Beautification of City Models based on Mixed Integer Linear Programming

Steffen Goebbels and Regina Pohle-Fröhlich

Niederrhein University of Applied Sciences - Institute for Pattern Recognition,
Faculty of Electrical Engineering and Computer Science

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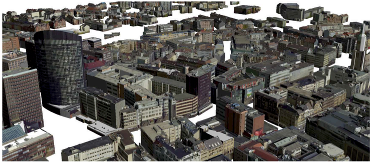
CityGML: Virtual 3D city models



Google Earth/Google Maps 3D

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Some applications of city models

- Building Information Modeling (BIM)
- emergency response planning
- solar potential analysis
- urban planning, cadastre
- visualization for navigation and routing
- energy demand estimation
- virtual tours, tourism
- facility management
- flooding simulation
- visibility analysis
- shadow estimation
- noise propagation
- estimation of floor space and population

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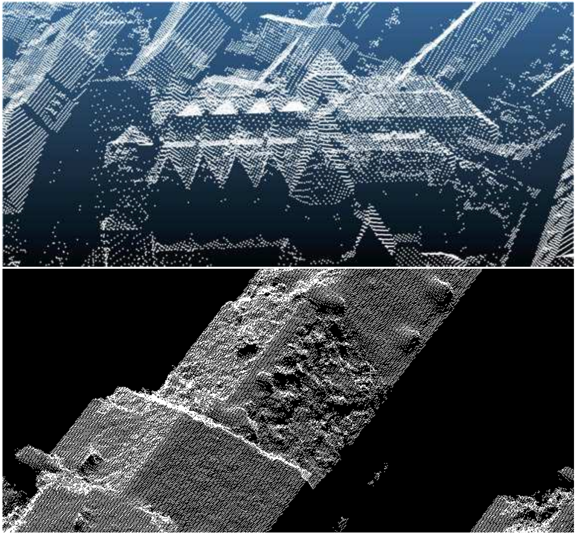
Laser scanning and photogrammetric point clouds



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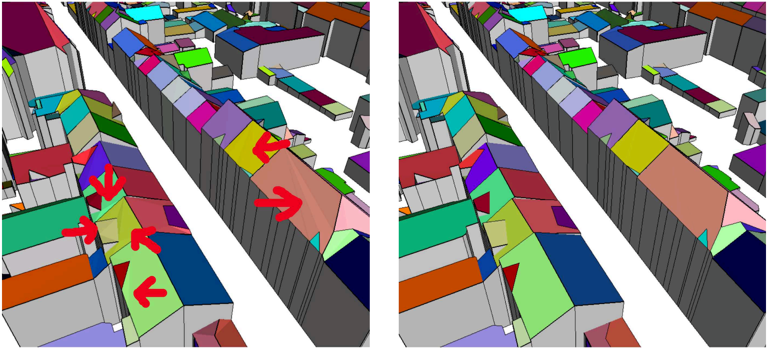
Previous applications of LP: Planarization of roof facets



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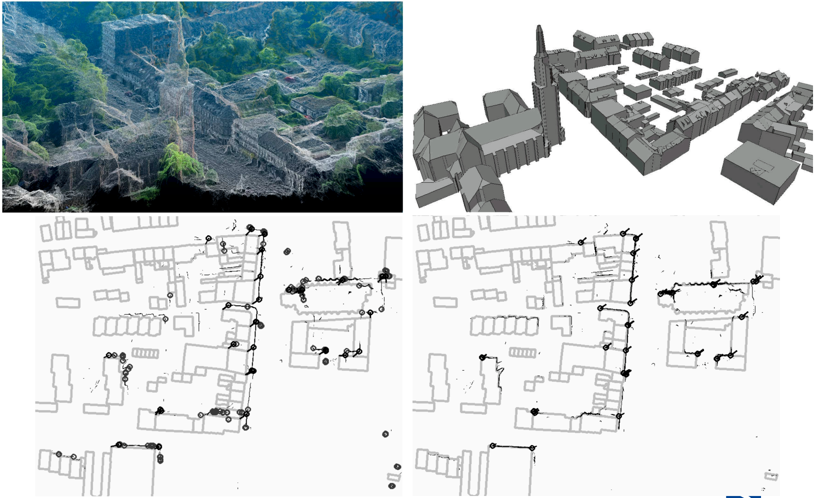
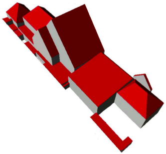
Previous applications of MIP: Point cloud registration

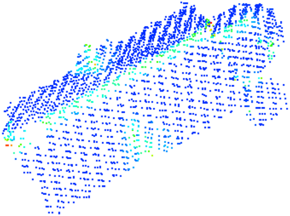
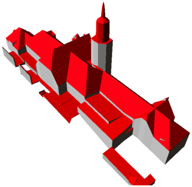


Model vs. data based method

- Model based North Rhine Westphalian city model (©Geobasis NRW 2016)


- Our institute's data based model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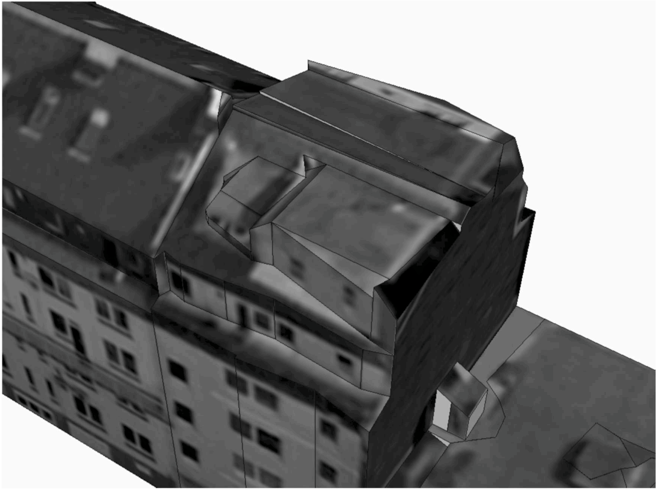
A Problem with data based models: noisy step edges



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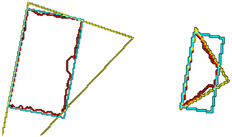
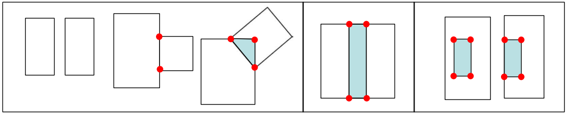
Solution: Beautification - elementary approach

- Project roof edges to the x-y-plane.
- Compute convex hulls of roof facet's boundary polygons
- Compare their area with the area of their smallest enclosing triangles, circles and rectangles
- If the rectangle area is closest to the convex hull's area and the difference is below a threshold value, then the contour might be rectangular.
- Replace contour with rectangle if additional heuristic conditions are fulfilled.





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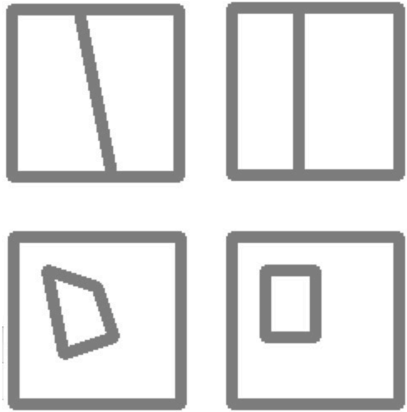
Solution: Beautification - optimization approach



- Project roof edges to the x-y-plane.
- Detect connected components of 2D graph
- Use a MIP to maximize the number of orthogonal edges for each connected component.

Notations (1)

- D is a set of normalized 2D direction vectors that are parallel or orthogonal to significant cadastral footprint edges.

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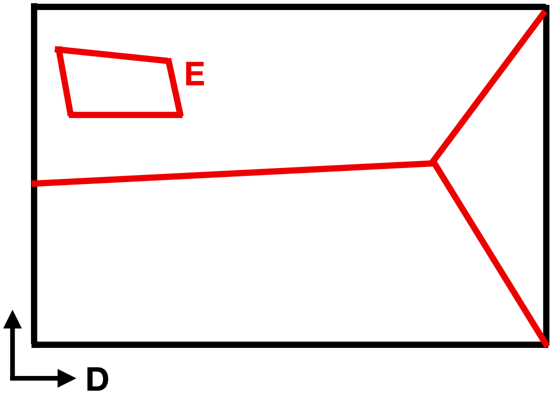
Notations (2)



The figure shows two connected components that are handled separately.

- For each component, E is the set of all non-trivial 2D edges $e = (e_1, e_2) = ((e_1.x, e_1.y), (e_2.x, e_2.y))$ that do not lie completely on the cadastral footprint.

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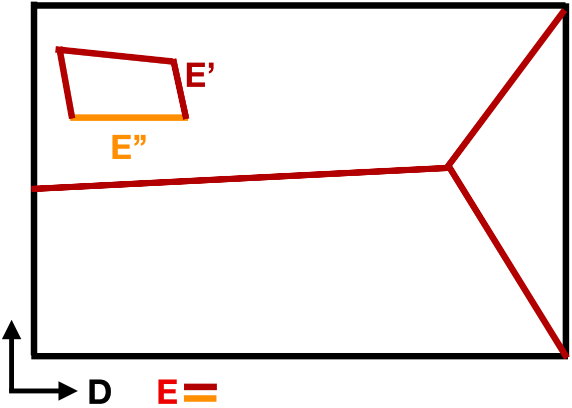
Notations (3)



- $E = E' \cup E''$, edges in E' are allowed to change their orientation, whereas edges in E'' have to keep their direction that already is orthogonal to a vector of D

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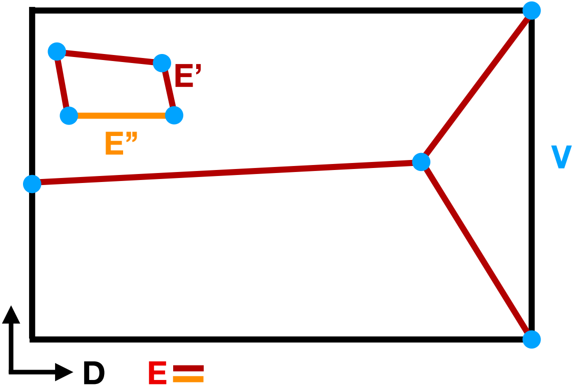
Notations (4)



- V denotes the set of vertices belonging to edges in E

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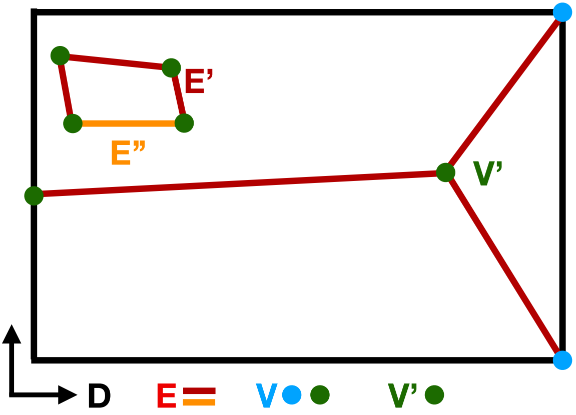
Notations (5)



- $V' \subset V$ is the set of vertices for which we allow position changes.

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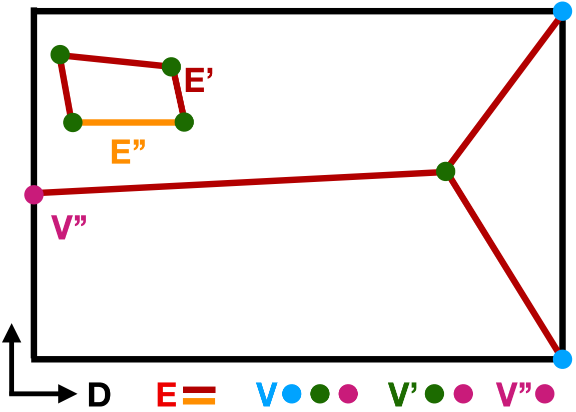
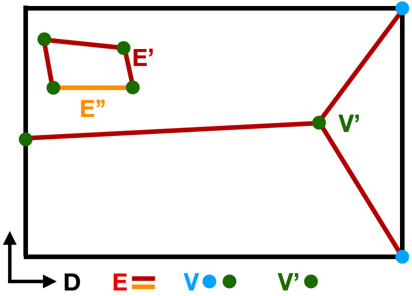
Notations (6)



- $V'' \subset V'$ is the set of vertices that lie on a footprint edge.

Variables

For $v \in V$, float variables x_v^+, x_v^- and y_v^+, y_v^- represent non-negative changes. New coordinates are $v.x + x_v^+ - x_v^-$, $v.y + y_v^+ - y_v^-$. For $v \in V \setminus V'$ their values are fixed set to zero.



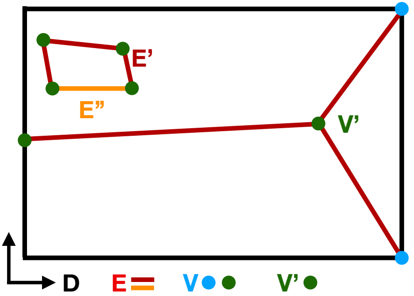
We introduce binary variables $x_{e,d}$ that indicate, if an edge $e \in E'$ becomes orthogonal to a direction vector $d \in D$:

$$x_{e,d} = \begin{cases} 1 & : \quad e \text{ is transformed to become orthogonal to } d \\ 0 & : \quad \text{else} \end{cases}$$

Objective function

- Primary goal: find a maximum number of orthogonal edges
- Secondary goal: minimize coordinate changes.

$$\text{maximize} \left(\sum_{e \in E'} \sum_{d \in D} x_{e,d} \right) - \frac{1}{8 \cdot |V'| \cdot \varepsilon} \sum_{v \in V'} \left(x_v^+ + x_v^- + y_v^+ + y_v^- \right).$$



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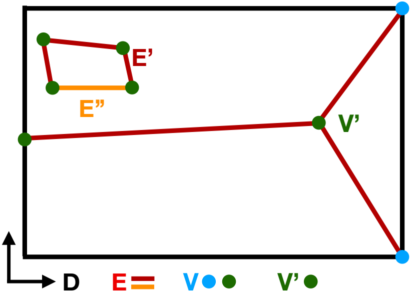
Restrictions (1)

We do not change vertices on the cadastral footprint and intersection points of ridge lines:

$$x_v^+ = x_v^- = y_v^+ = y_v^- = 0 \text{ for all } v \in V \setminus V'.$$

Other vertices can be moved but only within a threshold distance $\varepsilon > 0$:

$$0 \leq x_v^+, x_v^-, y_v^+, y_v^- < \varepsilon \text{ for all } v \in V'.$$

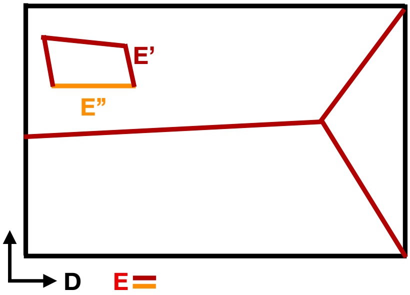


Restrictions (2)

Modified edges $e \in E'$ have to be orthogonal to direction $d \in D$ if $x_{e,d} = 1$:

$$
\begin{aligned}
-M \cdot (1 - x_{e,d}) \quad &\leq \quad (e_2.x + x^+_{e_2} - x^-_{e_2} - e_1.x - x^+_{e_1} + x^-_{e_1}) \cdot d.x \\
&\quad\; +(e_2.y + y^+_{e_2} - y^-_{e_2} - e_1.y - y^+_{e_1} + y^-_{e_1}) \cdot d.y \\
&\leq \quad M \cdot (1 - x_{e,d}),
\end{aligned}
$$

Constant M is larger than the longest occurring edge.



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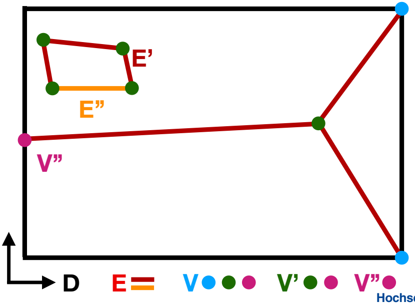
Restrictions (3)

Vertices in V'' are only allowed to change their positions so that they stay on the one footprint edge that they are positioned on: Let $0 \leq r_v \leq 1$ and

$$\begin{aligned} x_v^+ - x_v^- - (b_v.x - a_v.x) \cdot r_v &= a_v.x - v.x \\ y_v^+ - y_v^- - (b_v.y - a_v.y) \cdot r_v &= a_v.y - v.y, \end{aligned}$$

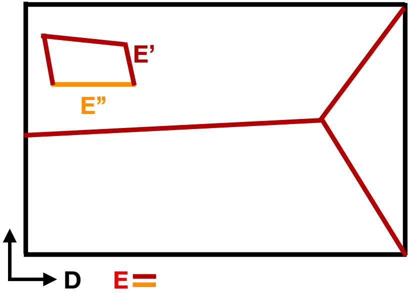
where a_v and b_v denote the 2D vertices of the corresponding footprint edge.



Restrictions (4)

We also keep the orientation of edges that are orthogonal to a footprint direction $d \in D$ from the beginning: For all $e \in E''$ let

$$\begin{aligned}&(x_{e_2}^{+} - x_{e_2}^{-} - x_{e_1}^{+} + x_{e_1}^{-}) \cdot (e_1.y - e_2.y)\\ + \quad &(y_{e_2}^{+} - y_{e_2}^{-} - y_{e_1}^{+} + y_{e_1}^{-}) \cdot (e_2.x - e_1.x) = 0.\end{aligned}$$

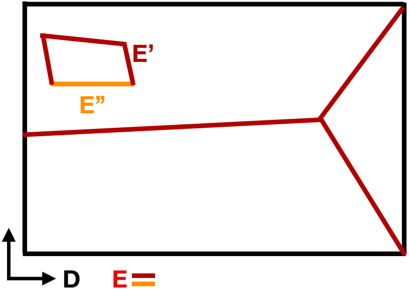


Restrictions (5)

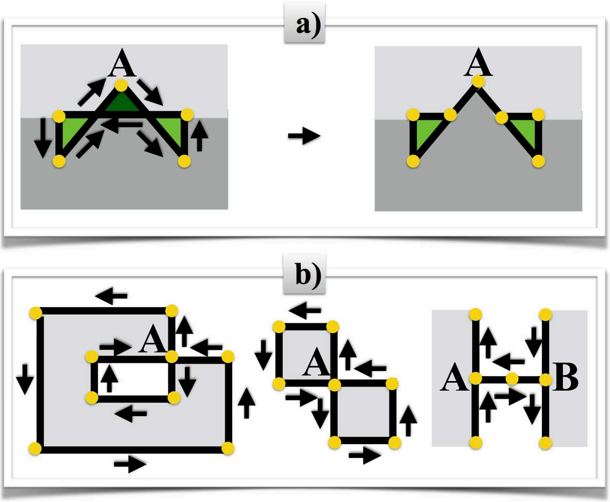
To reduce the degrees of freedom, we only consider edges that are roughly orthogonal to footprint directions. Maximum deviation from $\pm\frac{\pi}{2}$ is determined by the threshold angle α:

$$x_{e,d} = 0 \text{ for all } e \in E',\ d \in D$$

$$\text{with } \frac{|(e_2.x - e_1.x)\cdot d.x + (e_2.y - e_1.y)\cdot d.y|}{\sqrt{(e_2.x - e_1.x)^2 + (e_2.y - e_1.y)^2}} > \left|\cos\left(\frac{\pi}{2} + \alpha\right)\right|,$$



Elimination of self-intersections[1]



[1] Quality enhancement techniques for building models derived from sparse point clouds, Proc. GRAPP 2017, pp. 93–104

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Results for a city model of a square kilometer

- For $\varepsilon = 1$ m, $\alpha = \frac{\pi}{6}$: 1826 non-trivial problem instances for connected components, 61 reach the time limit of two seconds
- For $\varepsilon = 2$ m, $\alpha = \frac{\pi}{4}$: 1876 instances, 89 exceed the time limit.

		minimum	maximum	arithmetic mean	median	quartiles
$\varepsilon = 1$ m, $\alpha = \frac{\pi}{6}$	variables	9	2709	66.69	35	20, 45
	binary variables	1	1210	10.34	4	2, 8
	conditions	2	3004	43.61	20	11, 39
	changed vertices	0	233	4.01	3	2, 5
	running time [ms]	0.09	1697.96	17.45	0.46	0.29, 1.28
$\varepsilon = 2$ m, $\alpha = \frac{\pi}{4}$	variables	9	2951	68.05	36	20, 45
	binary variables	1	1500	12.51	4	2, 9
	conditions	2	3679	48.88	22	11, 42
	changed vertices	0	261	4.44	3	2, 5
	running time [ms]	0.12	1765.27	19.08	0.52	0.31, 1.51

Running times are measured on one kernel of a Macbook Pro (2013) with 2.4 GHz i5 processor.

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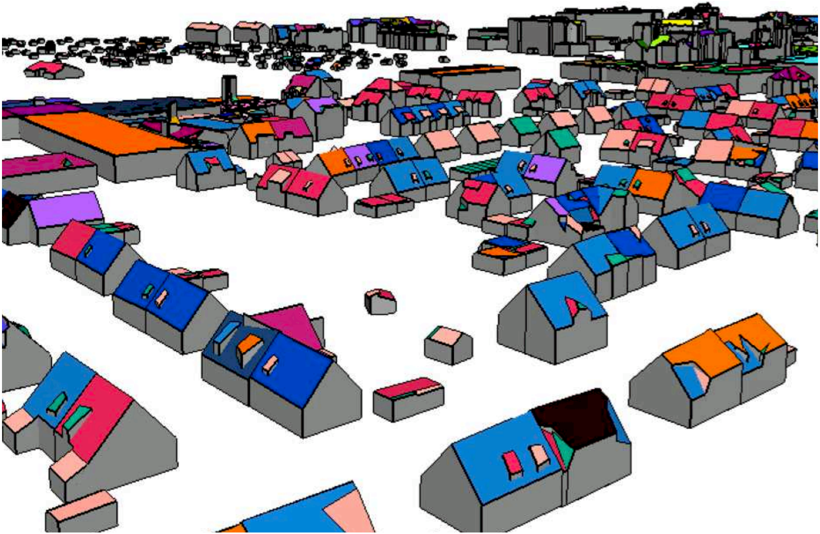
Results ($\varepsilon = 2$ m, $\alpha = \frac{\pi}{4}$)



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Results ($\varepsilon = 2$ m, $\alpha = \frac{\pi}{4}$)

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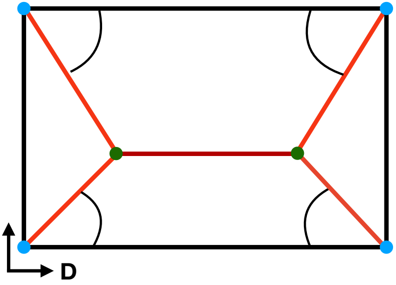
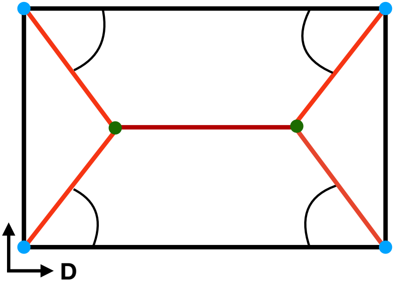
Outlook: Symmetry enhancement





Impressum

Prof. Dr. Steffen Goebbels
Niederrhein University of Applied Sciences, iPattern Institute
E-Mail: steffen.goebbels@hsnr.de
Tel.: +49 2151 822 4648

Prof. Dr. Regina Pohle-Fröhlich
Niederrhein University of Applied Sciences, iPattern Institute
E-Mail: regina.pohle@hsnr.de
Tel.: +49 2151 822 4760