Analysing Optimisation Data for Multicriteria Building Spatial Design

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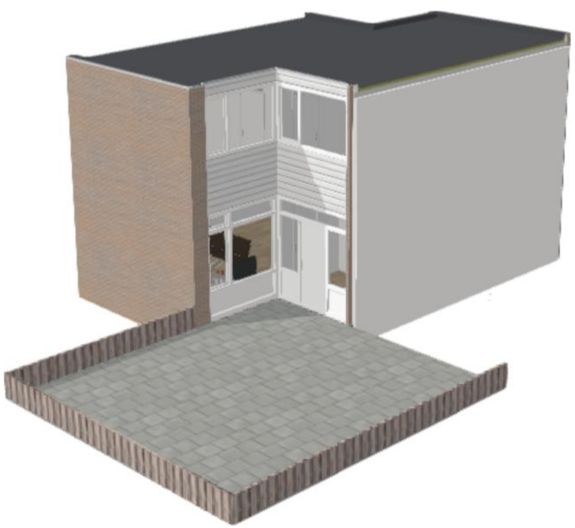
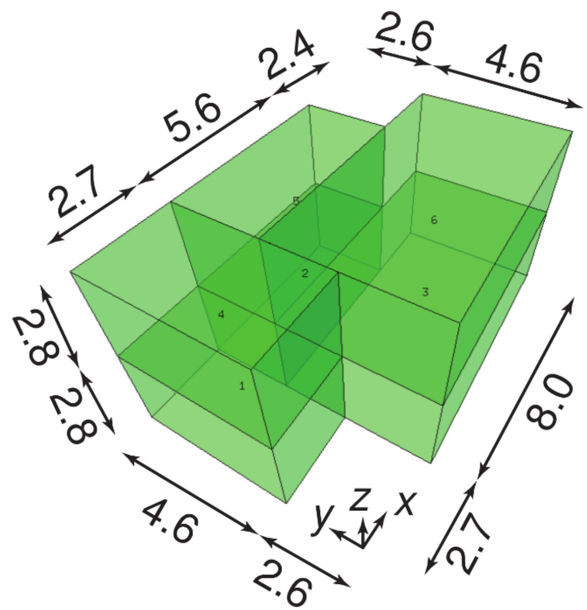
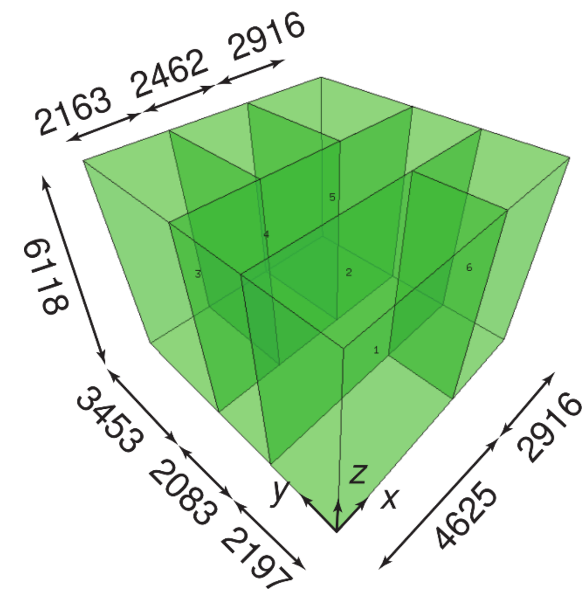
Building spatial design

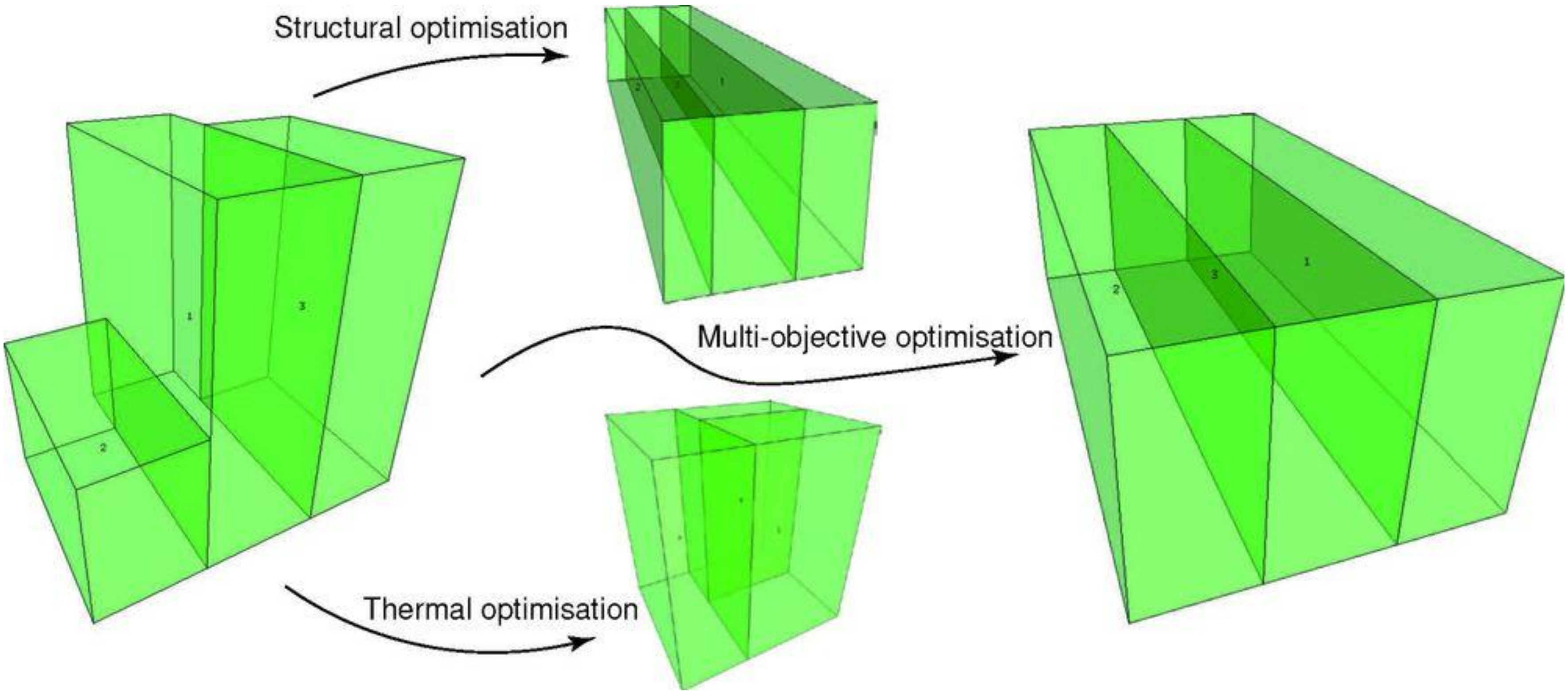
- Shape of a building
  - External
  - Internal







Conflicting disciplines

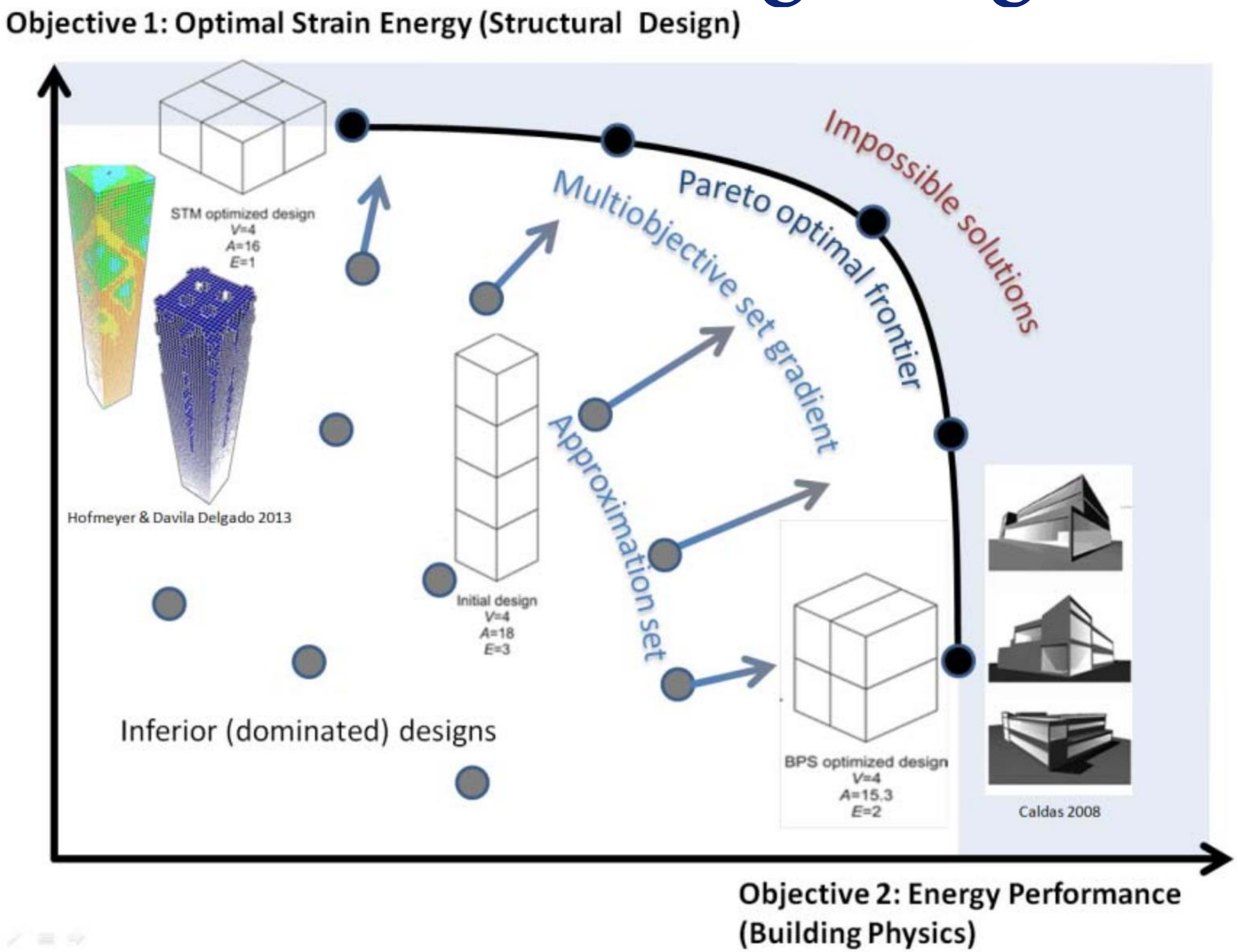


Objectives

- Structural performance
  - Sum of strain energy over all walls and ceilings
  - FEM simulation

- Thermal performance
  - Total heating and cooling energy used
  - Resistor-capacitator network simulation

Pareto based building design



Problem representation

$$i \in \{1,2,\ldots,N_w\} \qquad w_i \in \mathbb{R}$$

$$j \in \{1,2,\ldots,N_d\} \qquad d_j \in \mathbb{R}$$

$$k \in \{1,2,\ldots,N_h\} \qquad h_k \in \mathbb{R}$$

$$\ell \in \{1,2,\ldots,N_{spaces}\} \quad b^{\ell}_{i,j,k} = \begin{cases} 1, & \text{if } cell_{i,j,k} \in space_\ell \\ 0, & \text{otherwise} \end{cases}$$

$\mathbf{w}\{w_1, w_2, w_3, w_4\}$,

$\mathbf{d}\{d_1, d_2\}$, $\mathbf{h}\{h_1\}$,

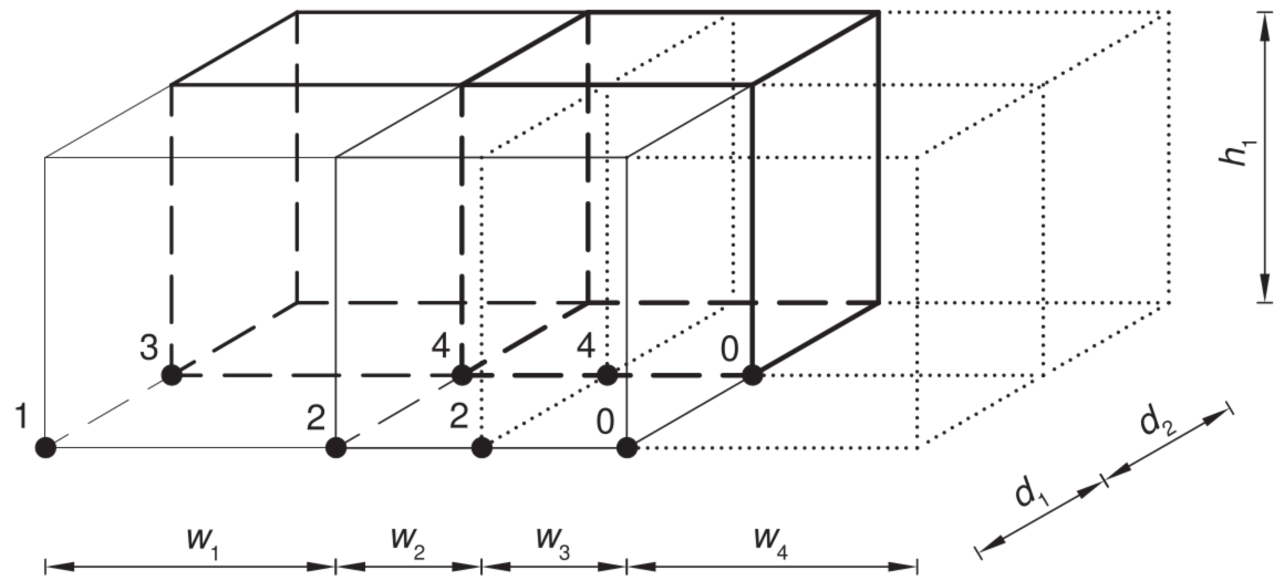
$\mathbf{b}\{\mathbf{b}^1, \mathbf{b}^2, \mathbf{b}^3, \mathbf{b}^4\}$

$\mathbf{b}^1\{1, 0, 0, 0, 0, 0, 0, 0\}$,

$\mathbf{b}^2\{0, 0, 1, 0, 1, 0, 0, 0\}$,

$\mathbf{b}^3\{0, 1, 0, 0, 0, 0, 0, 0\}$,

$\mathbf{b}^4\{0, 0, 0, 1, 0, 1, 0, 0\}$

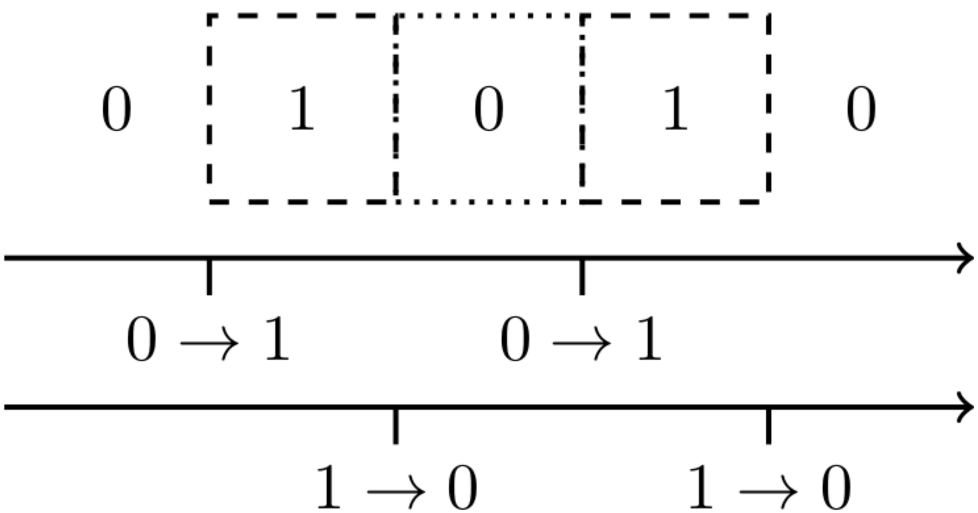


Constraints (example)

- Cuboid (3D rectangle) rooms

$$\forall_\ell : \forall_{i,j,k} \in \{0,\ldots,N_w+1\} \times \{0,\ldots,N_d+1\} \times \{0,\ldots,N_h+1\} :$$
$$i = 0 \lor j = 0 \lor k = 0 \lor i = N_w + 1 \lor j = N_d + 1 \lor k = N_h + 1 \Rightarrow b^\ell_{i,j,k} = 0$$

$$\forall_\ell : \forall_{i_1,j_1,i_2,j_2} : \left(\left(\sum_{k=1}^{N_h} k\left(1-b^\ell_{i_1,j_1,k-1}\right)b^\ell_{i_1,j_1,k}\right) - \left(\sum_{k=1}^{N_h} k\left(1-b^\ell_{i_2,j_2,k-1}\right)b^\ell_{i_2,j_2,k}\right)\right)\left(\sum_{k=1}^{N_h} b^\ell_{i_1,j_1,k}\right)\left(\sum_{k=1}^{N_h} b^\ell_{i_2,j_2,k}\right) = 0$$



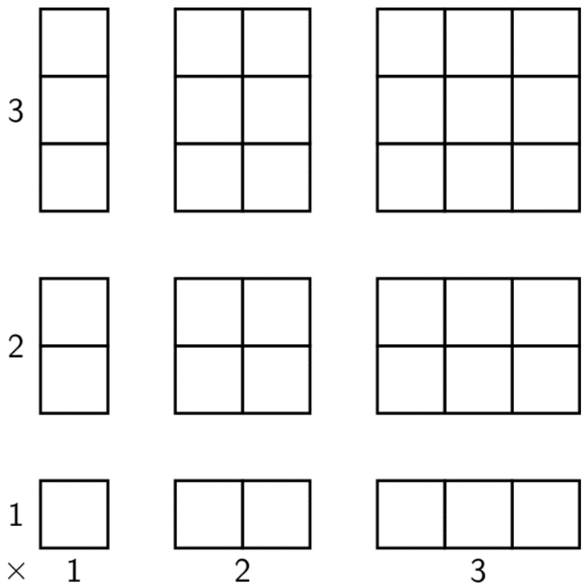
Constraints are challenging

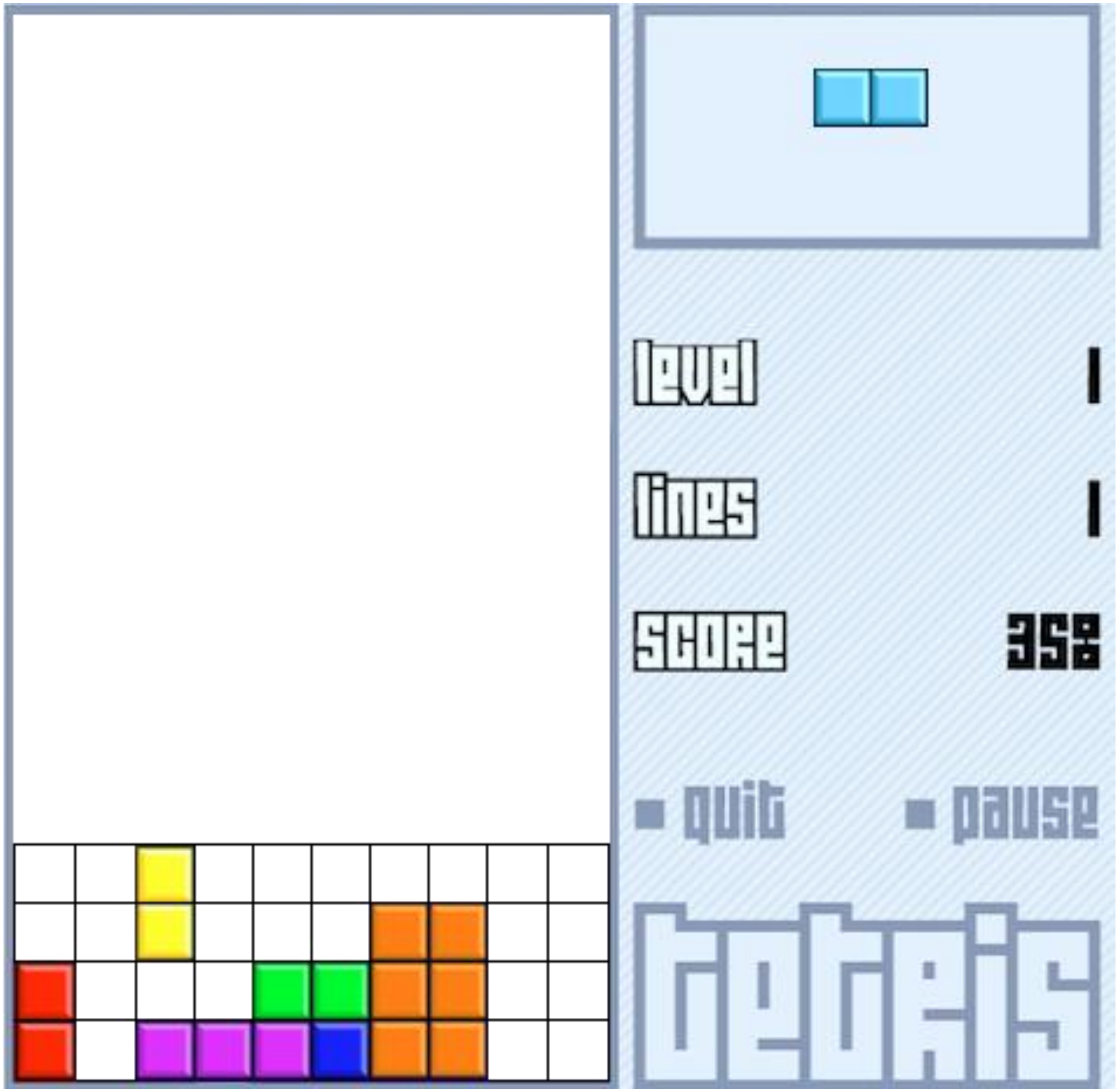
- Standard algorithms struggle

Config.	Non overlap	Ground connected	Existence	Cuboid shape	Connected cuboid
2221	N/A	0.365825317	0.058657830	0.444417496	N/A
2223	0.360701373	0.370035639	0.140828056	0.515696088	N/A
2225	0.806357513	0.735303689	0.130767034	0.784227148	N/A
3331	N/A	0.502740860	0.017993546	0.587753423	0.115546192
3333	0.479018371	0.701397235	0.054896992	0.755925962	0.481095119
3335	0.999327413	0.999974401	0.816441071	0.999885802	0.998834023

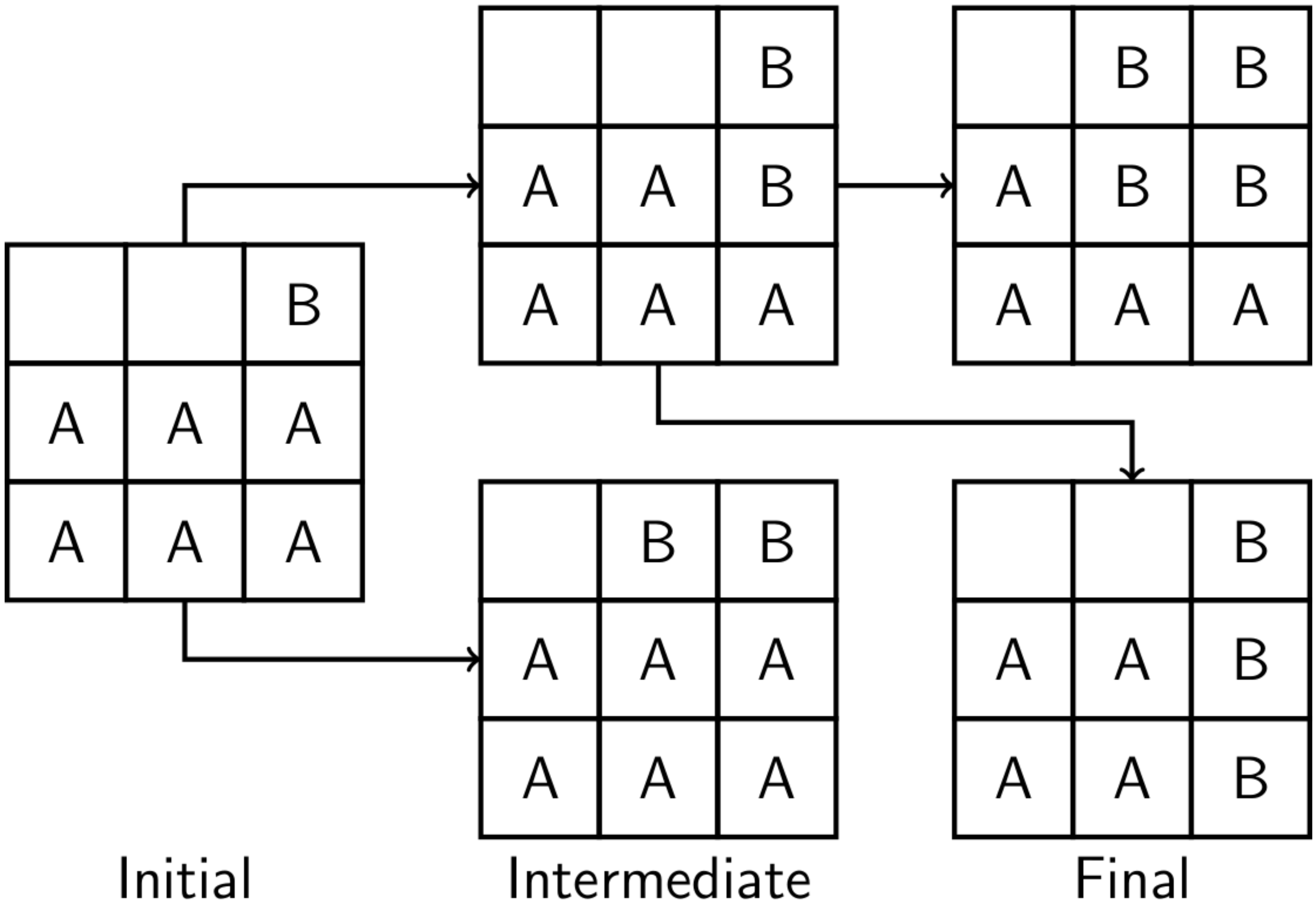
Config.	Non overlap	Ground connected	Existence	Cuboid shape	Connected cuboid
2221	N/A	0.294695023	0.065057210	0.449316221	N/A
2223	0.352604824	0.150746218	0.153169050	0.475316636	N/A
2225	0.527390468	0.389167427	0.285392221	0.455517944	N/A
3331	N/A	0.482476598	0.048915412	0.523626333	0.121148832
3333	0.130755993	0.477704137	0.144945542	0.573464583	0.106156523
3335	0.173648794	0.400757221	0.839106603	0.477907732	0.086331151

Specialised operators - initialisation

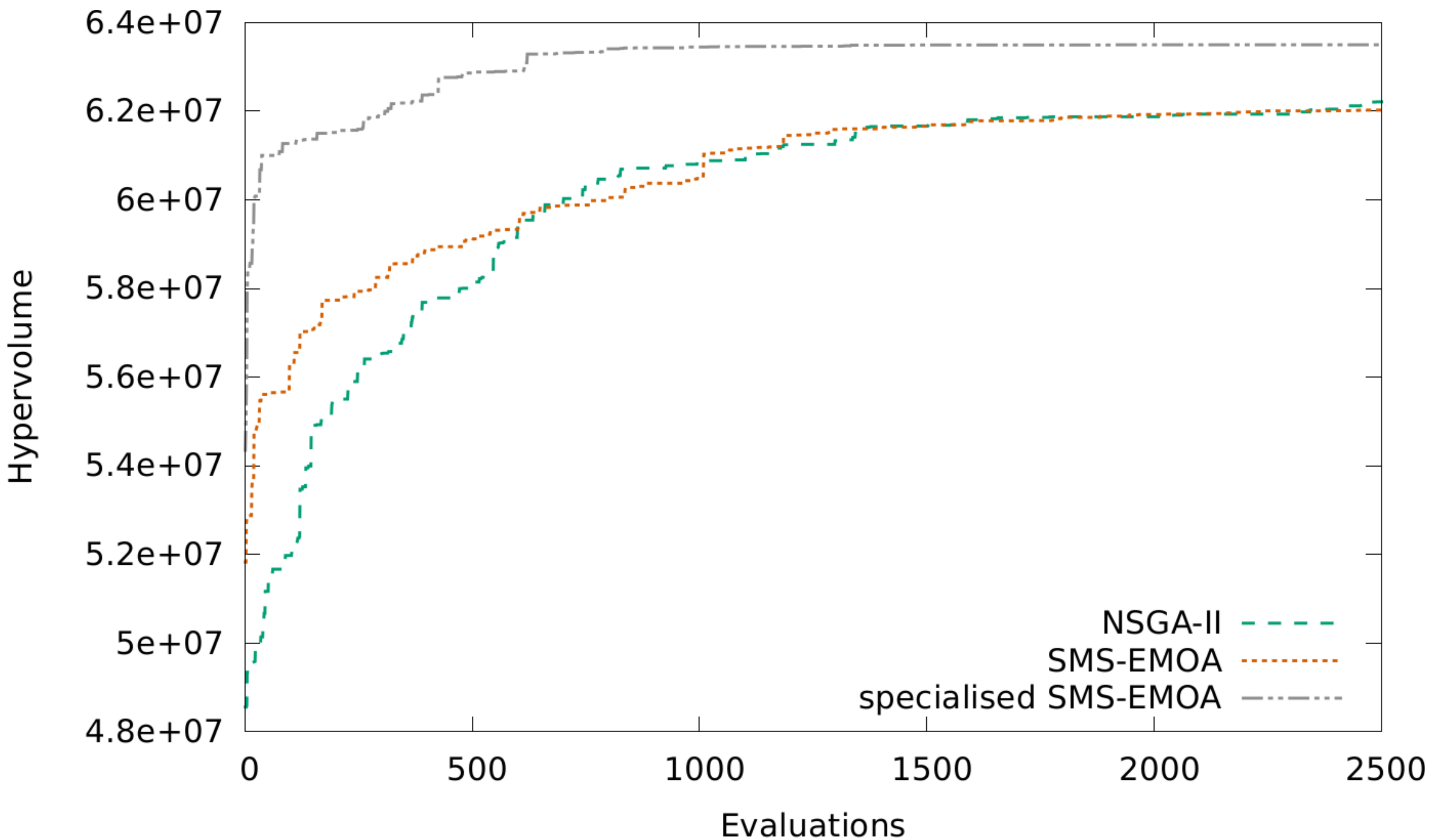




Specialised operators - mutation



Specialised operators are effective



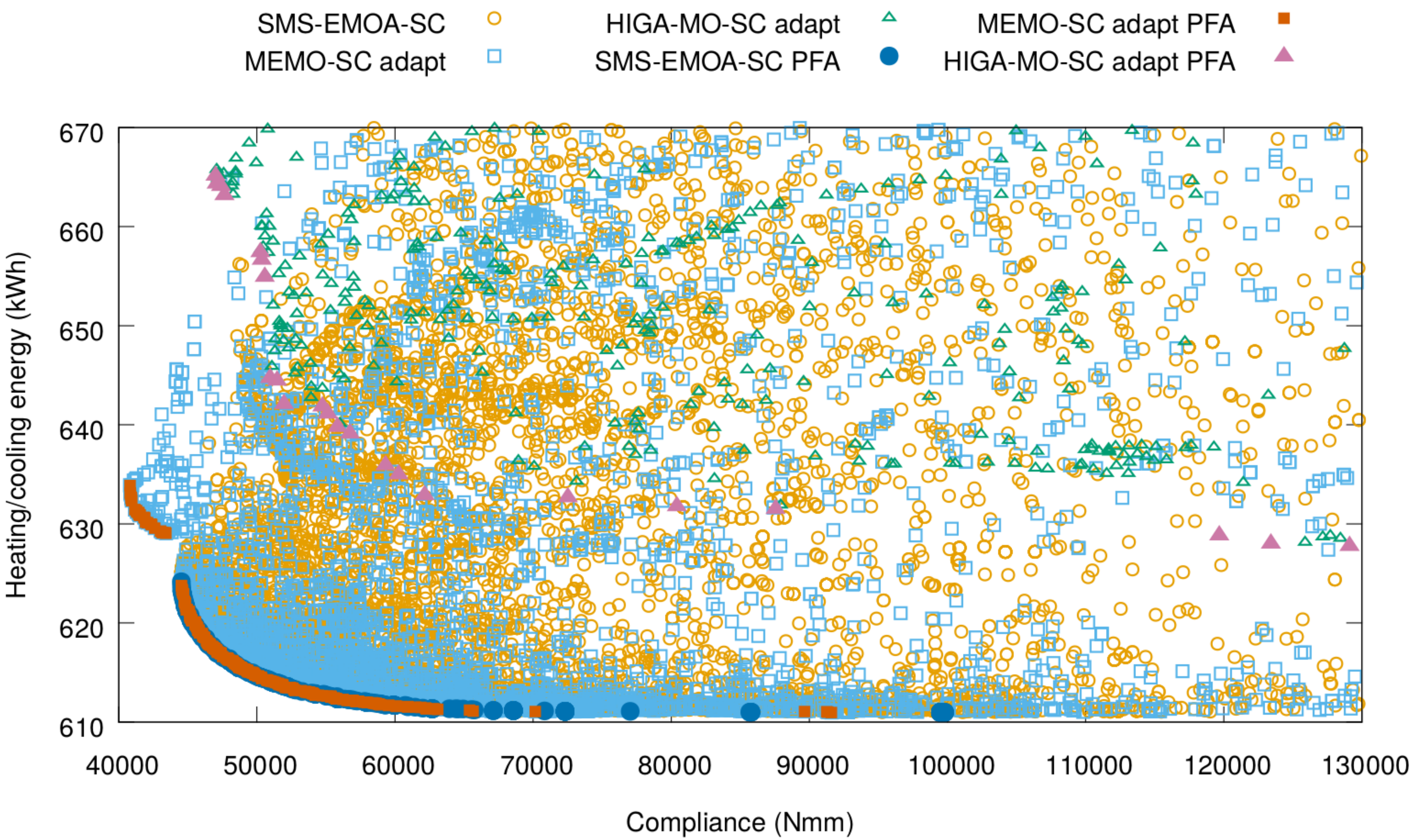
[van der Blom et al, PPSN 2016]

Local search

- Hypervolume indicator gradient

- Expensive
  - Approximate gradients based on simulations
  - Many variables

Local search



Learning from optimisation data

- Why?
- Prove solution quality to expert
- Learn new problem insights
- And… data is there anyway!

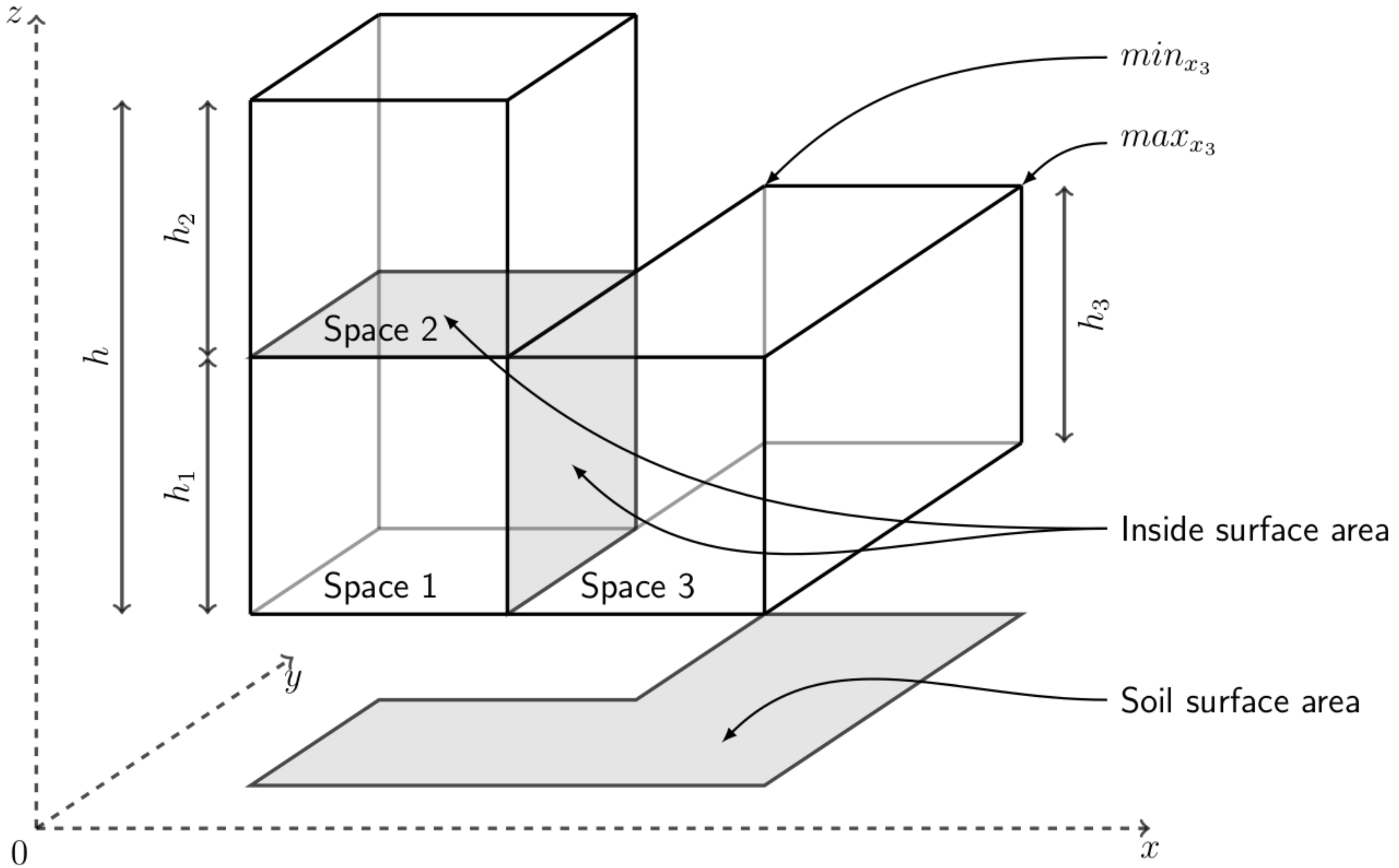
Learning from optimisation data

- What?
- Known design rules
- New design rules
- Differences between regions in objective space

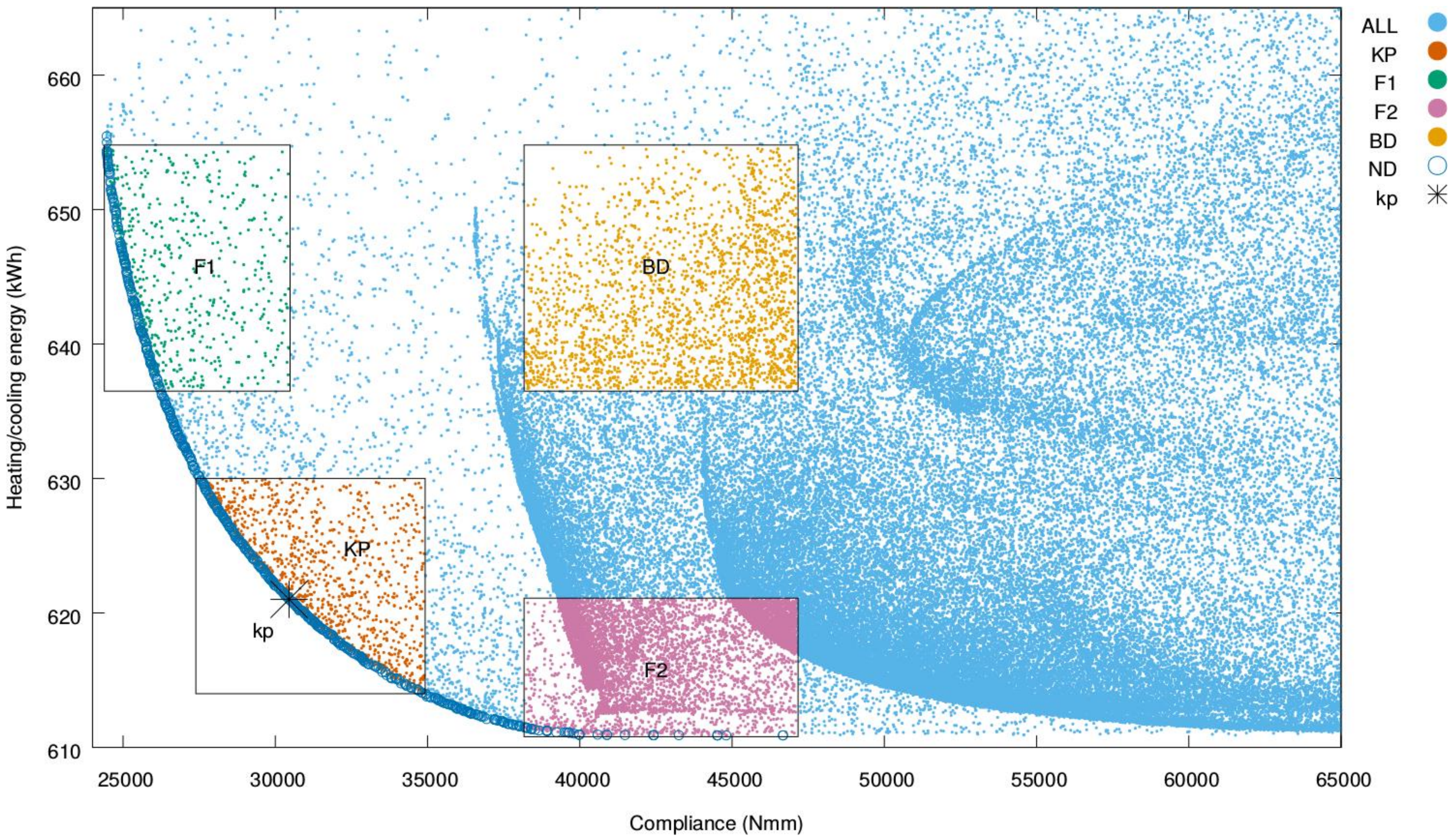
Elementary BSD features

Feature	Definition	Explanation
vol	$w \times d \times h$	Volume of the space, or sum of spaces for the full design
short	$min(w, d)$	Shortest horizontal edge, indicator of span
long	$max(w, d)$	Longest horizontal edge, indicator of span
height	$max_z - min_z$	Height of the space or the full building spatial design
out	$sum(out\_area)$	Outside surface area, indicator of energy flow
in	$sum(in\_area)$	Inside surface area, indicator of energy flow
soil	$sum(soil\_area)$	Soil (ground floor) surface area, indicator of spread
horz	$sum(horz\_area)$	Horizontal surface area, indicator of total wall area
vert	$sum(vert\_area)$	Vertical surface area, indicator of floor and roof area
in_out	$in/(in + out)$	Ratio between inside- and outside surface area
out_vol	out/vol	Ratio between outside surface area and volume
long_short	$long/(long + short)$	Ratio between longest- and shortest horizontal edge
meanh	$sum(h \times roof\_area)/soil$	Mean height of the building
meanh_h	$meanh/height$	Ratio between the mean height and the height
height_soil	$height/soil$	Ratio between the height and the soil area

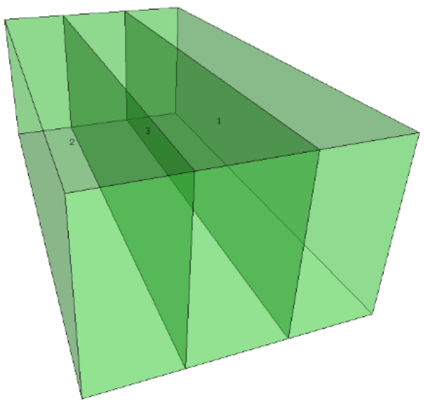
Elementary BSD features



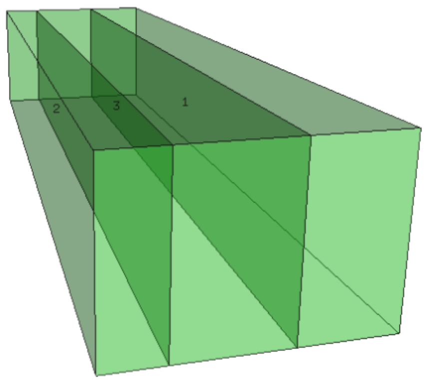
Data preparation



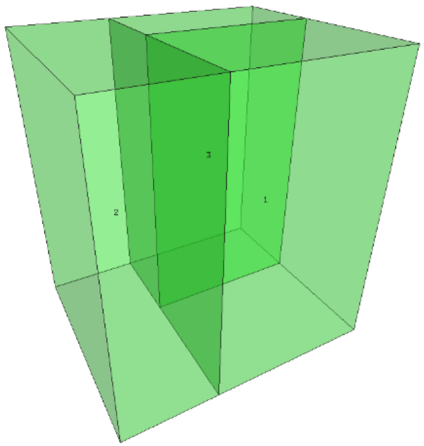
Examples per class



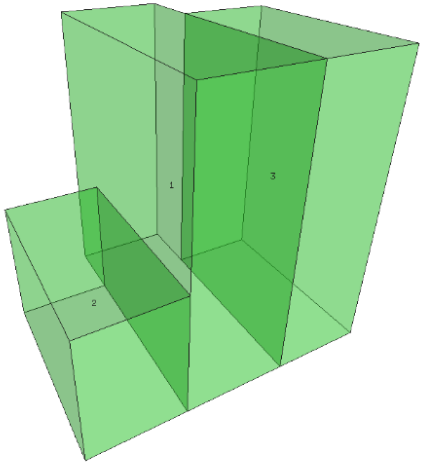
Knee point region



Structural performance



Thermal performance

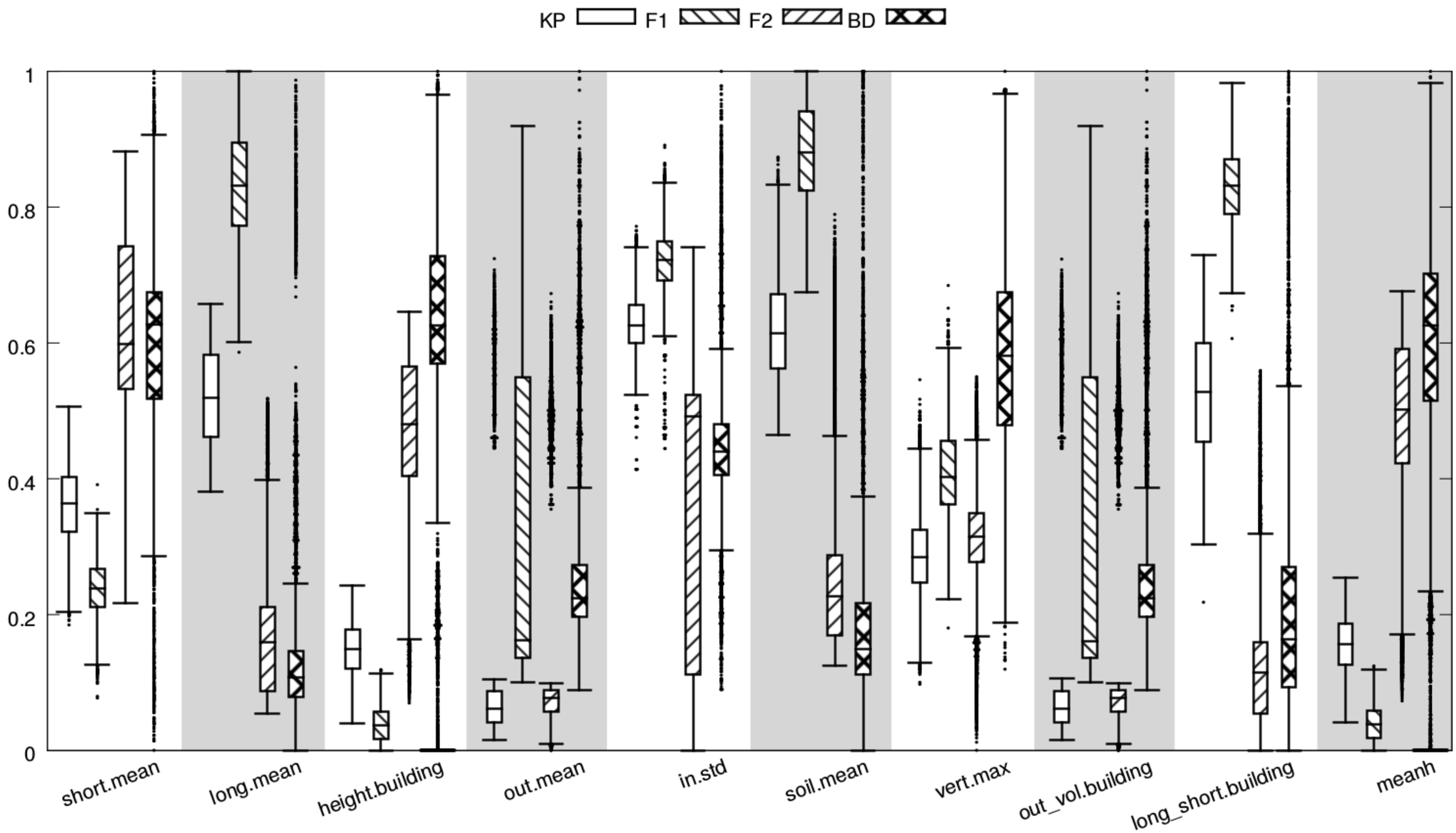


Low quality

Analysis

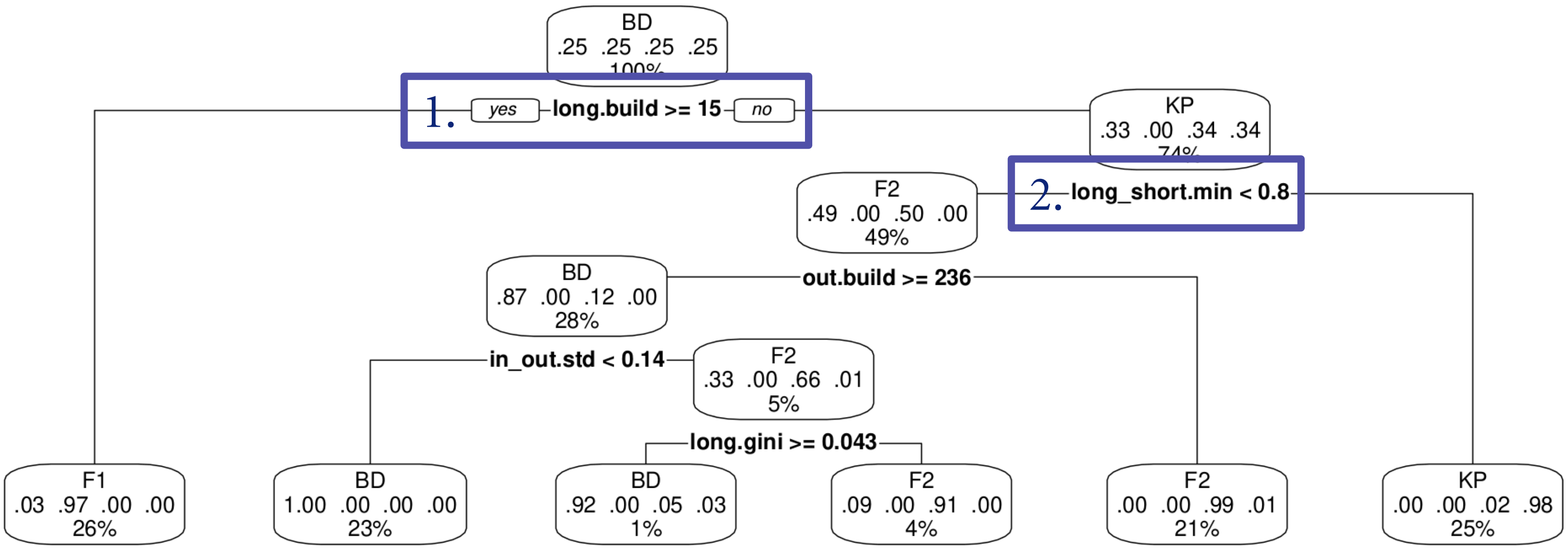
- Box plots
  - Which features appear useful?
- Decision tree
  - Can classes be distinguished?
- Validation
  - Does the learned tree generalise?

Results


KP
F1
F2
BD
1
0.8
0.6
0.4
0.2
0
short.mean
long.mean
height.building
out.mean
in.std
soil.mean
vert.max
out_vol.building
long_short.building
meanh

Results

1. Long buildings are structurally efficient (objective 1)
2. Less long + high ratio between long and short edge indicates knee point



Prob.	.0000	.0008	.0046	.0048	.0051	.0162	.0276	.0345	.0483	.0926	.9074	.9241	.9655	.9784	.9949	.9952
BD	1758	0	0	0	728	0	54	0	0	0	0	0	0	860	0	0
F1	1649	860	0	0	0	0	0	0	0	0	0	0	891	0	0	0
F2	891	0	0	748	0	860	0	0	54	0	119	0	0	0	728	0
KP	728	0	860	0	0	0	0	891	0	119	0	54	0	0	0	748

Future work

- Integrate knowledge into optimization process
  - Steer search based on learned rules
- Test generality of methods for larger BSDs
- Explore how this work relates to innovization and design exploration techniques
- Analyse the effect on the objective values for changes to individual feature values

Summary

- **Goal:**
  - Learn from optimisation data
  - Convince practitioners of the quality of found solutions
- **Method:**
  - Learn rules that differentiate between classes of solutions
- **Result:**
  - High precision (>96%) classification of solutions based on human understandable features
- **Future:**
  - Integrate knowledge into optimization process