

Multi-agent path finding for facade-integrated ductwork

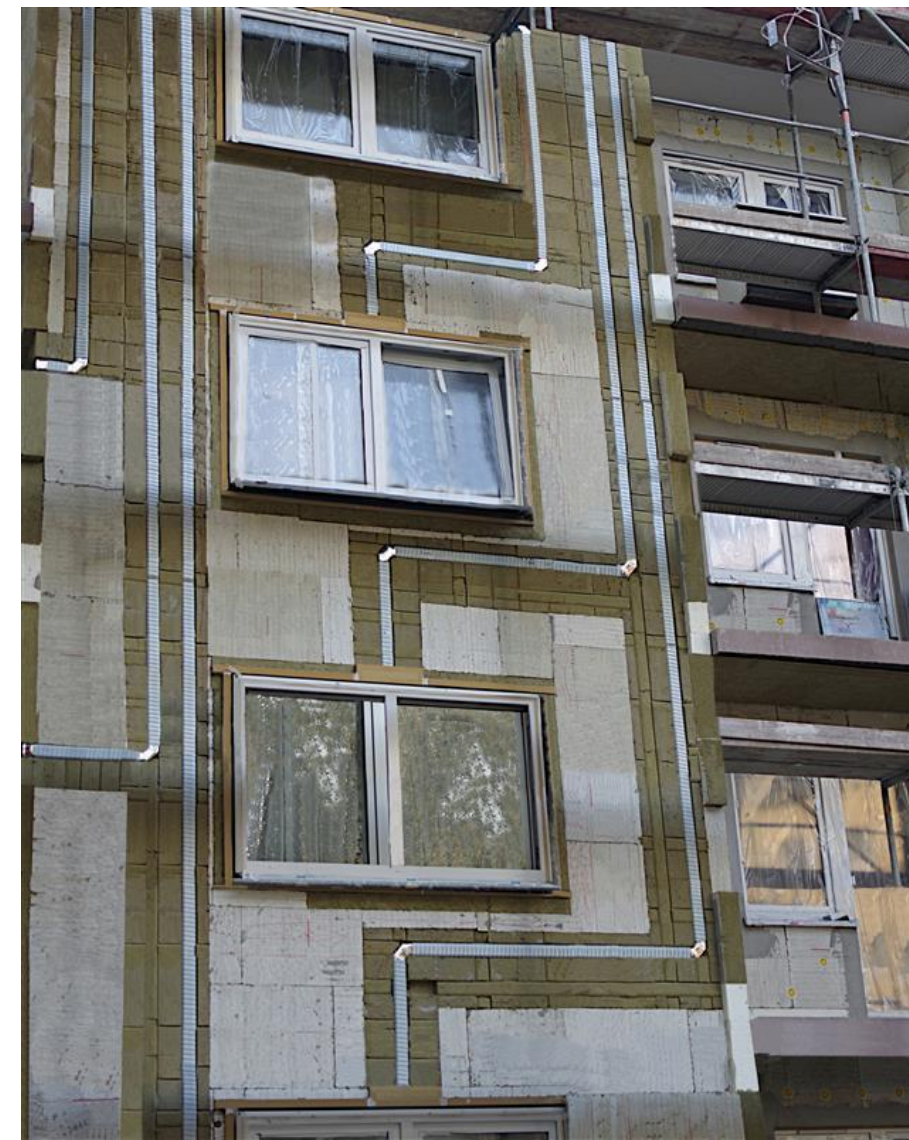
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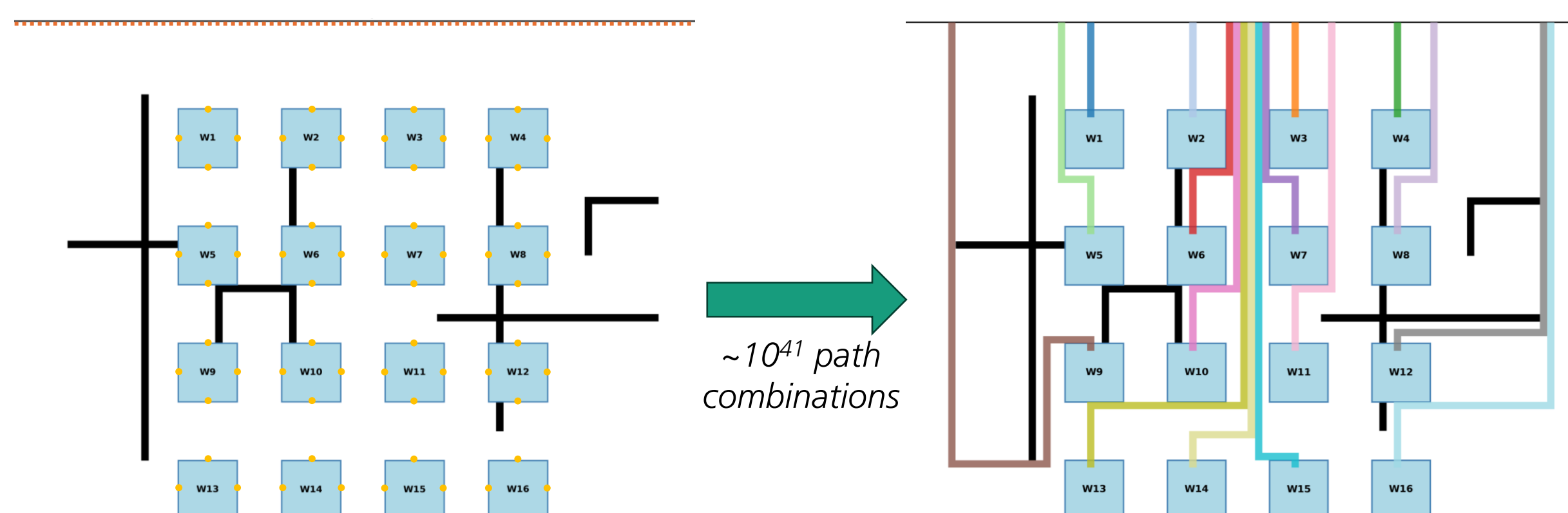
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Motivation

- EU Buildings: ~40% of energy use
 - 80% of stock older than 2001
 - large scale renovation needed.
 - Mechanical Ventilation with Heat Recovery (MVHR) cuts energy use and ensures fresh air supply
 - façade-integrated ducts (AEGIR¹ concept) allow low-intrusion retrofit alongside insulation upgrades
 - But manual routing design is slow and doesn't scale to prefabrication needs.
- Automated routing required for large-scale retrofit with façade-integrated-ventilation.



AEGIR concept:
prefabricated façade modules combining windows, insulation, electronics, and ventilation ducts



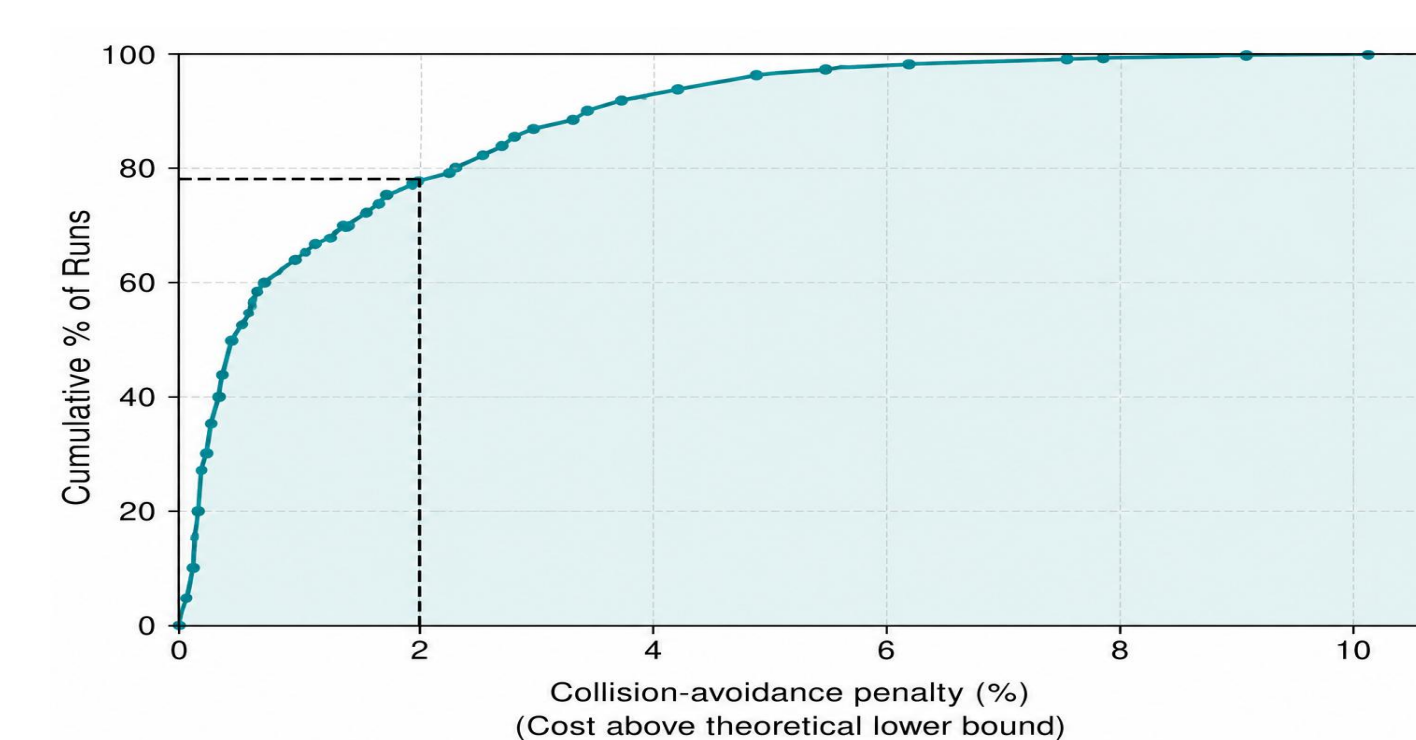
The autorouting method can decide in seconds the best ventilation duct paths connecting e.g. the attic and Air Terminal Devices (ATD) located on windows.

Methodology

- A hybrid algorithm combining **pathfinding** with **optimization**:
 - Input: façade image + source domain + target ATD² positions
 - A* variants³ and graph-based techniques generate candidate paths
 - ILP⁴ optimizer selects one collision-free path per ATD, minimizing total pressure loss
 - Constraints: obstacles, minimum distance to windows, **no overlap between ducts**
- Avoids the exponential cost of pure ILP, which becomes intractable even for moderate facade sizes.

Validation

- No single building represents all façade configurations
 - Methodology tested on 250 random synthetic façades
 - Varying facade sizes, window placement & obstacles
- **Runtime:** ~15s per facade
- **Quality:** 78% of runs within 2% of a theoretical (infeasible) lower bound



Distribution of the Collision-Avoidance Penalty (CAP) across 250 random façades: CAP measures the added cost of enforcing conflict-free routing relative to the infeasible lower bound, not the distance from the true optimum.

- The method stays robust across a wide variety of façade complexities

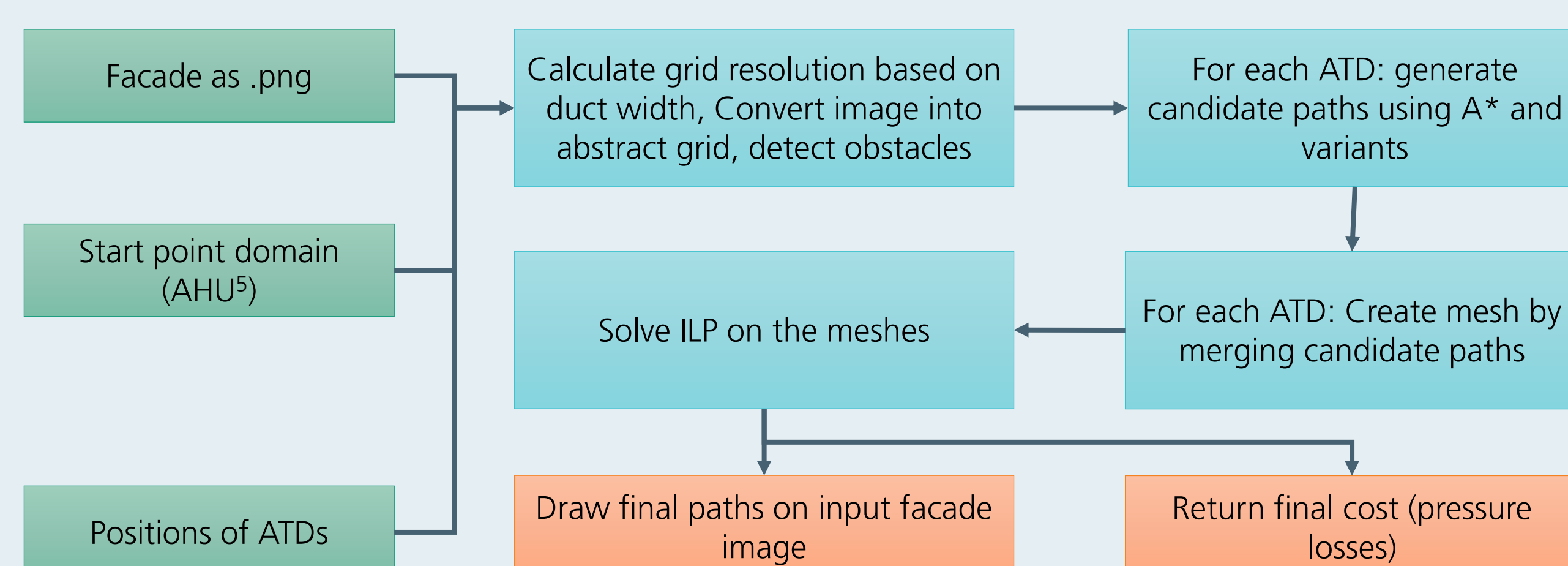
Results

- Example building (retirement home), south facade:
 - 11 x 49m, 22 headers, 12 branches
 - full routing computed in 30 seconds
- Benchmark with manual routing (10 façades):
 - on average 8.5% fewer bends and 5% shorter duct length;
 - up to 10% improvement on complex façades
- Cuts design time drastically compared to manual planning



Example building (retirement home), south facade: results of the automatic routing vs manual routing. Although very similar, the automatic routing allows for reduction in total duct length in only about a minute time.

Simplified Flowchart of the algorithm



Conclusion: The presented methodology matches or outperforms manual routing while being much faster, making it suitable for real design workflows. Validated on over 250 synthetic and 4 real façades, it reliably finds collision-free, near-optimal duct paths within design-appropriate runtimes. Beyond ventilation, this method is generalizable to other network-routing problems, such as water piping or electrical cabling.

Contact

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¹ The European AEGIR project (<https://aegirproject.eu/>) aims at developing modular, renewable & industrialised building envelopes for low energy renovation

² ATD: Air Terminal Device

³ The A* search algorithm is a reference method for finding the shortest path between two points.

⁴ Integer Linear Programming: mathematical optimization program in which some or all of the variables are restricted to be integers

⁵ AHU: Air Handling Unit