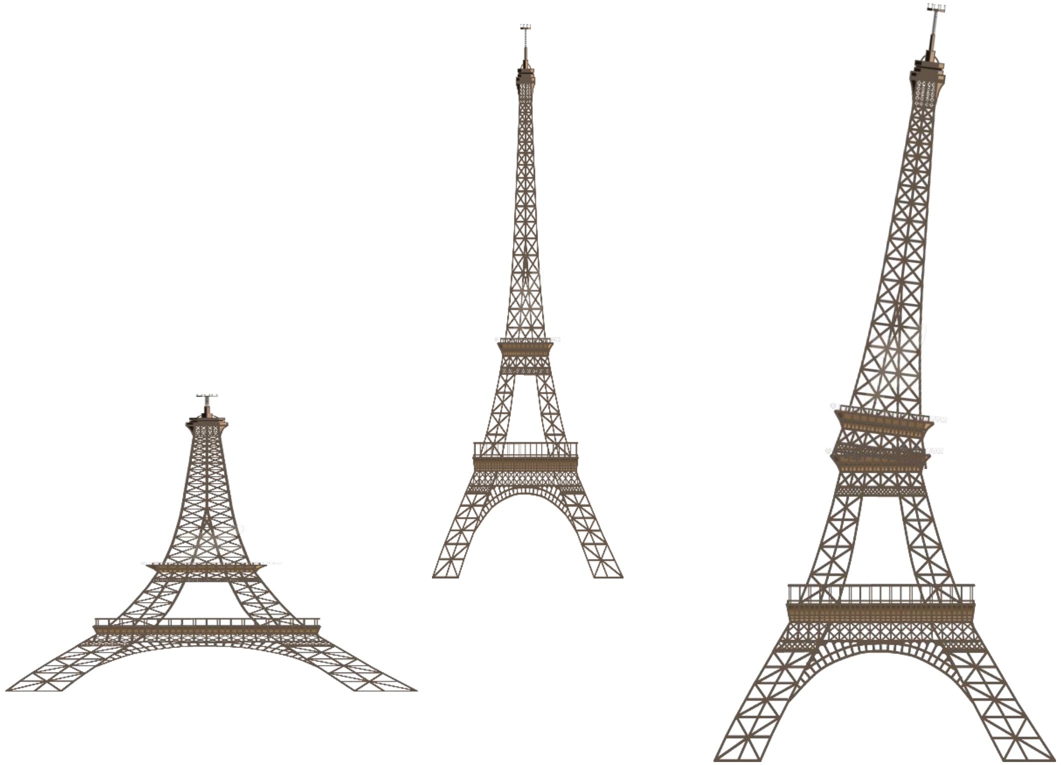
There are nearly no opportunities for experiments. Experiences are missing and very difficult to gather.



Changing Flight Height: What are we really doing? And why?

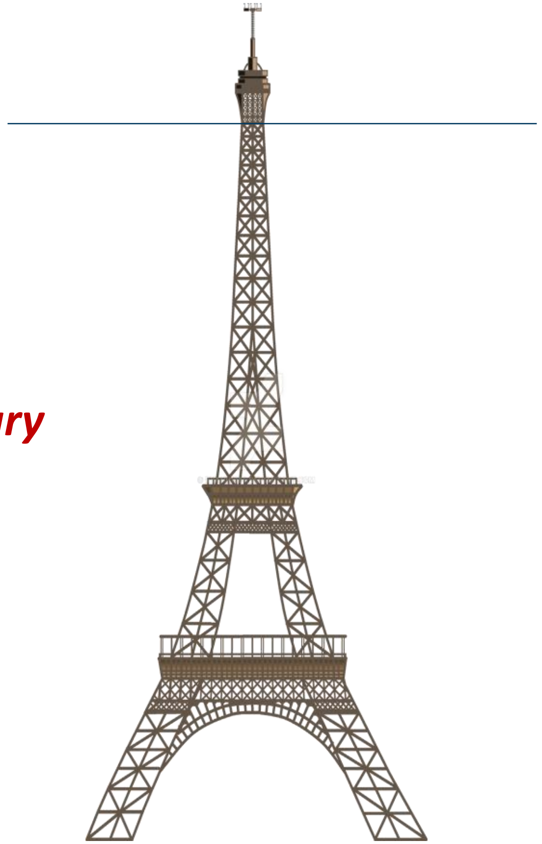
1. Let us find a border line with the help of a third example.

Task description

What do we want to get?

$$
\begin{aligned}
\sum_{(i,v)\in E} q^E_{s,i,v} &= q^V_{s,v} && \forall s \in S, v \in V : v \neq v_s \\
q^V_{s,v} &= \sum_{(i,v)\in E} q^E_{s,i,v} && \forall s \in S, v \in V : v \neq v_t \\
h^{V-}_{s,i} - h^{V+}_{s,i} &\leq 2h^{S+}_s \cdot (1 - x^E_{s,i,j}) && \forall s \in S, (i,j) \in E \\
h^{V+}_{s,i} - h^{V-}_{s,i} &\leq 2h^{S+}_s \cdot (1 - x^E_{s,i,j}) && \forall s \in S, (i,j) \in E \\
h^{V+}_{s,v} + h^V_{s,v} &= h^{V-}_{s,v} && \forall s \in S, v \in V \\
\sum_{(p,l)\in K^{(2D)}:(p,l+1)\in K^{(2D)}} k^z_{s,p,l} &= 1 && \forall s \in S, p \in P^{(2D)} \\
k^s_{s,p,l} &\leq k^z_{s,p,l} && \forall s \in S, (p,l) \in K^{(2D)} : (p,l+1) \in K^{(2D)} \\
q^V_{s,p} &= \sum_{(p,l)\in K^{(2D)}} k^q_{p,l} \cdot k^z_{s,p,l} + (k^q_{p,l+1} - k^q_{p,l}) \cdot k^s_{s,p,l} && \forall s \in S, p \in P^{(2D)} \\
h^V_{s,p} &= \sum_{(p,l)\in K^{(2D)}} k^h_{p,l} \cdot k^z_{s,p,l} + (k^h_{p,l+1} - k^h_{p,l}) \cdot k^s_{s,p,l} && \forall s \in S, p \in P^{(2D)} \\
p^V_{s,p} &= \sum_{(p,l)\in K^{(2D)}} k^p_{p,l} \cdot k^z_{s,p,l} + (k^p_{p,l+1} - k^p_{p,l}) \cdot k^s_{s,p,l} && \forall s \in S, p \in P^{(2D)} \\
n^V_{s,p} &= n^{(max)}_P && \forall s \in S, p \in P
\end{aligned}
$$

Algorithmic support *necessary*



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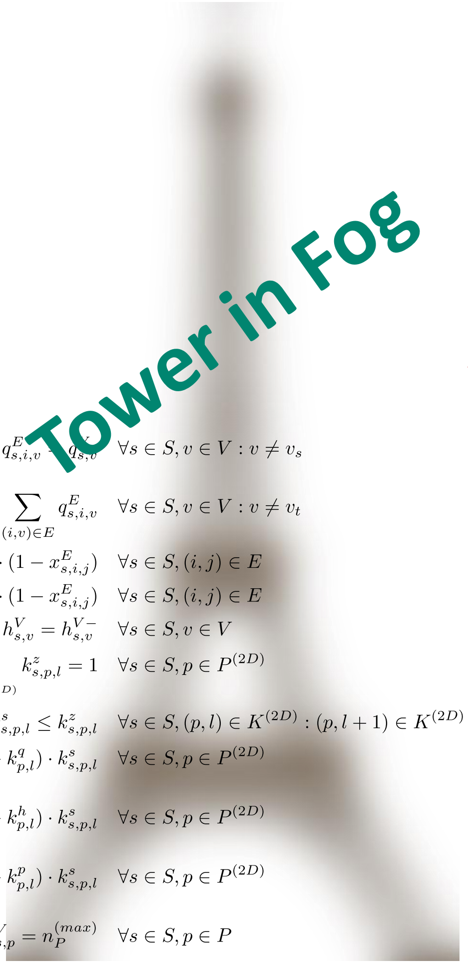

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$$q^V_{s,v} = \sum_{(i,v)\in E} q^E_{s,i,v} \quad \forall s \in S, v \in V : v \neq v_t$$

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$$h^{V+}_{s,i} - h^{V-}_{s,i} \leq 2h^{S+}_s \cdot (1 - x^E_{s,i,j}) \quad \forall s \in S, (i,j) \in E$$

$$h^{V+}_{s,v} + h^V_{s,v} = h^{V-}_{s,v} \quad \forall s \in S, v \in V$$

$$\sum_{(p,l)\in K^{(2D)}:(p,l+1)\in K^{(2D)}} k^z_{s,p,l} = 1 \quad \forall s \in S, p \in P^{(2D)}$$

$$k^s_{s,p,l} \leq k^z_{s,p,l} \quad \forall s \in S, (p,l) \in K^{(2D)} : (p,l+1) \in K^{(2D)}$$

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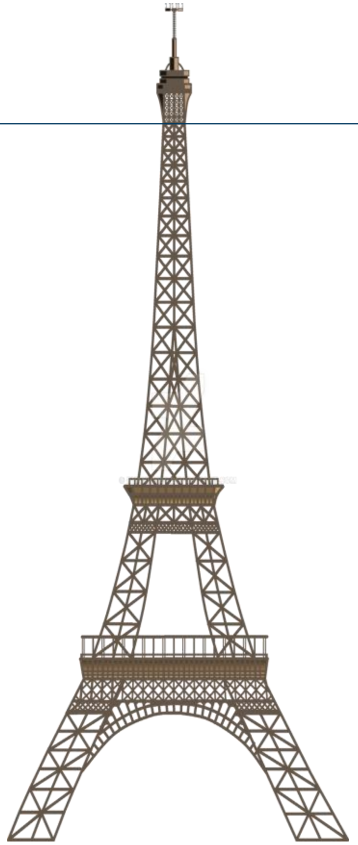
$$p^V_{s,p} = \sum_{(p,l)\in K^{(2D)}} k^p_{p,l} \cdot k^z_{s,p,l} + (k^p_{p,l+1} - k^p_{p,l}) \cdot k^s_{s,p,l} \quad \forall s \in S, p \in P^{(2D)}$$

$$n^V_{s,p} = n^{(max)}_P \quad \forall s \in S, p \in P$$

Algorithmic support *necessary*



Some Literature to Technical Operations Research Methodology

J. H. Breuer and P. F. Pelz (2024). Algorithmic planning of ventilation systems: Optimising for life-cycle costs and acoustic comfort. *Journal of Building Engineering*.

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This was a talk about

Technical Operations Research

Thank you
for your
attention!