A Super-Structure Based Optimisation Approach for Building Spatial Designs

Koen van der Blom, Sjonnie Boonstra,
Hèrm Hofmeyer and Michael Emmerich

08-06-2016

Universiteit Leiden
The Netherlands

TU/e Technische Universiteit Eindhoven University of Technology

STW Enabling new technology

Outline

- Introduction
- Problem Representation
- Experimental Setup
- Results
- Future Work

Introduction

- Building design optimisation
  - So far focussed on a single discipline, e.g.
  - Compliance: Hofmeyer, Davila Delgado (2015)
  - Building Physics: Hopfe et al. (2012)
- Mainly continuous optimisation
- Multidisciplinary and mixed integer techniques common in other fields e.g. aerospace and chemical engineering
  - Li et al. (2013), Liao et al. (2008)
- Here: Multidisciplinary & Mixed-Integer for building design optimisation

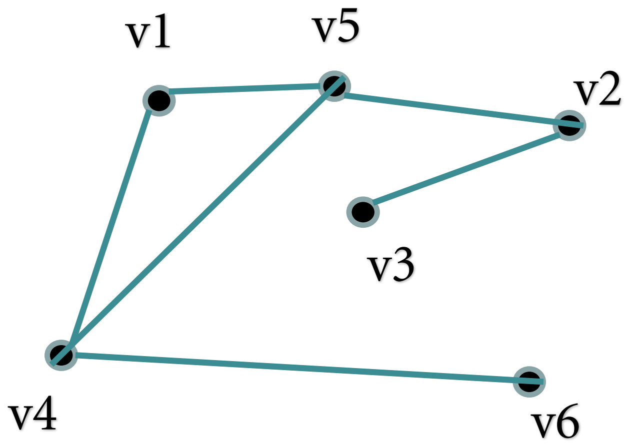
This Work

- Building design optimisation
  - Compliance
  - Building Physics (Energy use)
- Problem representation
- Representation in practice
- Single objective optimisation
- Improve understanding of objectives

Design Spaces

- Superstructure
  - All possible solutions are pre-encoded by binary variables
- Superstructure free
  - Solutions are not pre-encoded, a dynamic data structure is used (graph/tree)

	v1	v2	v3	v4	v5	v6
v1	1	0	0	1	1	0
v2	0	1	1	0	1	0
v3	0	1	1	0	0	0
v4	1	0	0	1	0	1
v5	1	1	0	0	1	0
v6	0	0	0	1	0	1



Supercube Representation

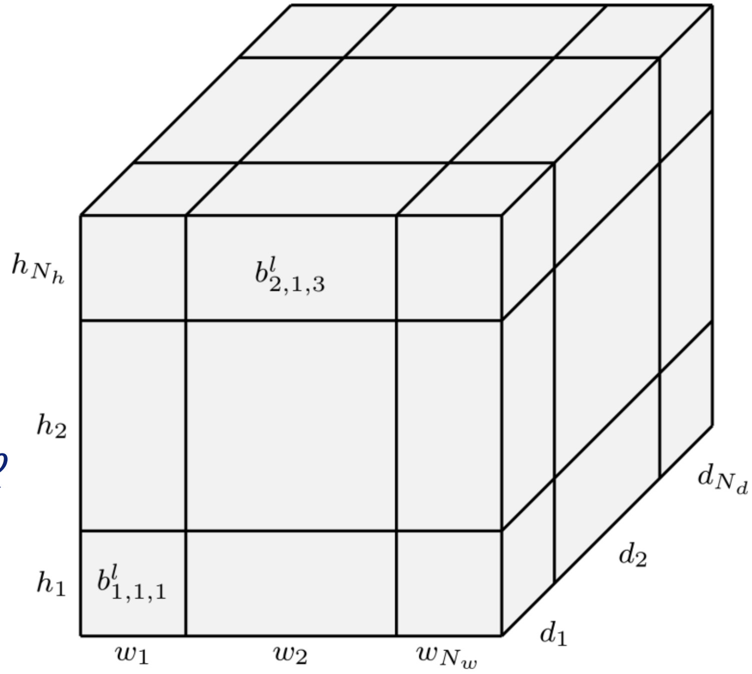
$i \in \{1,2,\dots,N_w\}$ $\quad w_i \in \mathbb{R} \geq 0$

$j \in \{1,2,\dots,N_d\}$ $\quad d_j \in \mathbb{R} \geq 0$

$k \in \{1,2,\dots,N_h\}$ $\quad h_k \in \mathbb{R} \geq 0$

$l \in \{1,2,\dots,N_{spaces}\}$

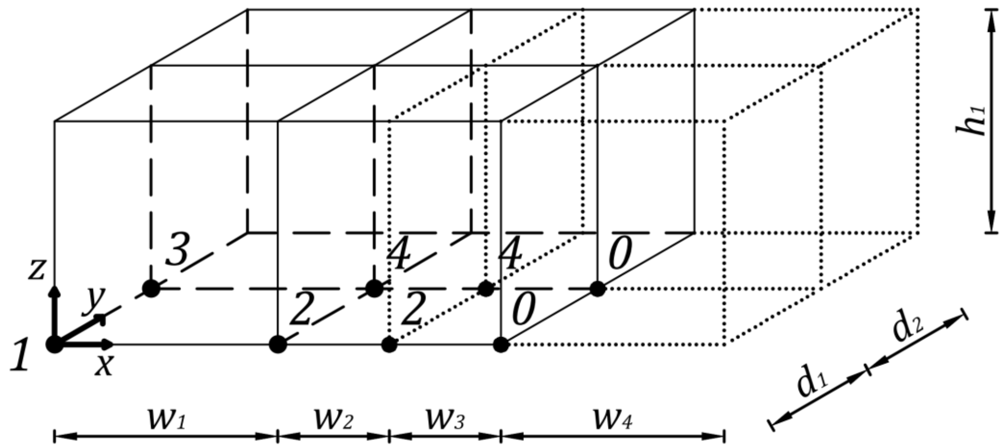
$$b^{\ell}_{i,j,k} = \begin{cases} 1 & \text{if cell } (i,j,k) \text{ belongs to space } \ell \\ 0 & \text{otherwise} \end{cases}$$



Supercube Example

$$\vec{w}\{w_1, w_2, w_3, w_4\}$$
$$\vec{d}\{d_1, d_2\}$$
$$\vec{h}\{h_1\}$$

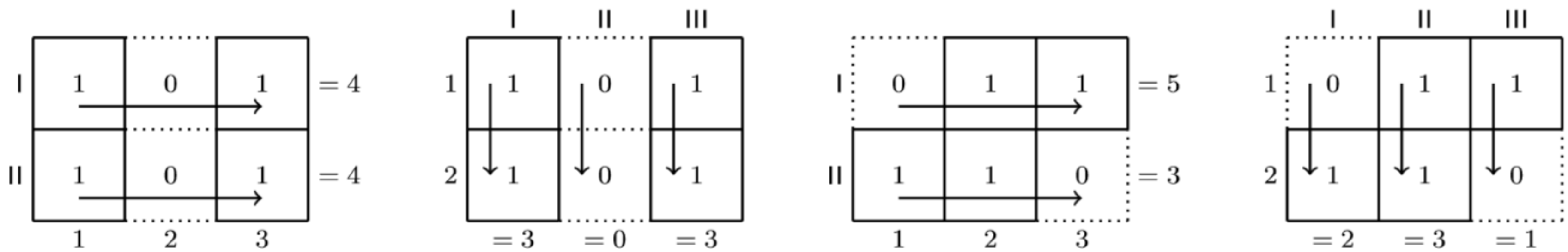
$$\overrightarrow{b^{\ell}_{i,j,k}}\{b^1_{i,j,k}, b^2_{i,j,k}, b^3_{i,j,k}, b^4_{i,j,k}\}$$
$$b^1_{i,j,k}\{1,0,0,0,0,0,0,0\}$$
$$b^2_{i,j,k}\{0,0,1,0,1,0,0,0\}$$
$$b^3_{i,j,k}\{0,1,0,0,0,0,0,0\}$$
$$b^4_{i,j,k}\{0,0,0,1,0,1,0,0\}$$



Problem Constraints

- Constraints
  - Fixed number of spaces (rooms)
  - No overlap between spaces
  - No vertical gaps (overhanging cells)
  - Spaces must be cuboid (3D rectangle)
  - Fixed volume – achieved by rescaling
- Numerical constraint checks
  - Written as sums and products of binary variables
  - Allows algebraic operations and analysis
  - Application of standard MINLP algorithms

Constraint Example



$$\forall_{\ell} : \forall_{i_1,j_1,i_2,j_2} :$$

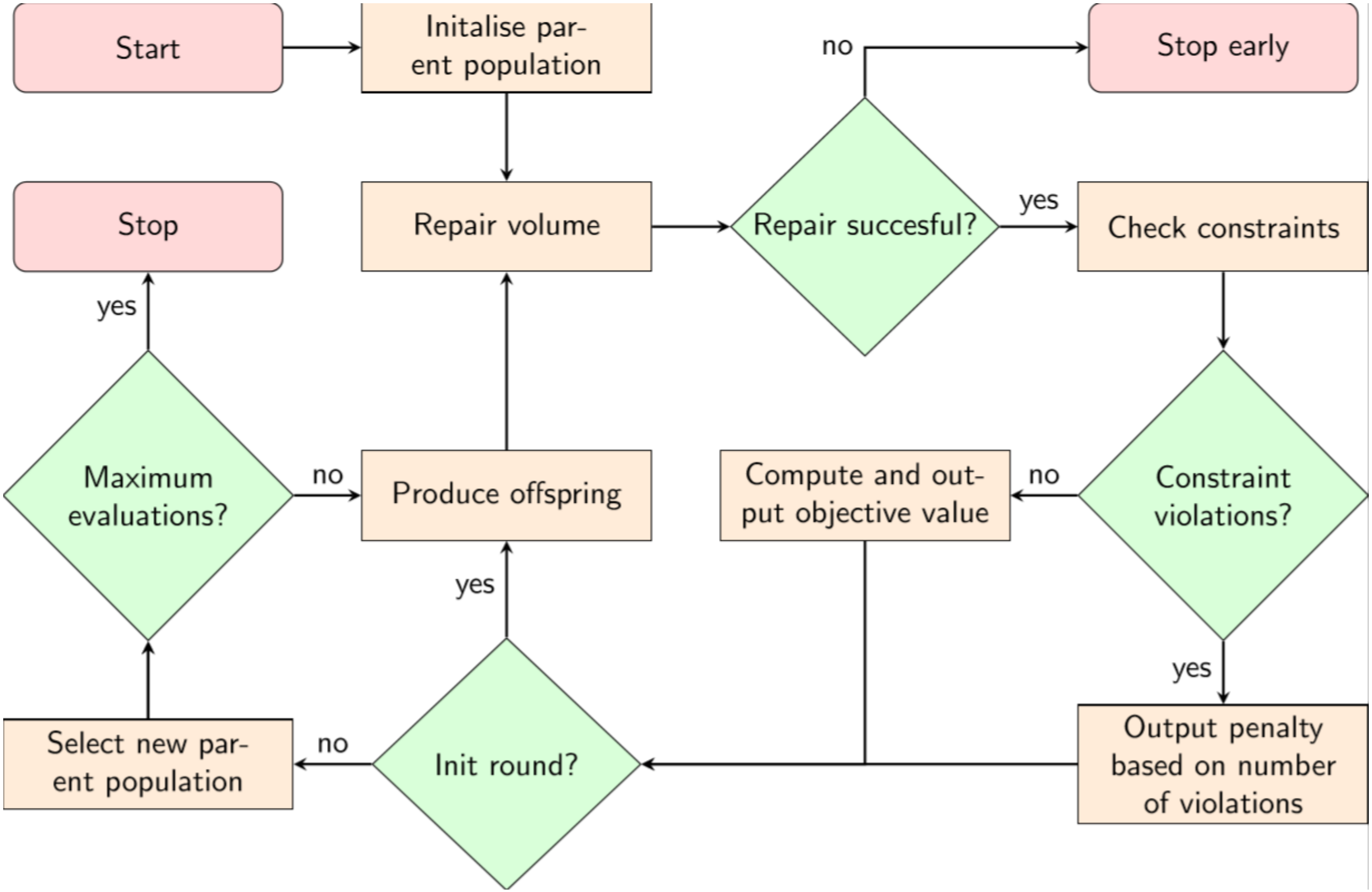
$$\left(\left(\sum_{k=1}^{N_h} k \left(1 - b^{\ell}_{i_1,j_1,k-1}\right) b^{\ell}_{i_1,j_1,k} \right) - \left(\sum_{k=1}^{N_h} k \left(1 - b^{\ell}_{i_2,j_2,k-1}\right) b^{\ell}_{i_2,j_2,k} \right) \right)$$

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

$(\mu + \lambda)$-Evolution Strategy (Beyer, Schwefel 2002)

1. Initialise Population $P_0 \in S$
2. Evaluate P_0
3. $t \rightarrow 0$
4. While (Termination criterion is not satisfied)
5. $t \rightarrow t + 1$
6. C_t = Randomly select λ pairs of individuals from P_{t-1}
7. $R_t = \{recombine(c, c') | (c, c') \in C_t\}$
8. $M_t = \{mutate(r) | r \in R_t\}$
9.   Evaluate M_t
10. P_t = Select μ best individuals from $M_t \cup P_{t-1}$
11. End While
12. Return best individual in P_t

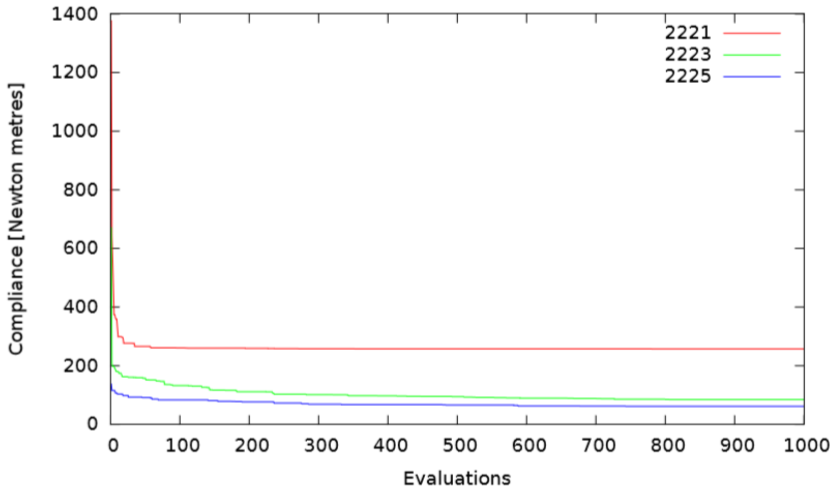
Experimental Setup

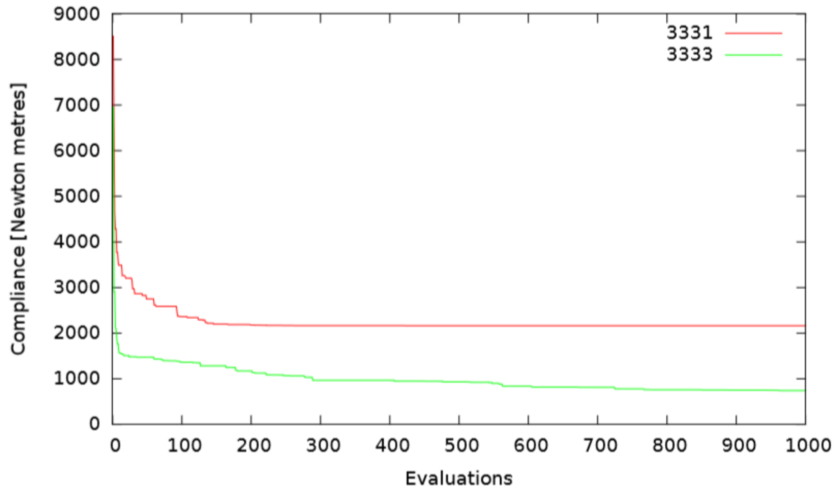


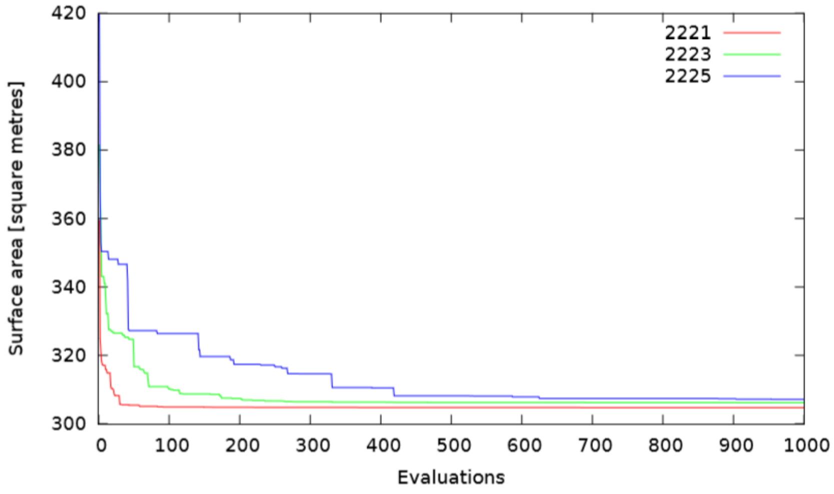
Experimental Setup

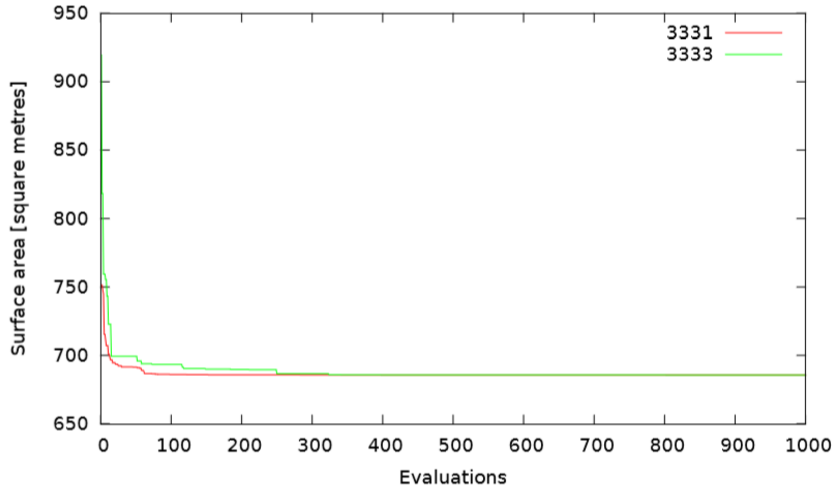
- Comparison between:
  - A single penalty value
  - Penalty based on number of constraint violations
- Problem sizes:
  - Supercube size 2x2x2 and 3x3x3
  - Each for one, three and five spaces (rooms)
- Objectives to (individually) minimise:
  - Compliance (black box simulator)
  - Surface area (dummy for energy use)

Results – Single Penalty









Constraint Violations – Compliance

- Single penalty:

Configuration	Existence	No-overlap	Cuboid shape	Connected cuboid	No vertical gaps
2221	0.072030329	N/A	0.430918281	N/A	0.350463353
2223	0.148770246	0.373125375	0.528494301	N/A	0.393521296
2225	0.197997775	0.610956619	0.565072303	N/A	0.482480534
3331	0.014877790	N/A	0.590860786	0.160821821	0.501239816
3333	0.000360993	0.999218016	0.999928001	0.999147017	0.999986000
3335	0.816557669	0.999294014	0.999885002	0.999008020	0.999954001

- Graduated penalties:

Configuration	Existence	No-overlap	Cuboid shape	Connected cuboid	No vertical gaps
2221	0.066305819	N/A	0.423545332	N/A	0.328371673
2223	0.156955204	0.322667565	0.467497474	N/A	0.313910408
2225	0.305234899	0.484563758	0.455570470	N/A	0.334228188
3331	0.013302295	N/A	0.605919521	0.119388094	0.518789491
3333	0.143656716	0.112873134	0.559701493	0.078358209	0.456778607
3335	0.840781999	0.154225102	0.462875022	0.082638026	0.422732114

Constraint Violations – Surface Area

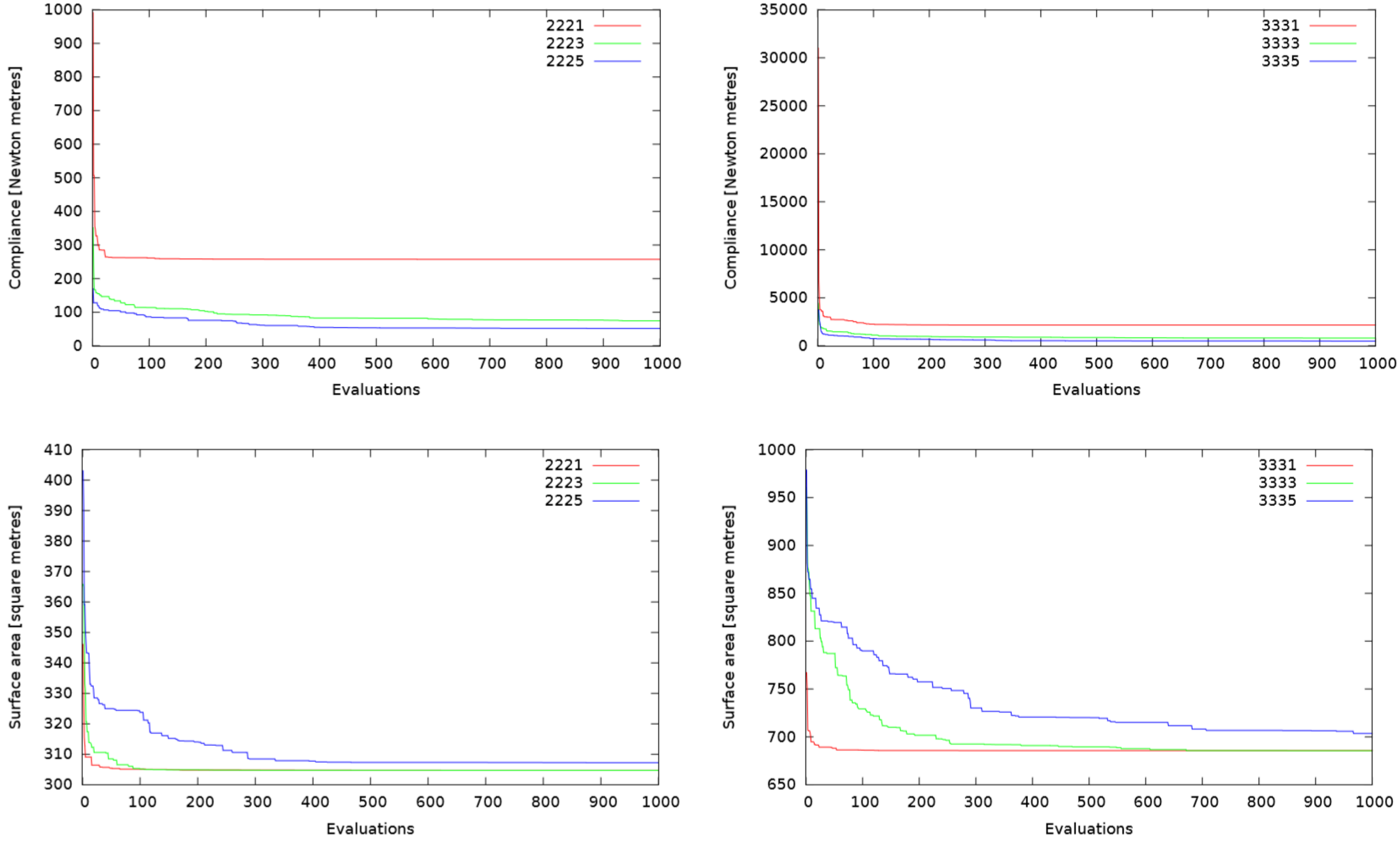
- Single penalty:

Configuration	Existence	No-overlap	Cuboid shape	Connected cuboid	No vertical gaps
2221	0.054300608	N/A	0.477410947	N/A	0.288010426
2223	0.176321781	0.433341766	0.589931697	N/A	0.348343031
2225	0.021001580	0.999803004	0.999840003	N/A	0.998622028
3331	0.040989160	N/A	0.525406504	0.168021680	0.483739837
3333	0.080888636	0.195670749	0.656508117	0.158074623	0.558245514
3335	0.816465671	0.999535009	0.999898002	0.999337013	0.999976001

- Graduated penalties:

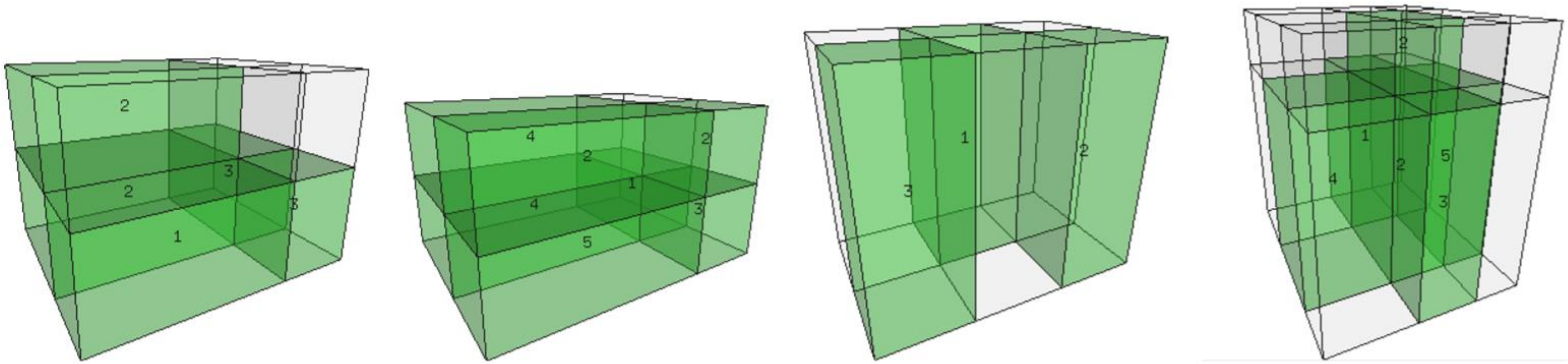
Configuration	Existence	No-overlap	Cuboid shape	Connected cuboid	No vertical gaps
2221	0.063636365	N/A	0.501581028	N/A	0.269960474
2223	0.144760533	0.320849838	0.453366943	N/A	0.142599928
2225	0.197621226	0.532174443	0.471790170	N/A	0.365965233
3331	0.063481457	N/A	0.521550284	0.105913799	0.467758102
3333	0.142694064	0.146689498	0.582191781	0.099029680	0.469463470
3335	0.859725404	0.193019717	0.495911166	0.101861297	0.420656555

Results – Graduated Penalties

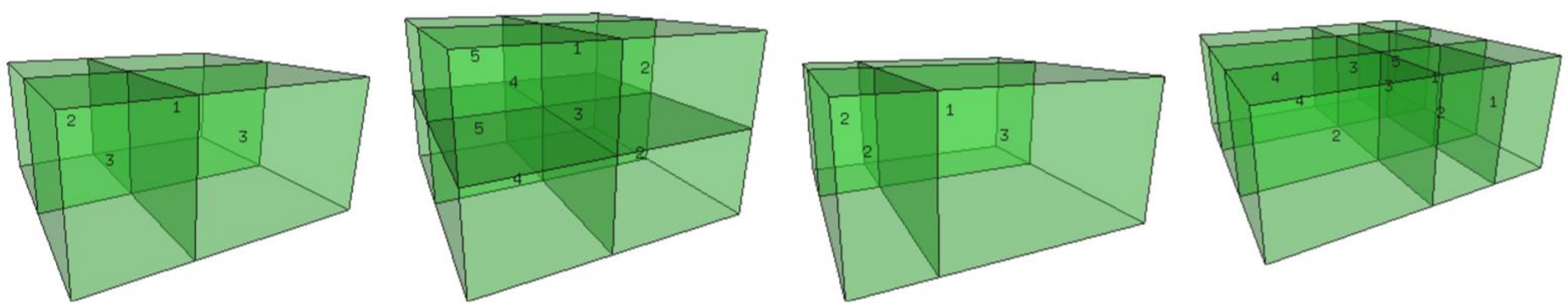


Results – Visualisations

- Compliance:



- Surface area:



Future Work

- Multi-objective (Pareto) optimisation
- ‘Intelligent’ search operators
  - Take into account constraints when producing offspring
- Memetic optimisation
  - Global evolutionary search
  - Local (gradient?) search
- Larger building designs
- Replace the surface area objective with building physics simulation

Thank you!

Acknowledgements: Financing of this project by the Dutch STW via project 13596 (Excellent Buildings via Forefront MDO, Lowest Energy Use, Optimal Spatial and Structural Performance).

Koen van der Blom, Sjonnie Boonstra,
Hèrm Hofmeyer and Michael Emmerich

08-06-2016

Universiteit Leiden
The Netherlands

TU/e Technische Universiteit Eindhoven University of Technology

STW Enabling new technology