A data-driven algorithm to optimize the placement of continuous monitoring sensors on oil and gas sites

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December 11, 2023,
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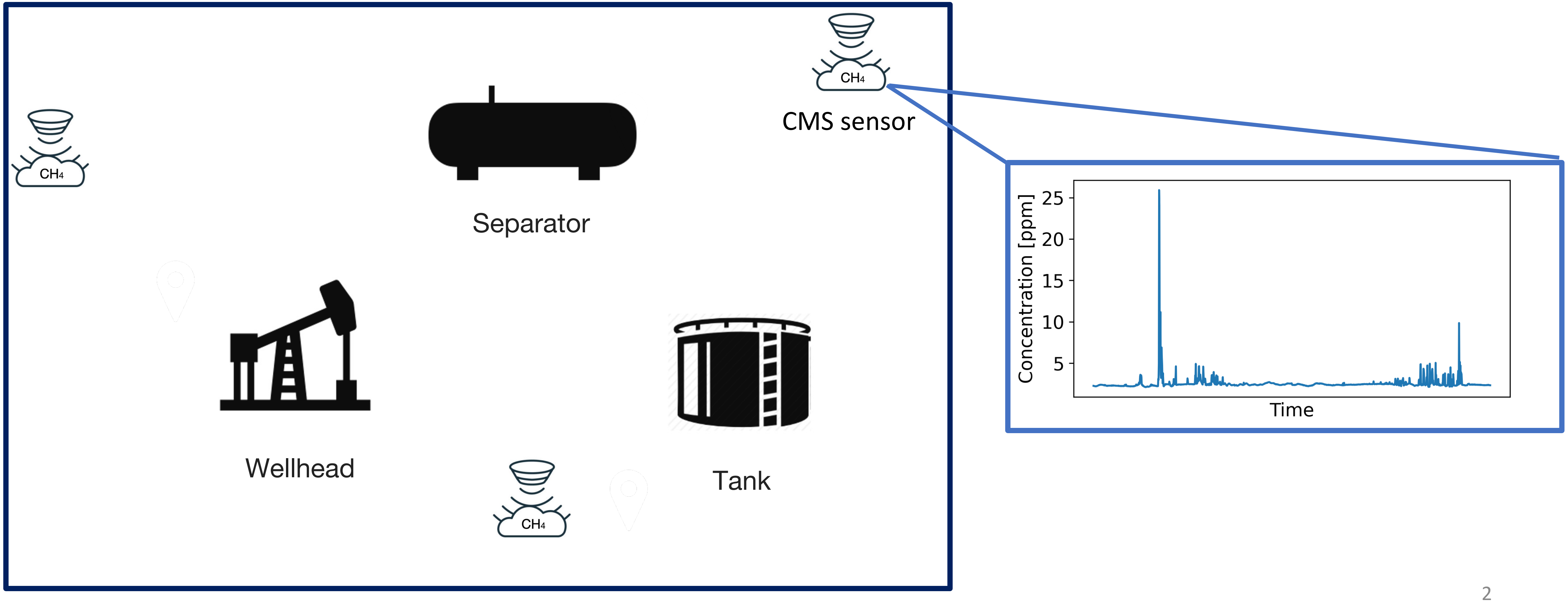
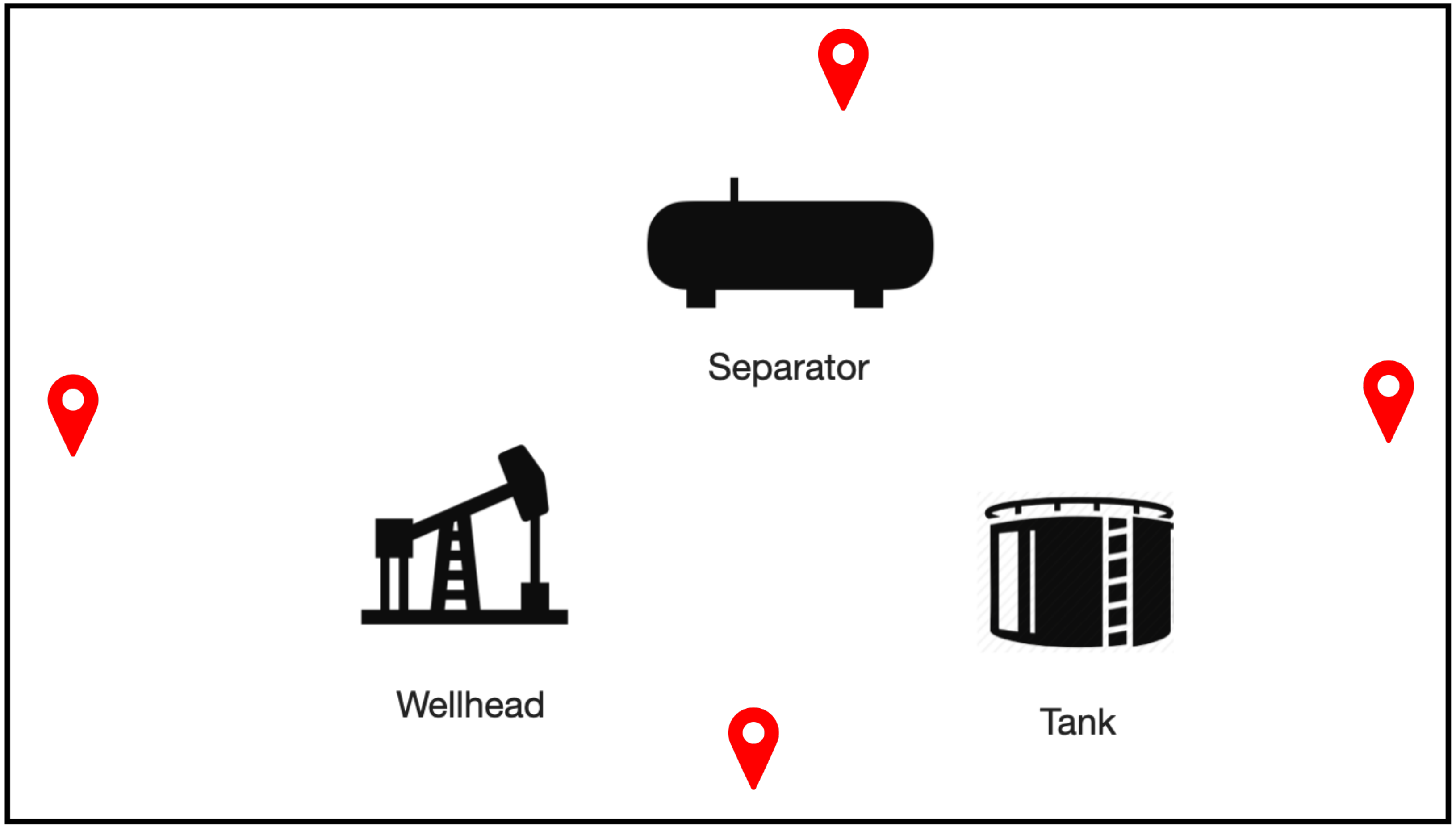
Problem Setup

- Continuous monitoring systems (CMS)



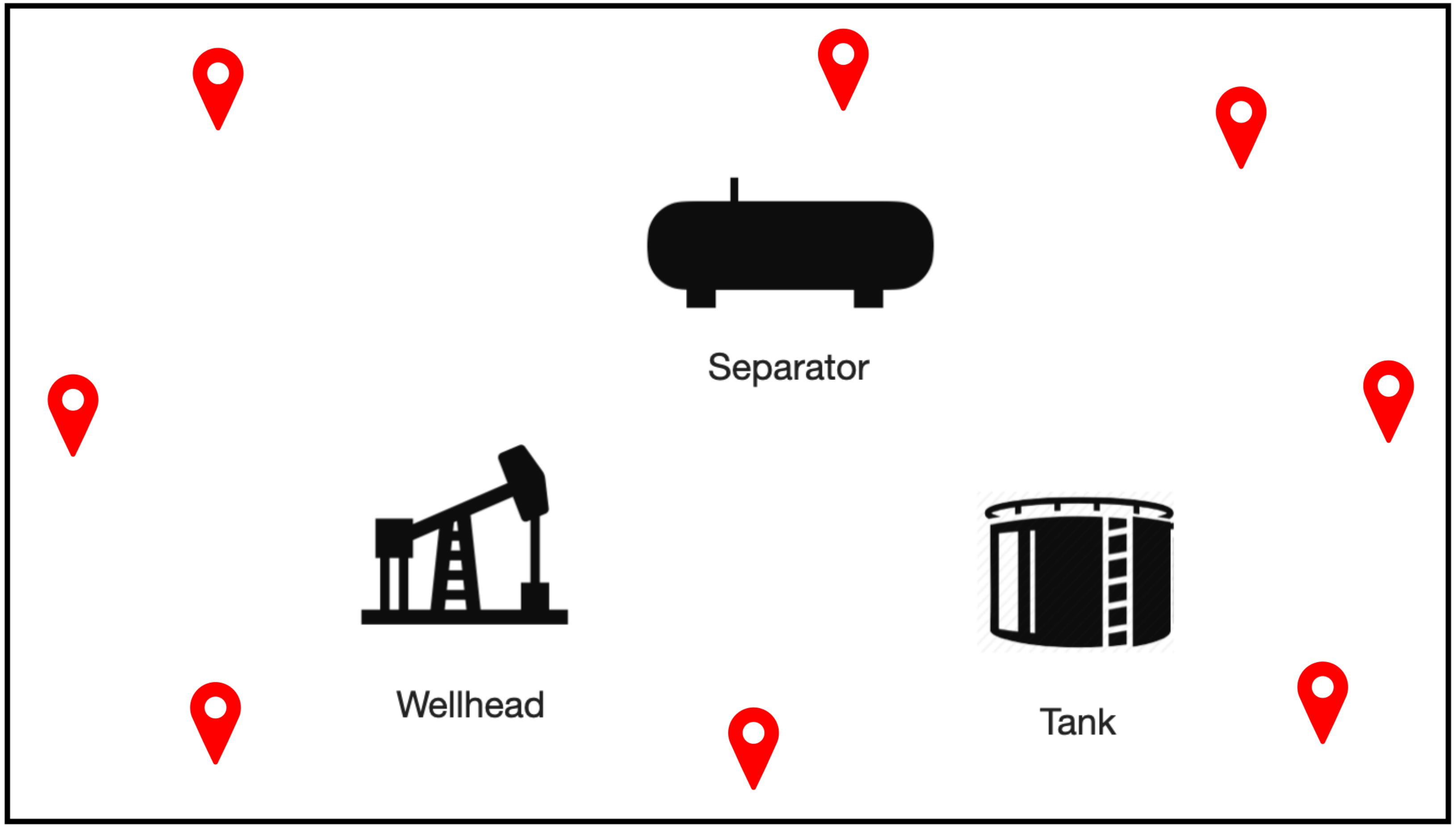
Problem Setup

- CMS sensor placement



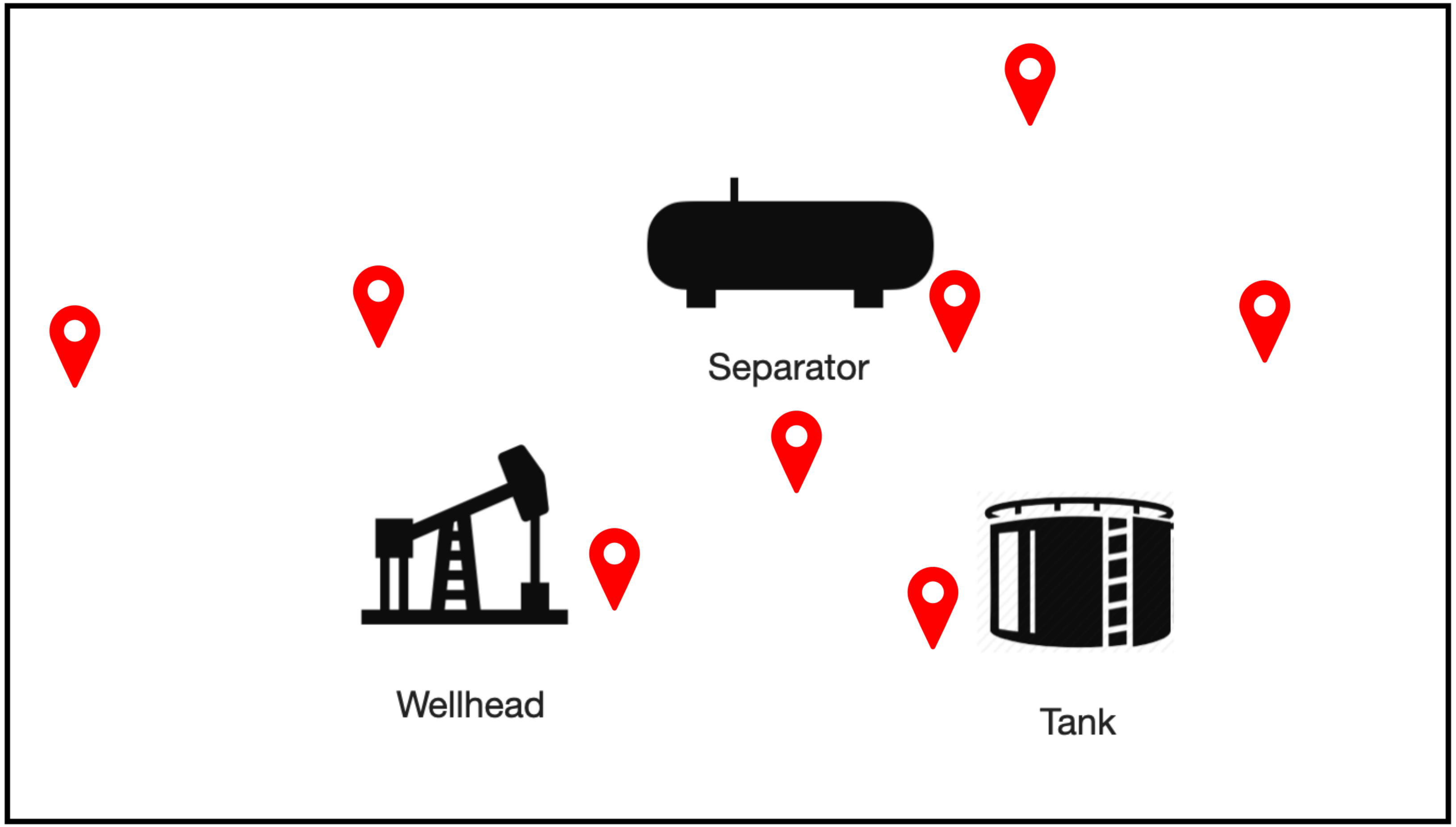
Problem Setup

- CMS sensor placement



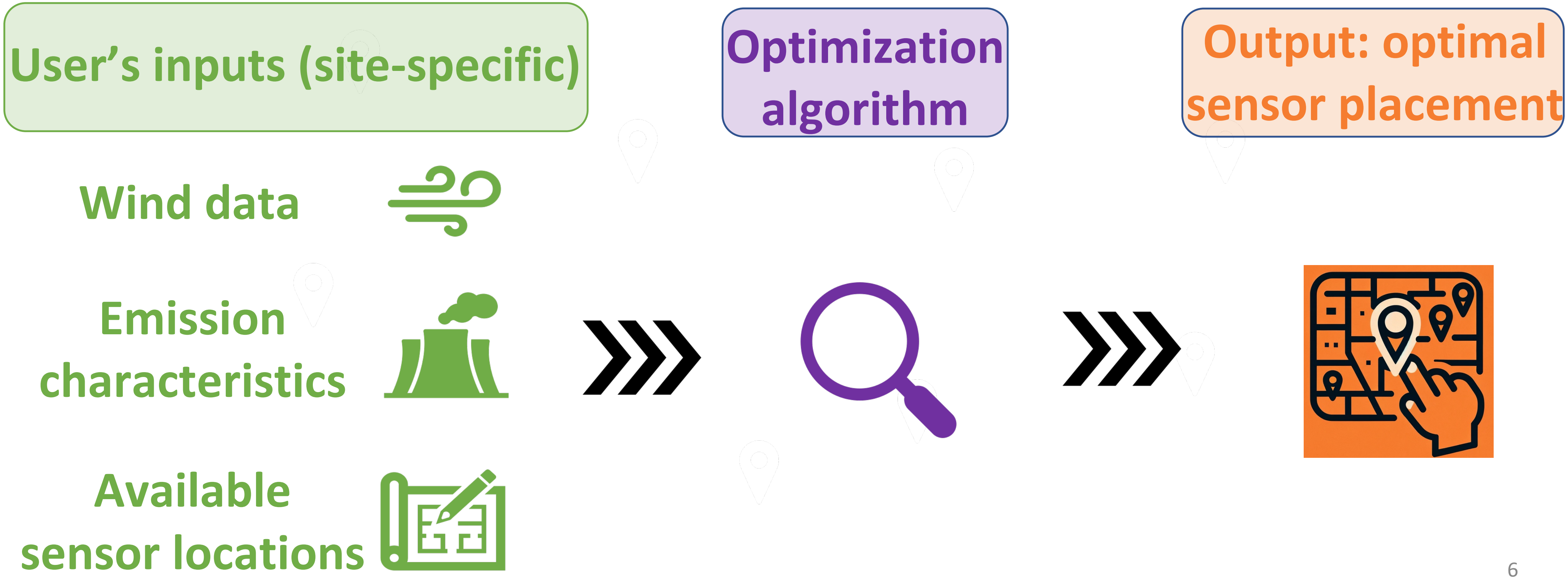
Problem Setup

- CMS sensor placement

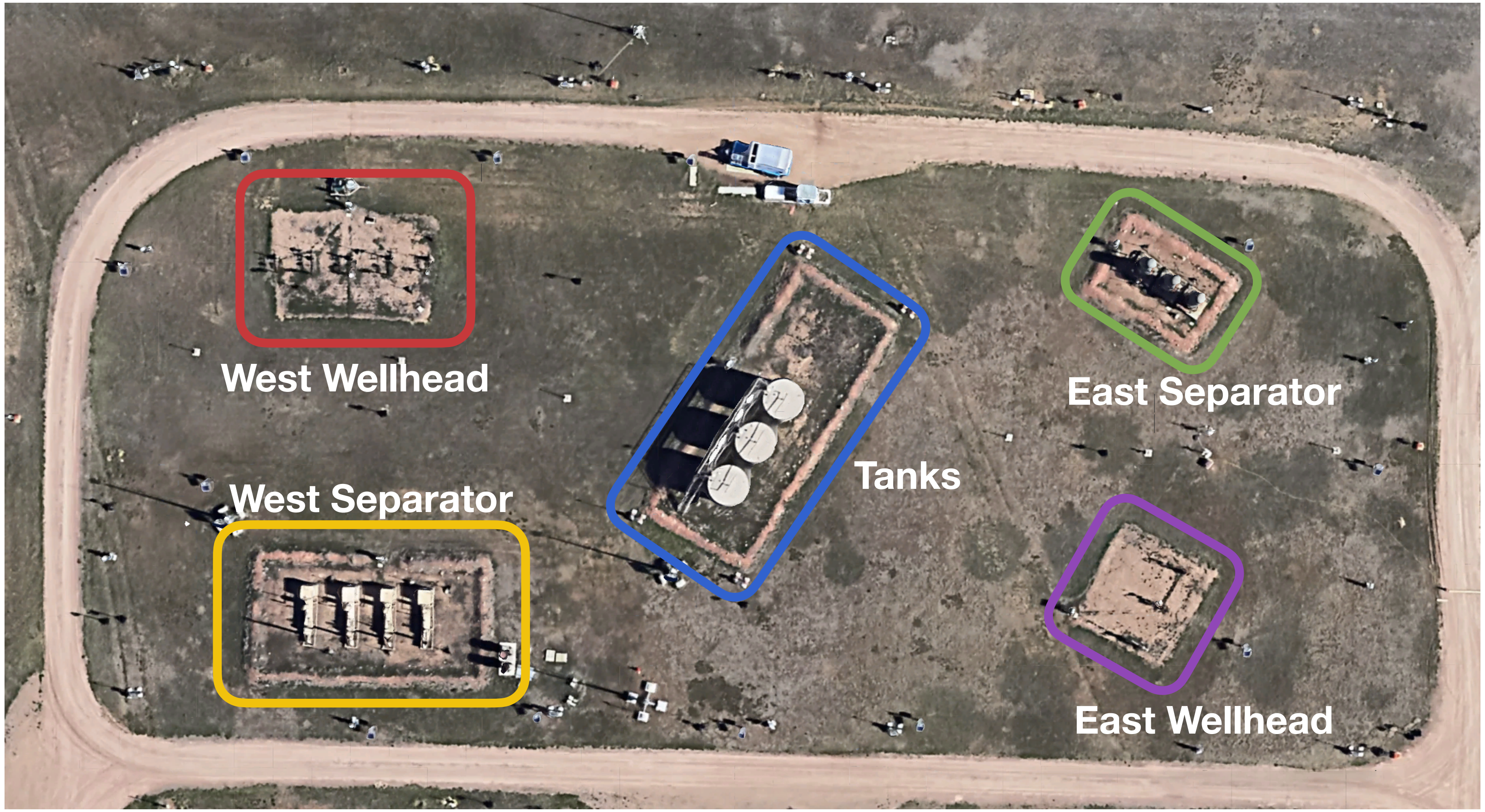


Problem Setup

- A data-driven algorithm to optimize sensor placement for best emission detection



Experiment Data



METEC Facility, 5 potential emission sources

Algorithm

1. Generate emission scenarios
2. Set possible sensor locations
3. Simulate concentrations & Check detection
4. Optimize sensor placement

Step 1 Generate Emission Scenarios

User's inputs (site-specific)

Wind data

Emission characteristics

Available sensor locations

Optimization algorithm

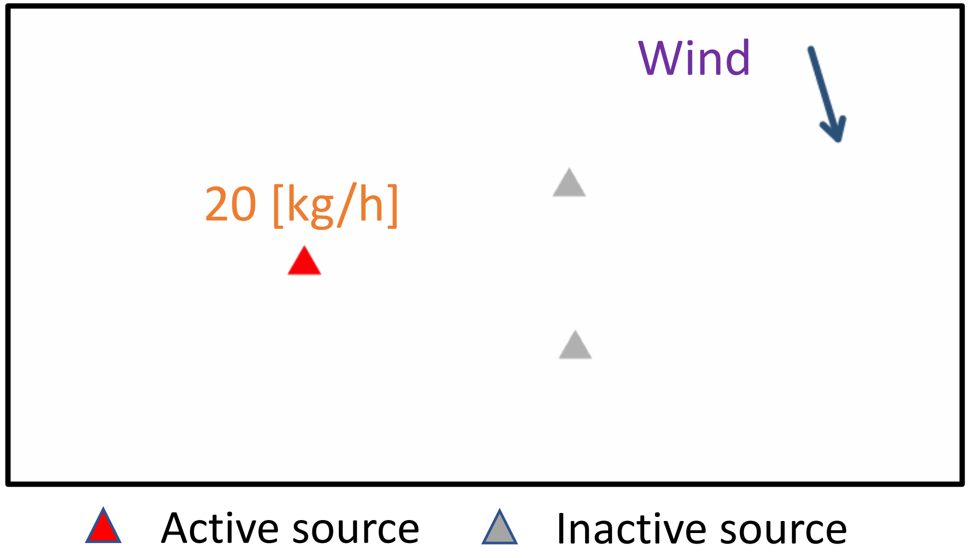
Output: optimal sensor placement

Step 1 Generate Emission Scenarios

A combination of

- wind speed time series
- wind direction time series
- emission source location
- emission rate

defines an emission scenario.



- Estimate probability distributions of wind & emission to sample → 38,130 emission scenarios

Step 2 Set Possible Sensor Locations

User's inputs (site-specific)

Emission scenarios
(# = 38,130)

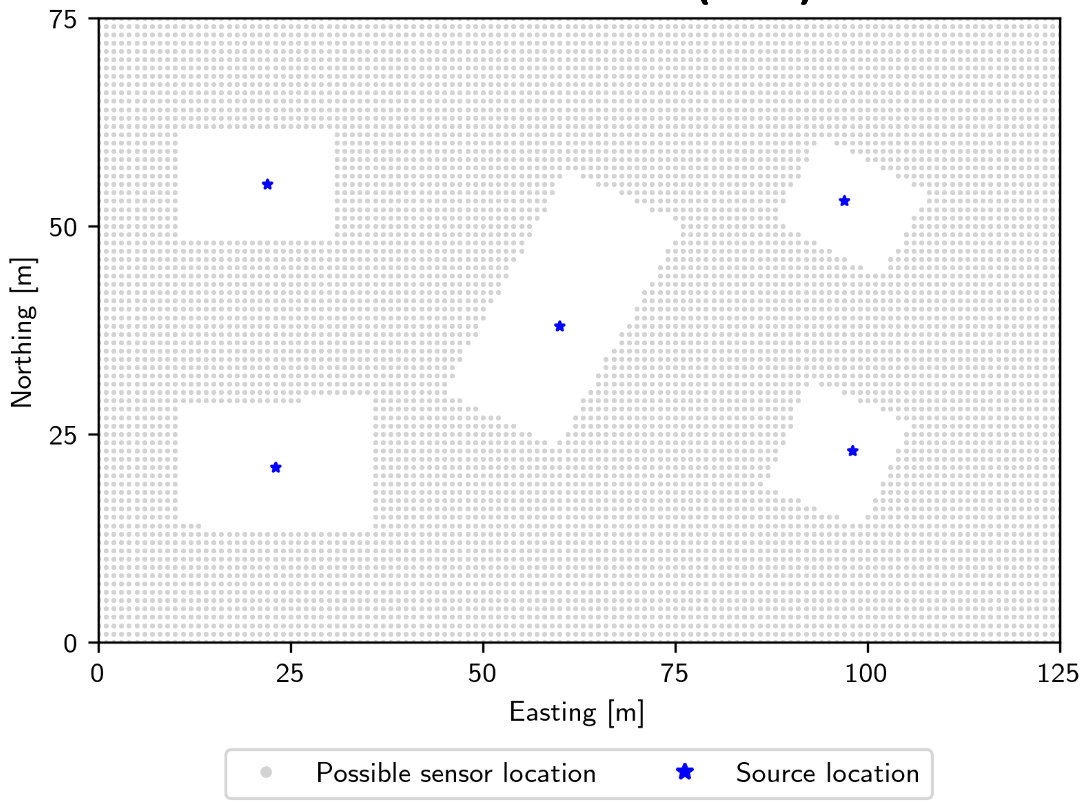
Available
sensor locations

Optimization algorithm

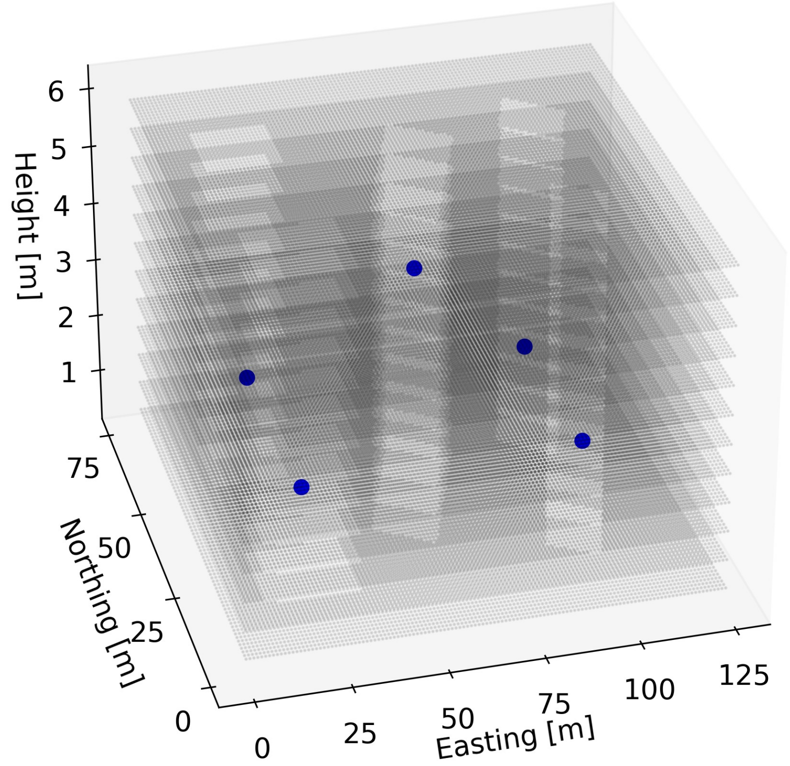
Output: optimal sensor placement

Step 2 Possible Sensor Locations

METEC site (2D)



METEC site (3D)



resolution = 1 m for Northing & Easting; = 0.5 m for vertical

possible locations = 96,840

Step 3 Concentration Simulation & Detection

User's inputs (site-specific)

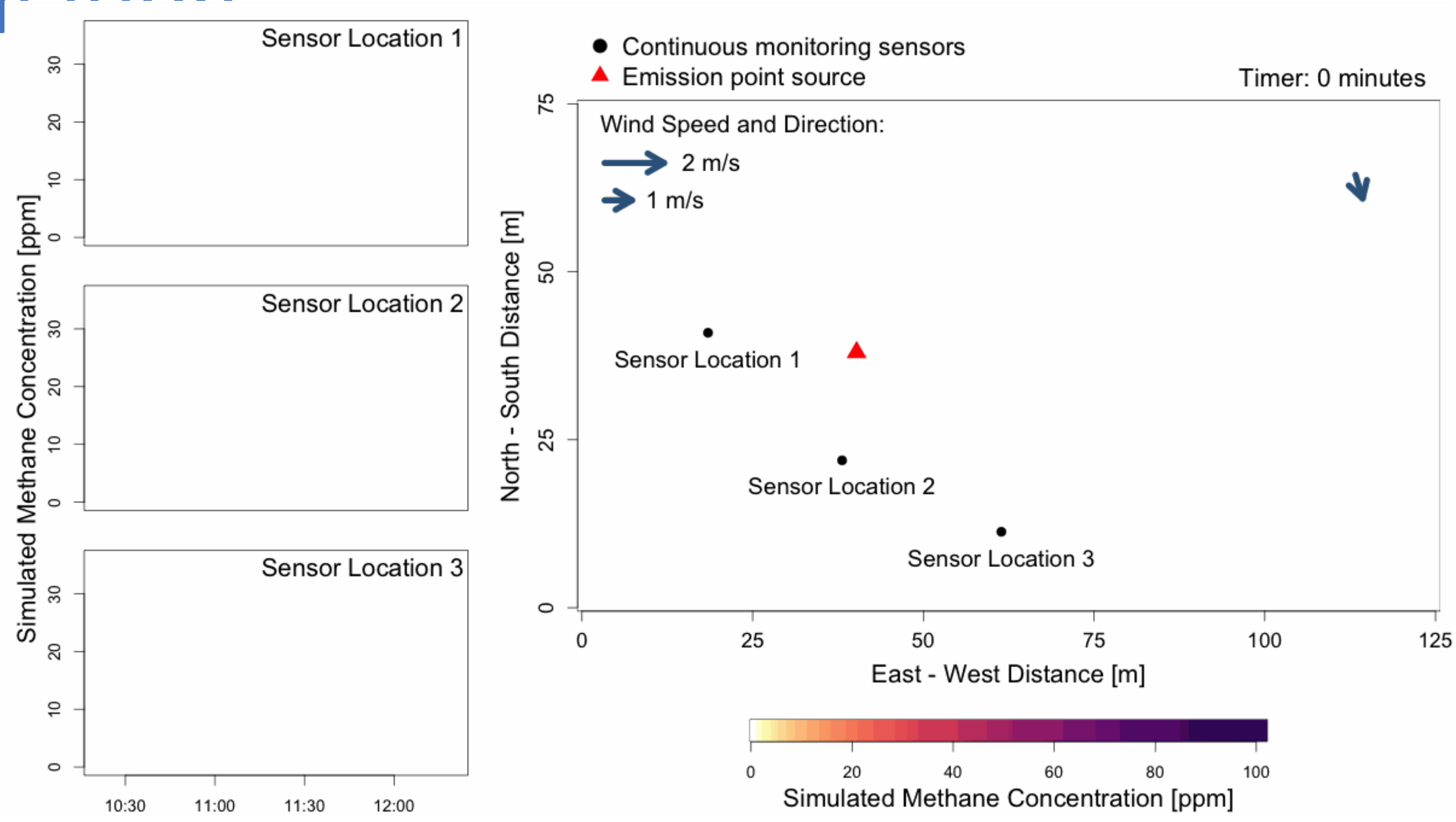
Emission scenarios
(# = 38,130)

Sensor locations
(# = 96,840)

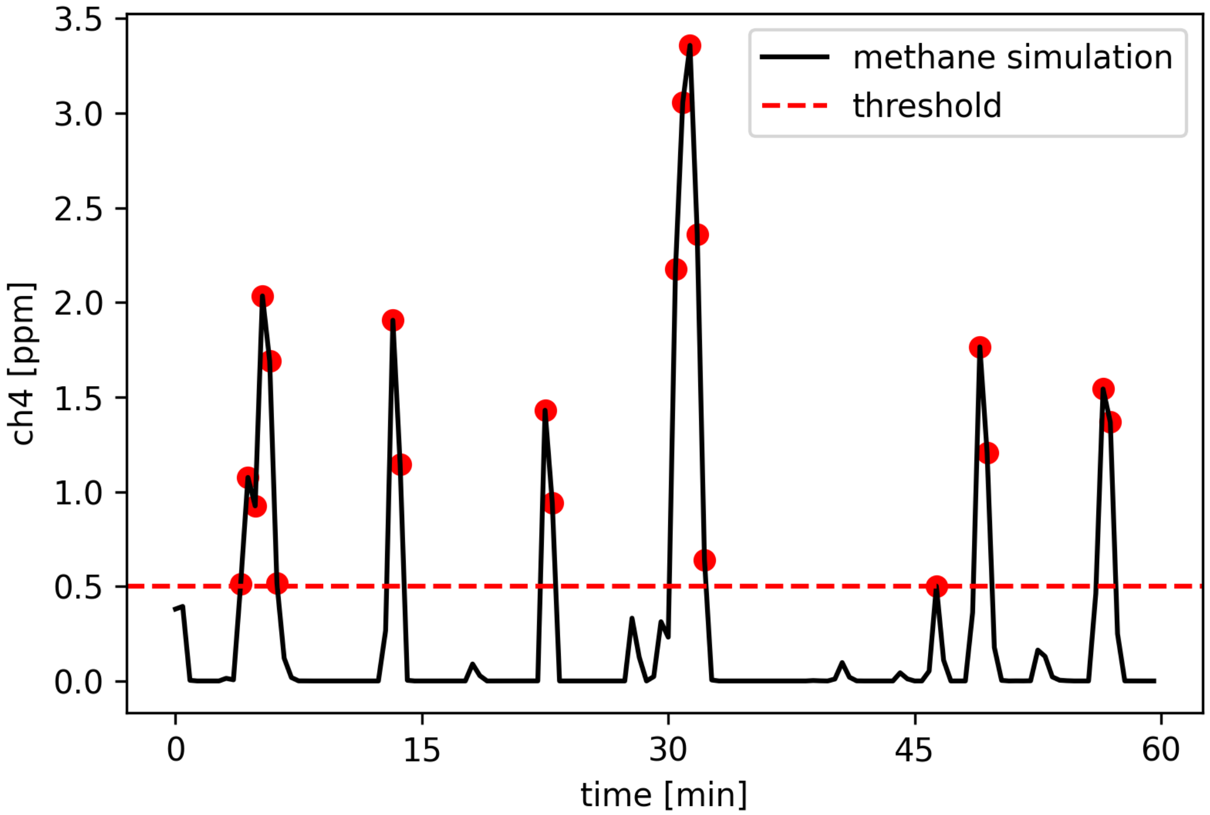
Optimization algorithm

Output: optimal sensor placement

Step 3.1 Gaussian puff simulation



Step 3.2 Detection



Example of simulated concentrations and detection for Emission Scenario j at Sensor Location i

Step 4 Optimize Sensor Placement

User's inputs (site-specific)

Emission scenarios
(# = 38,130)

Sensor locations
(# = 96,840)

Optimization algorithm

Output: optimal sensor placement

Step 4 Optimization

Rows of D: Sensor Locations (SL)

Cols of D: Emission Scenarios (ES)

$D_{ij} = 0$, if $\mathrm{SL_i}$ can detect ES_j;
$D_{ij} = 1$, otherwise

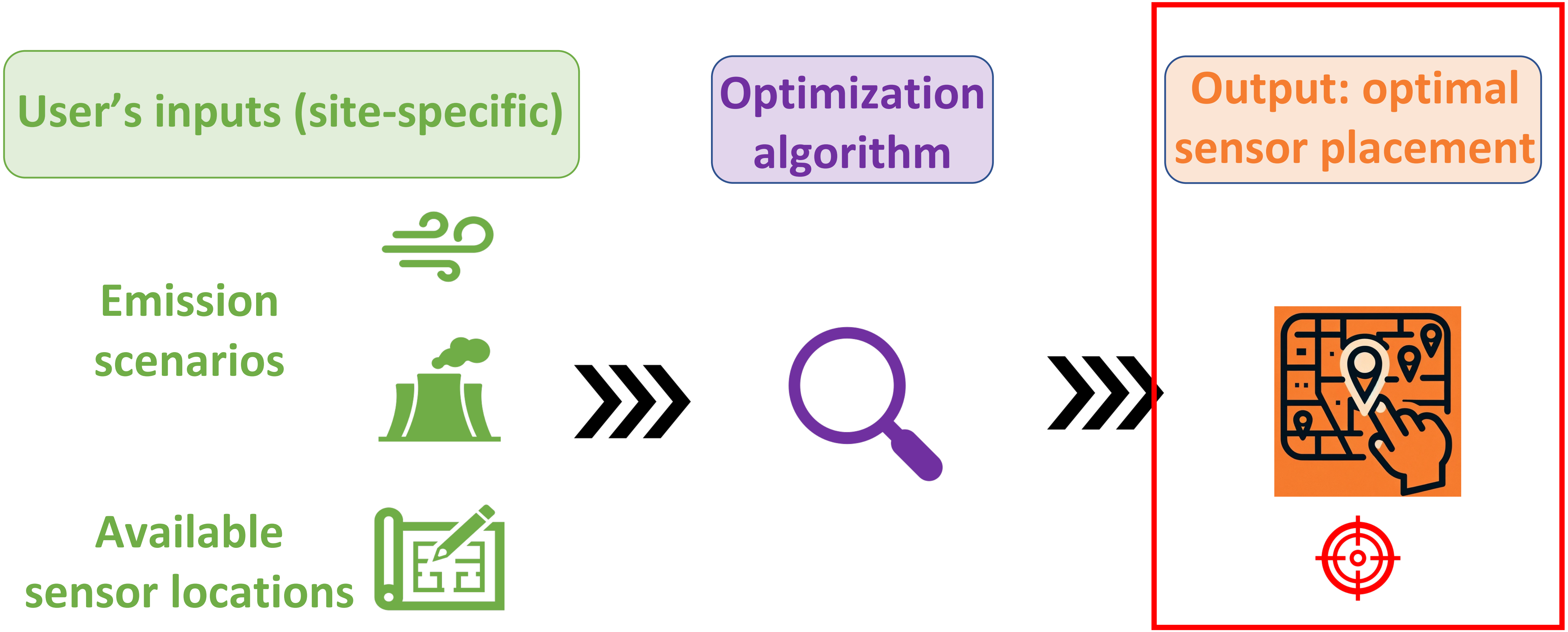
Evolutionary Algorithms
+
Pareto Optimization

	ES_1	ES_2	$\cdots$	ES_j	$\cdots$	ES_M
SL_1	1	1	$\cdots$	0	$\cdots$	1
SL_2	1	0	$\cdots$	0	$\cdots$	1
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\ddots$	$\vdots$
SL_i	0	0	$\cdots$	1	$\cdots$	1
$\vdots$	$\vdots$	$\vdots$	$\ddots$	$\vdots$	$\ddots$	$\vdots$
SL_N	1	1	$\cdots$	1	$\cdots$	1

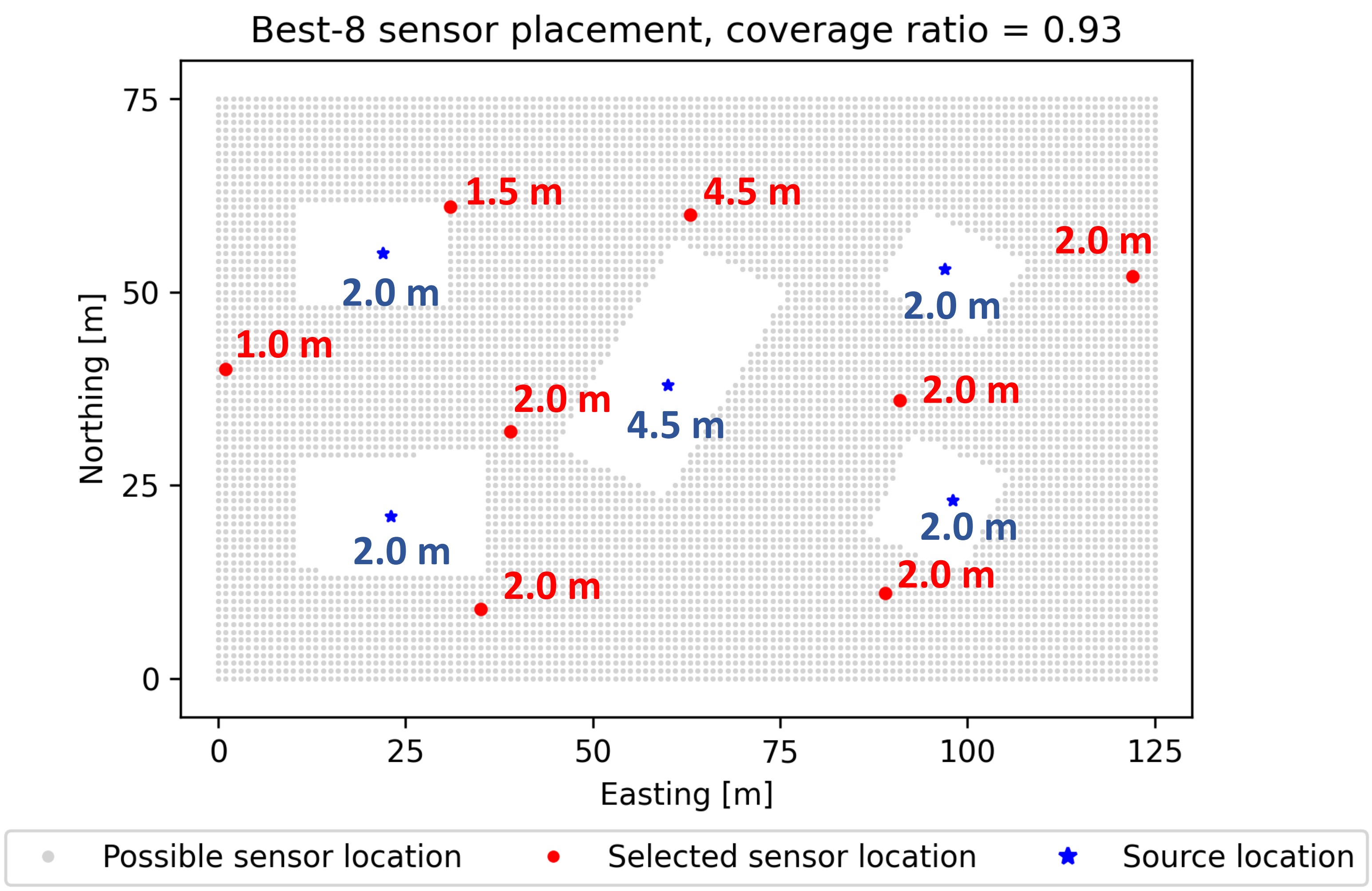
Detection Matrix D

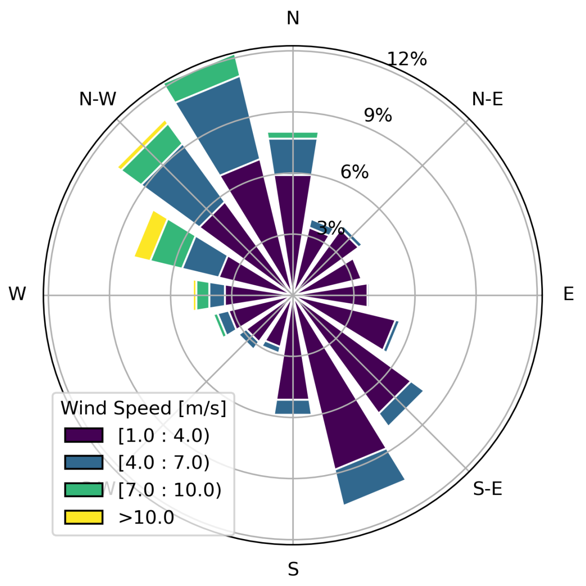
$\mathrm{N} = 96{,}840; M = 38{,}130$

Results

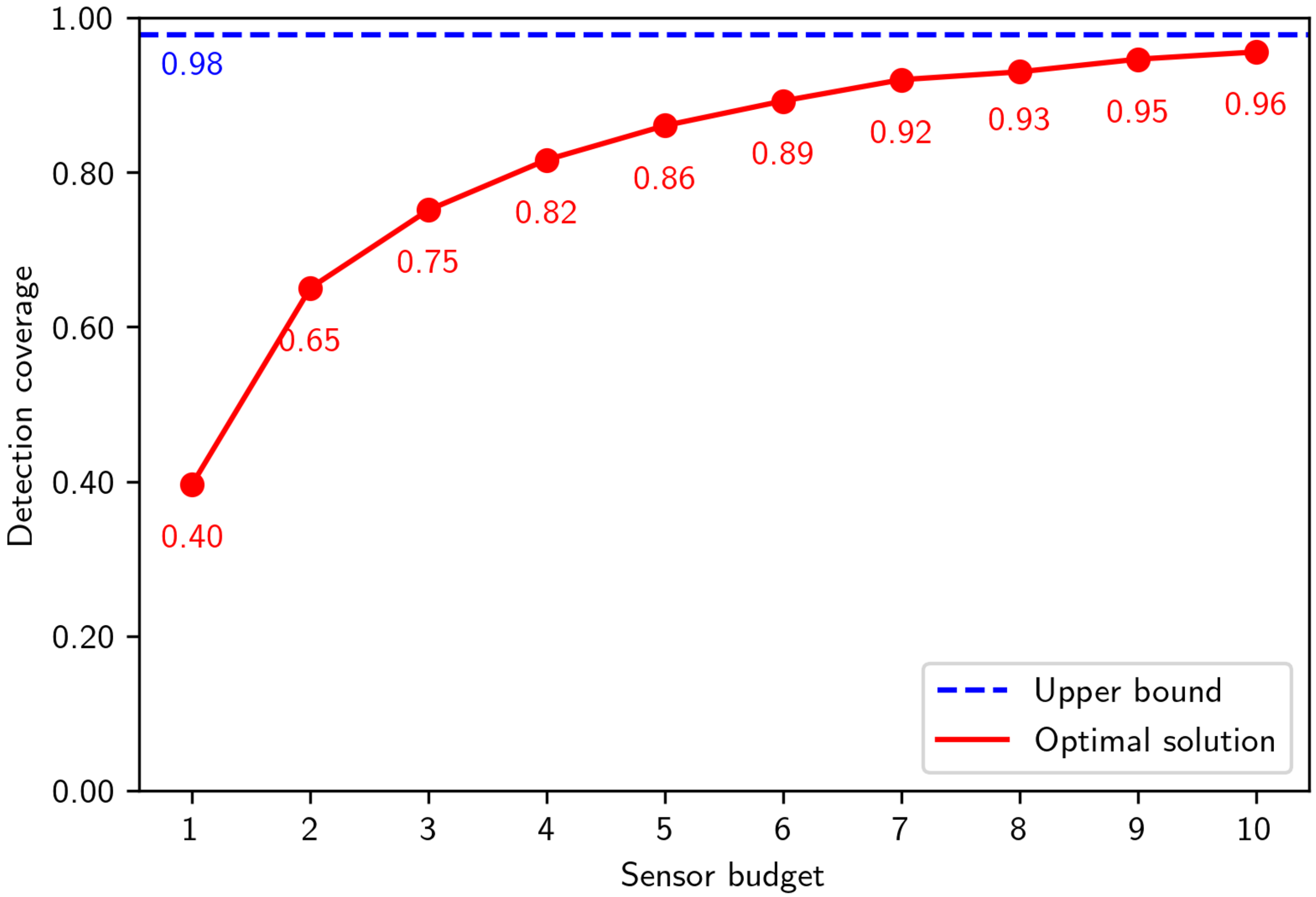

User's inputs (site-specific)
Emission scenarios
Available sensor locations
Optimization algorithm
Output: optimal sensor placement

Results: Best 8-sensor placement





Results: Budget vs. coverage



Thank you for attending!

Questions?

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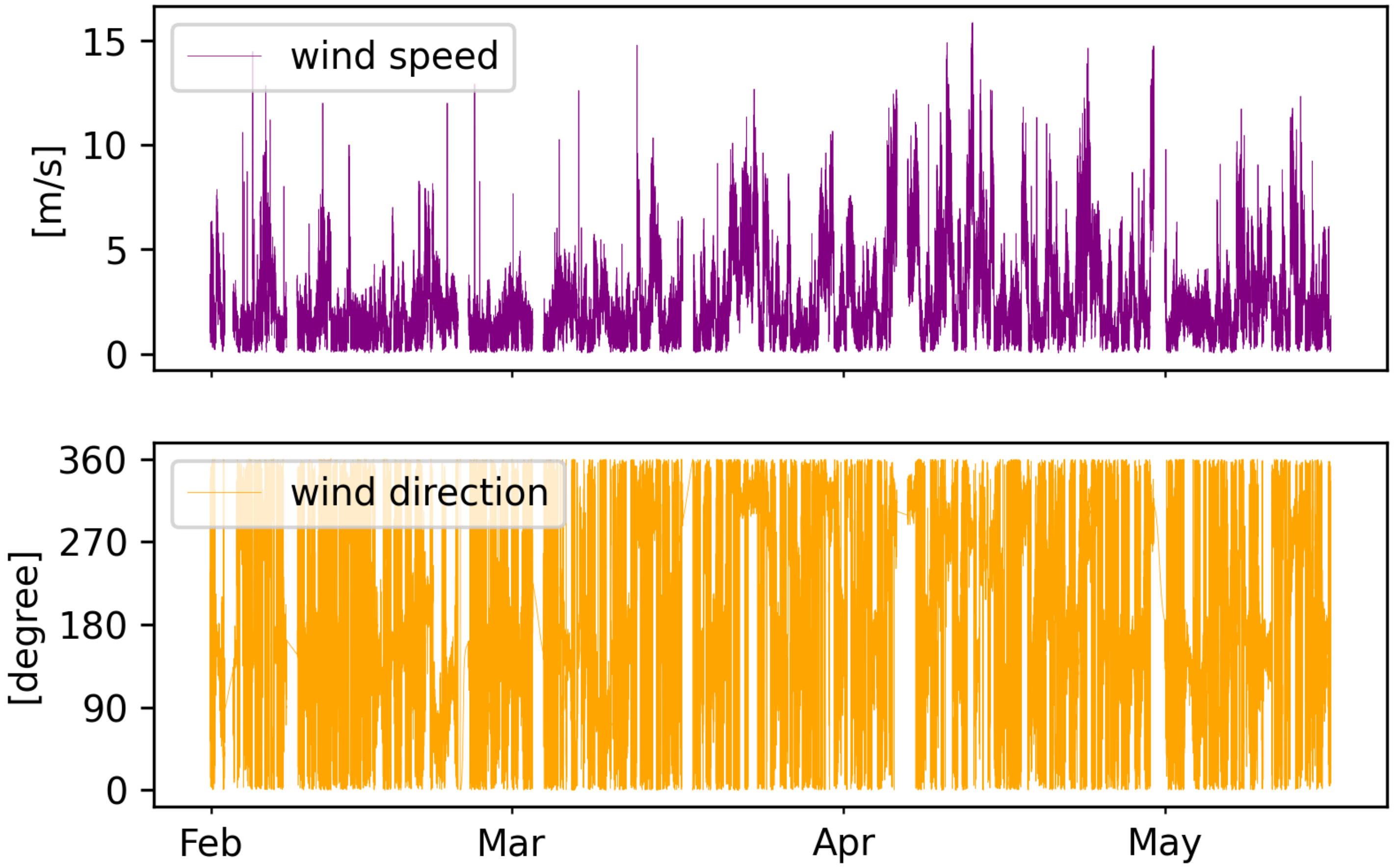
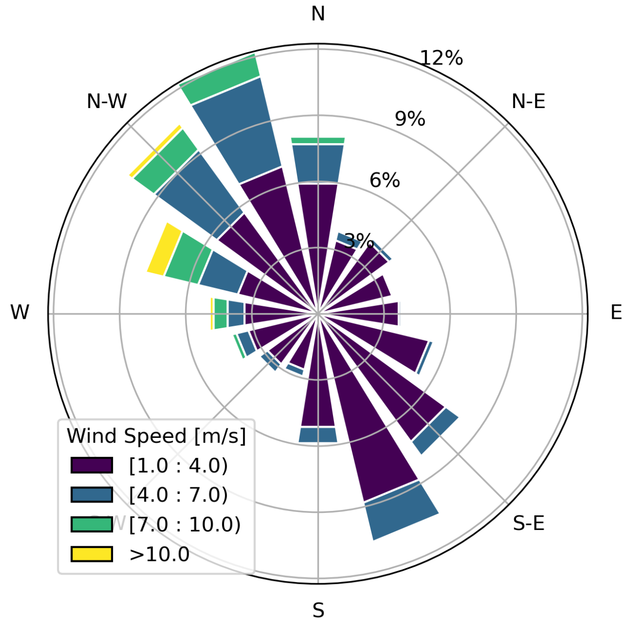
Back up

Experiment Data





Wind Data on METEC, February through May 2022

Step 4.2 Pareto Optimization & EA

Pareto Optimization

Objectives:

Find a subset of rows (a solution) from the detection matrix to

- maximize emission scenario coverage.
- minimize the size of the subset.

Exhaustive search and standard linear programming algorithms are impossible for large-scale problem!

Evolutionary Algorithms

Process:

1. Randomly initialize a population of solutions.
2. Propose new solutions by perturbing existing solutions.
3. Update the population by eliminating worse solutions.
4. Repeat Step 2 & 3 until converge.
5. Return the best k-size solution.

Conclusions & Future Work

- Developed a data-driven algorithm for sensor placement more accurate and efficient than traditional methods.
- The algorithm's modularity ensures adaptability to various monitoring needs.
- Optimized for solving large-scale problems efficiently.
- To implement a generative model for better approximation of wind distributions, thereby expanding the emission scenario database.
- To investigate advanced data embedding techniques to manage and solve problems of greater scale.

References

- Klise, Katherine A., et al. "Sensor placement optimization software applied to site-scale methane-emissions monitoring." *Journal of Environmental Engineering* 146.7 (2020): 04020054.

- Qian, Chao, Chao Bian, and Chao Feng. "Subset selection by pareto optimization with recombination." *Proceedings of the AAAI Conference on Artificial Intelligence*. Vol. 34. No. 03. 2020.

Close sensor locations

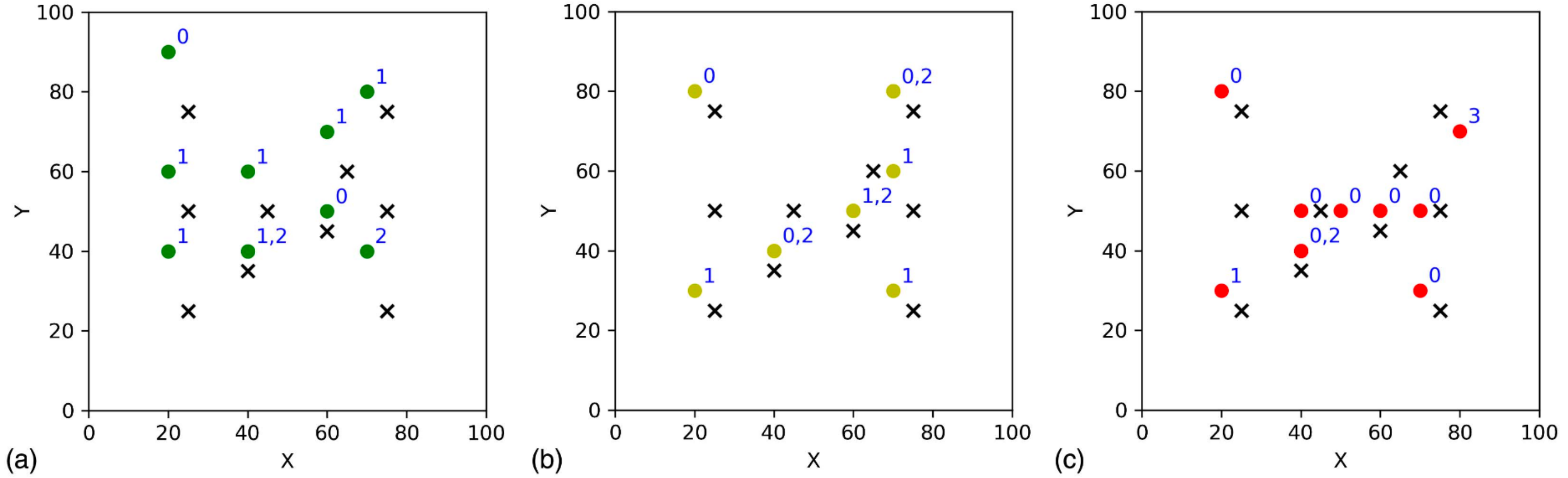
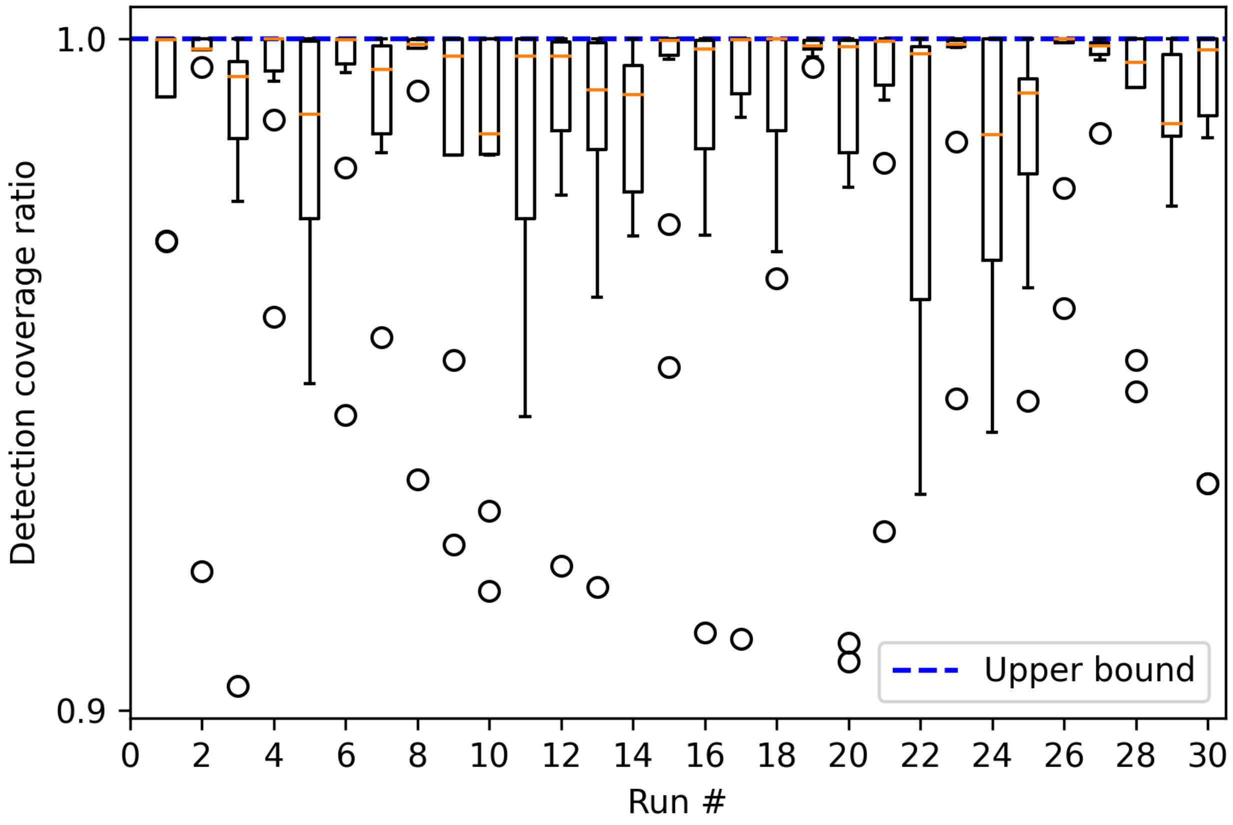


Fig. 9. Optimal sensor placements with 10 sensors maximizing scenario coverage considering (a) high-sensitivity; (b) moderate-sensitivity; and (c) low-sensitivity sensors. X's represent the potential leak locations. The height of each sensor is noted (some sensors overlap in plan-view).

Figure 9 in Klise et al. (2020)

Test EA on synthetic large matrix

- nrows = ncols = 100,000
- k = 10, randomly placement in the big matrix
- Test on 30 cases and run 10 EA algorithm for each case



Optimality Guarantee

- In theory, we prove that for subset selection with monotone objective functions, PORSS can achieve the optimal polynomial-time approximation guarantee, $1 - e^{\gamma}$ where γ is the submodularity ratio measuring how close your objective function is to submodularity.

Related Work

	Klise et al. (2020)	Our work
# emission scenarios	1,200	$\approx$ 40,000
# possible sensor locations	$\approx$ 2,500	$\approx$ 100,000
Forward model	Gaussian plume	Gaussian puff
Optimization algorithm	Mixed-integer linear programming	Pareto optimization using evolutionary algorithm (EA)

Pareto Optimization Algorithm

- General subset selection problem

  Given all items $V = \{v_i\}, i = 1,2, \ldots, N$, an objective function g and a budget k, to find a subset of at most k items maximizing g, i.e.,

$$\underset{S \subseteq V}{\operatorname{argmax}}\, g(S) \;\; \text{s.t.}\ |S| \leq k$$

  - In our case, V is the set of rows of the detection matrix D
  - g is the number of 0s in the column product of D^S (the k-row submatrix of D)

Pareto Optimization Algorithm

- Pareto Optimization
  - Find optimal solutions to two conflicting objectives

$$\underset{x \subseteq \{0,1\}^N}{\operatorname{argmax}} \ (g_1(x), g_2(x))$$

where

$$g_1(x) = \begin{cases} -\infty, & |x| \geq 2k \\ g(x), & \text{otherwise} \end{cases} \qquad g_2(x) = -|x|$$

Algorithm

Input: detection matrix D; objective function g; budget k

Parameters: the number I of iterations

Output: a subset of k rows of D

Process:

Let $x = \{0\}^N, P = \{x\}$ and $t = 0$

While $t < T$:

Select x, y from P randomly with replacement

Apply recombination on x, y to generate x', y'

Apply bit-wise mutation on x', y' to generate x'', y''

for each $z \in \{x'', y''\}$:

if $\nexists u \in P$ such that $u \succ z$:

$P = (P \backslash \{u \in P | u \prec z\}) \cup \{z\}$

Check early stop

$t = t + 1$

return $\underset{x \in P, |x| \leq k}{\operatorname{argmax}} g(x)$

$u \succ z \iff$

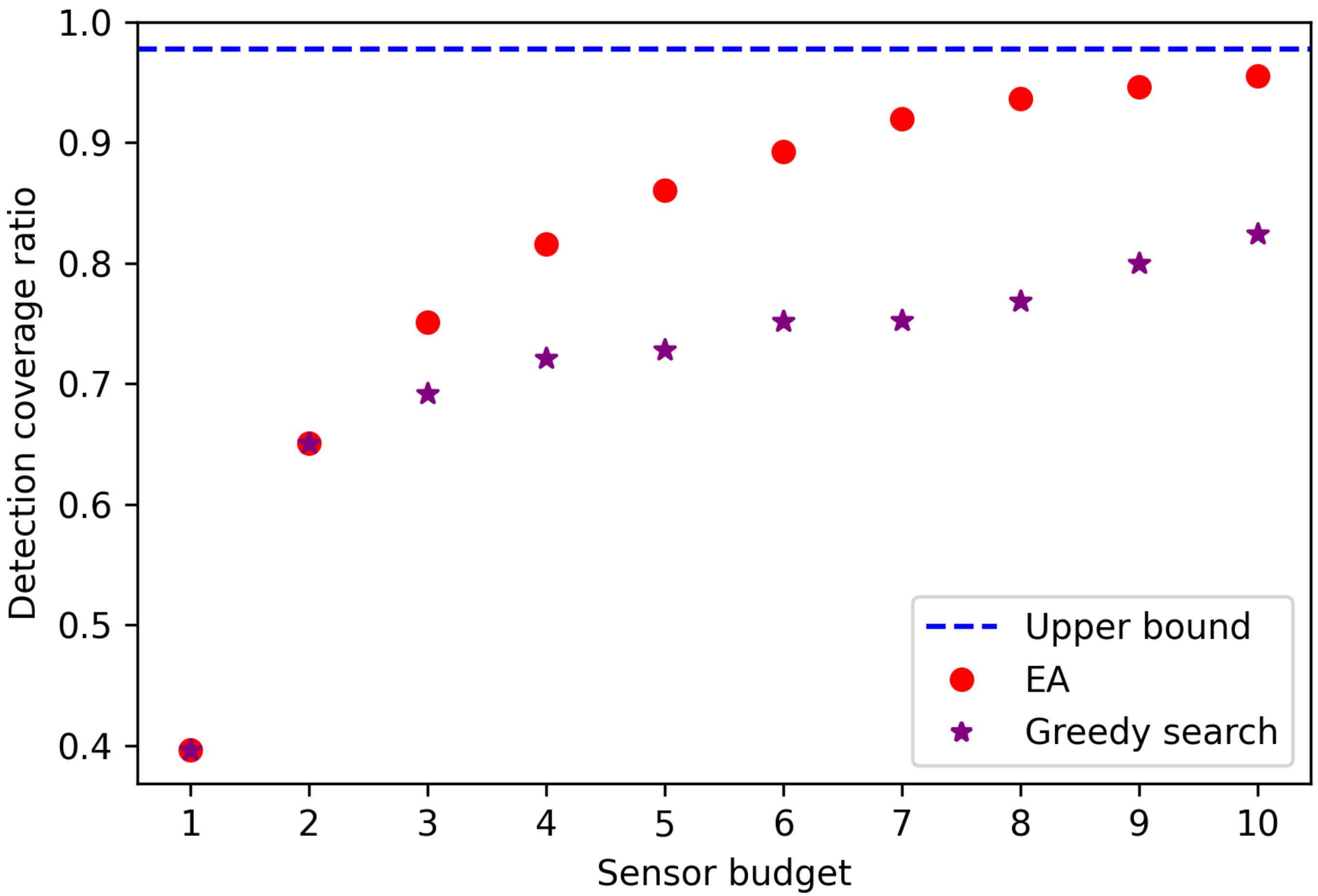
$g_1(u) > g_1(z)$ & $g_2(u) \geq g_2(z)$

or

$g_1(u) \geq g_1(z)$ & $g_2(u) > g_2(z)$

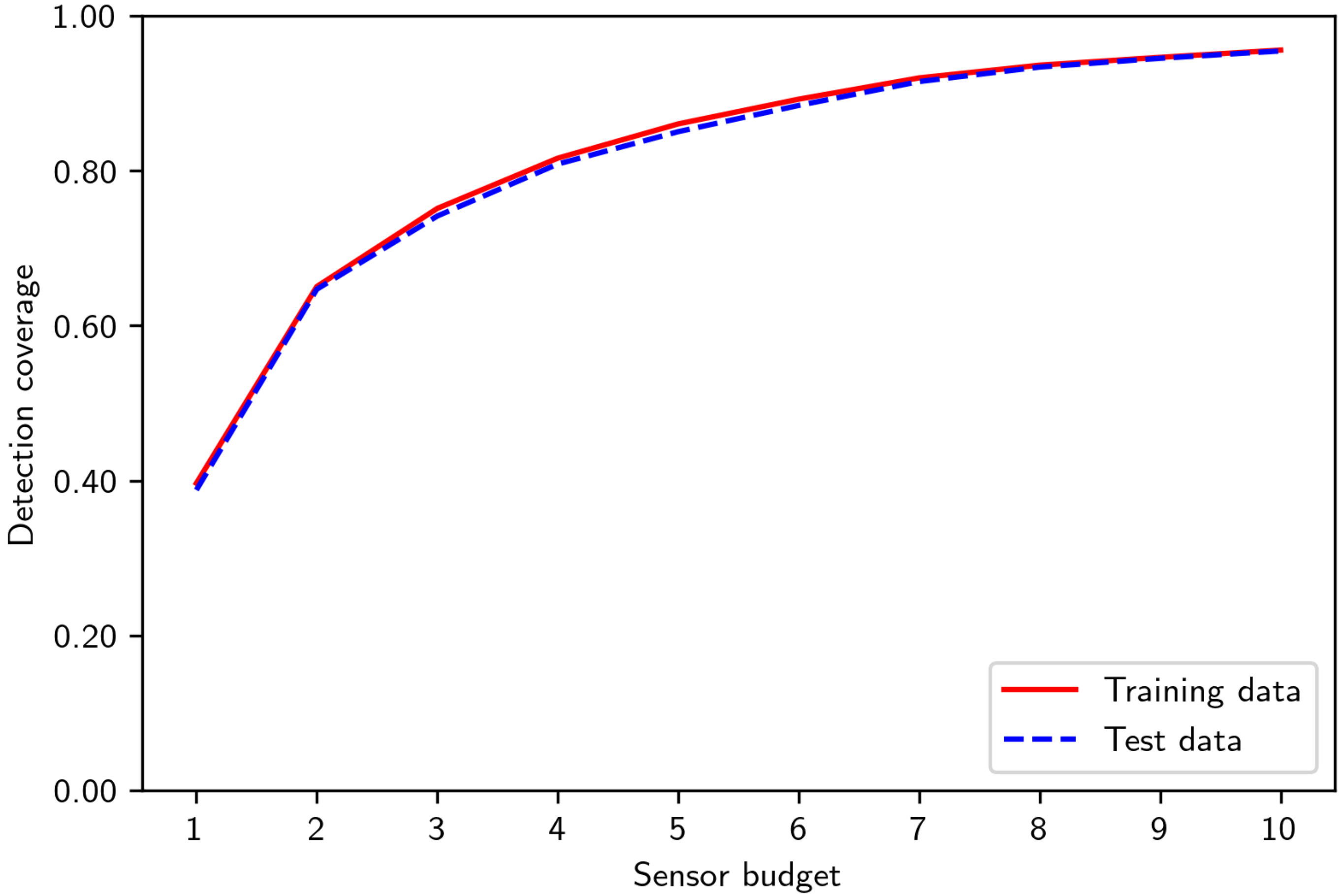
EA vs. Greedy Search

- EA vs. greedy search

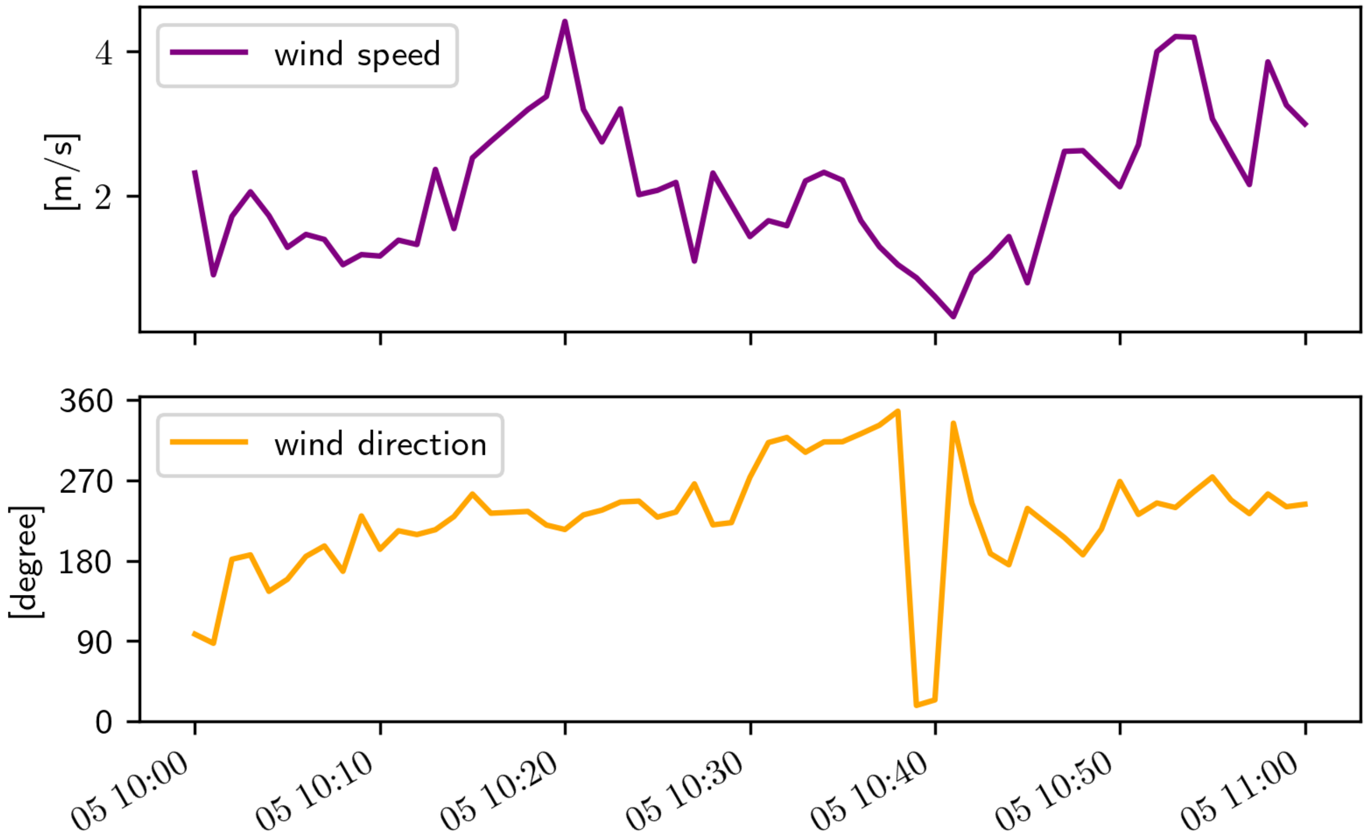


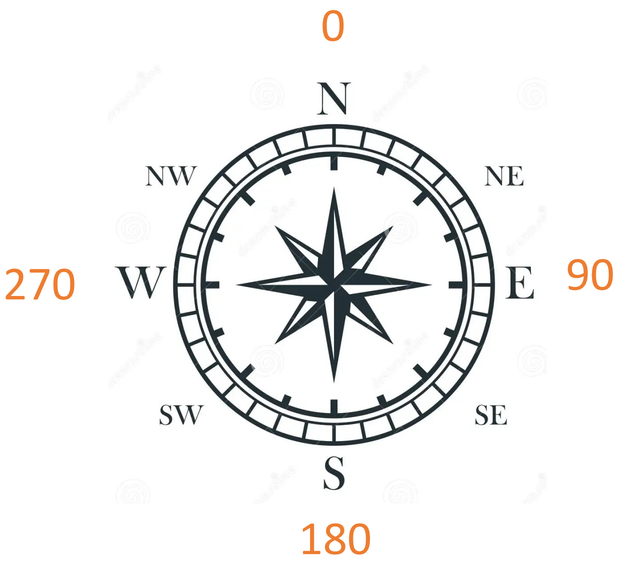
Experiments & Results - robustness

Use a different set of 10,000 emission scenarios to validate the performance of the optimal sensor placement.

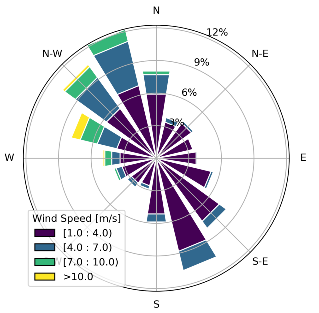


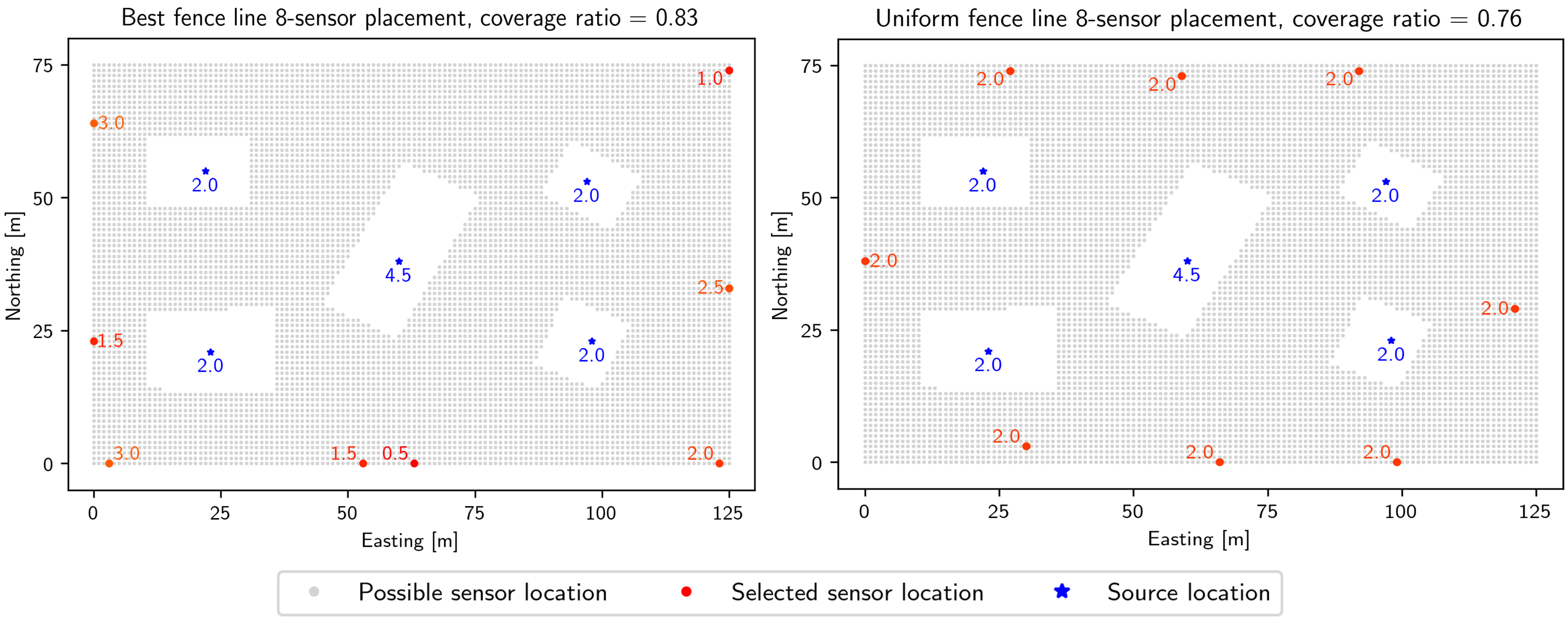
Why some scenarios are always undetected?



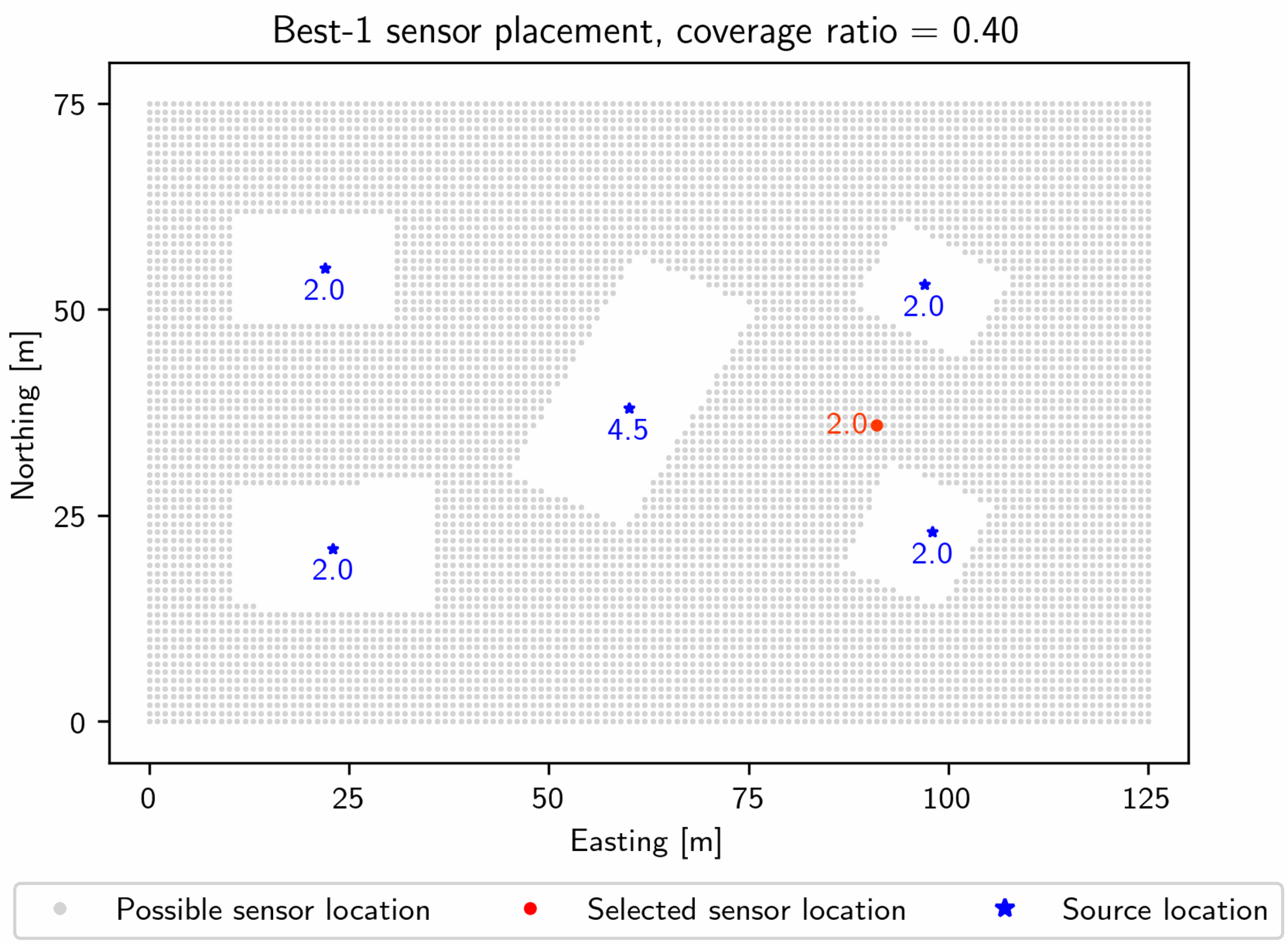


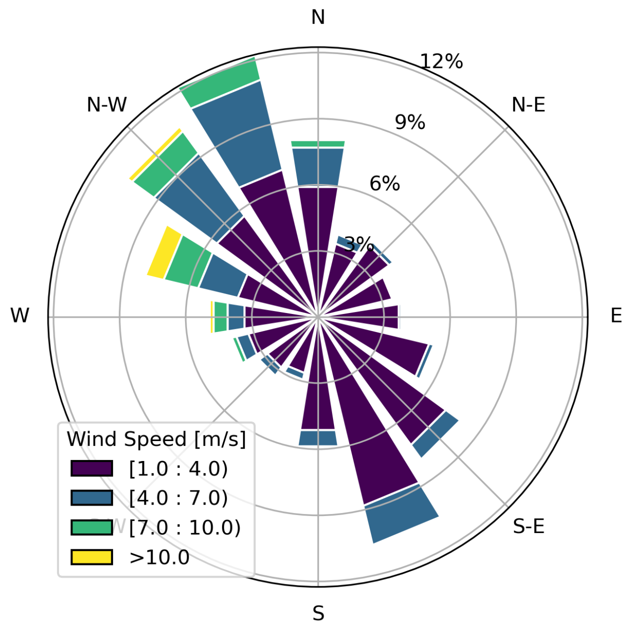
Experiments & Results – fence line placement



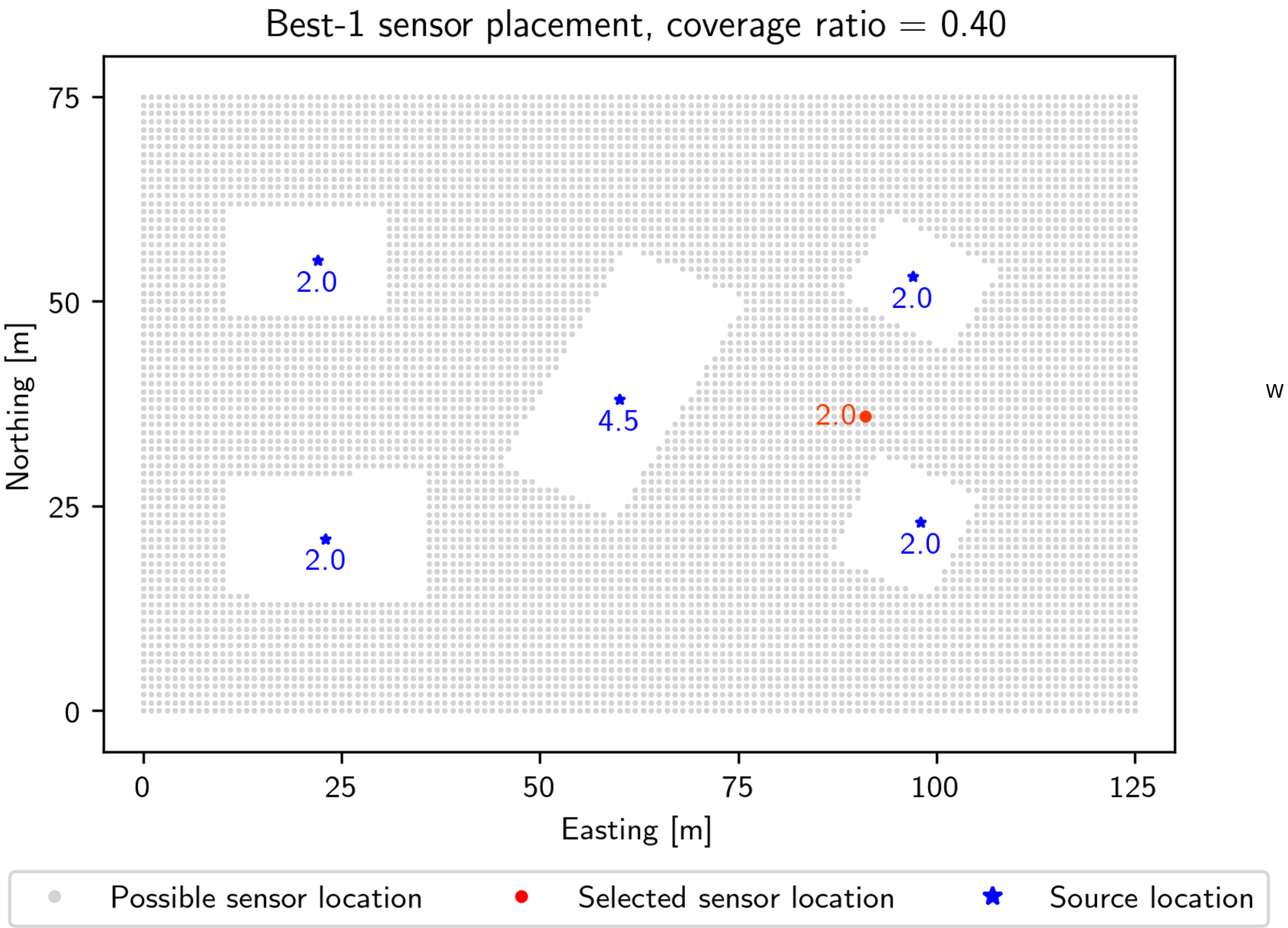


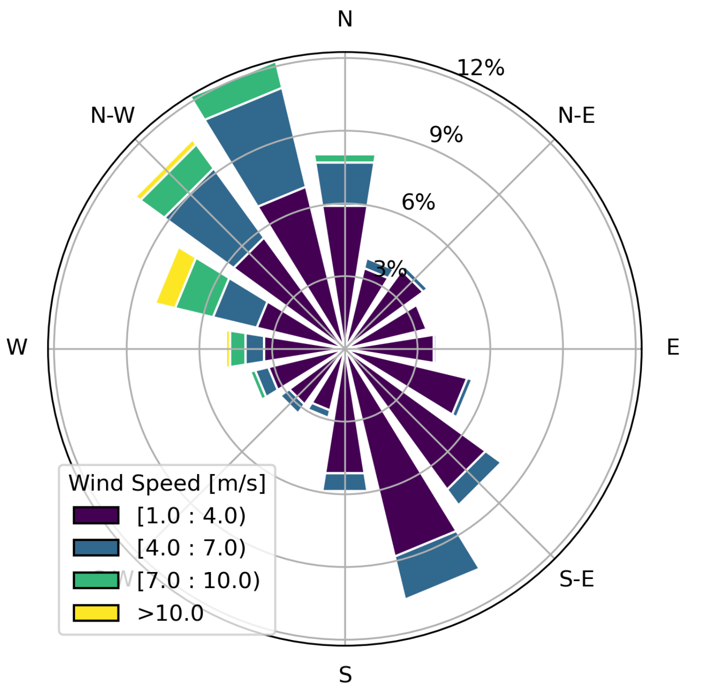
Results: Best k-sensor placement



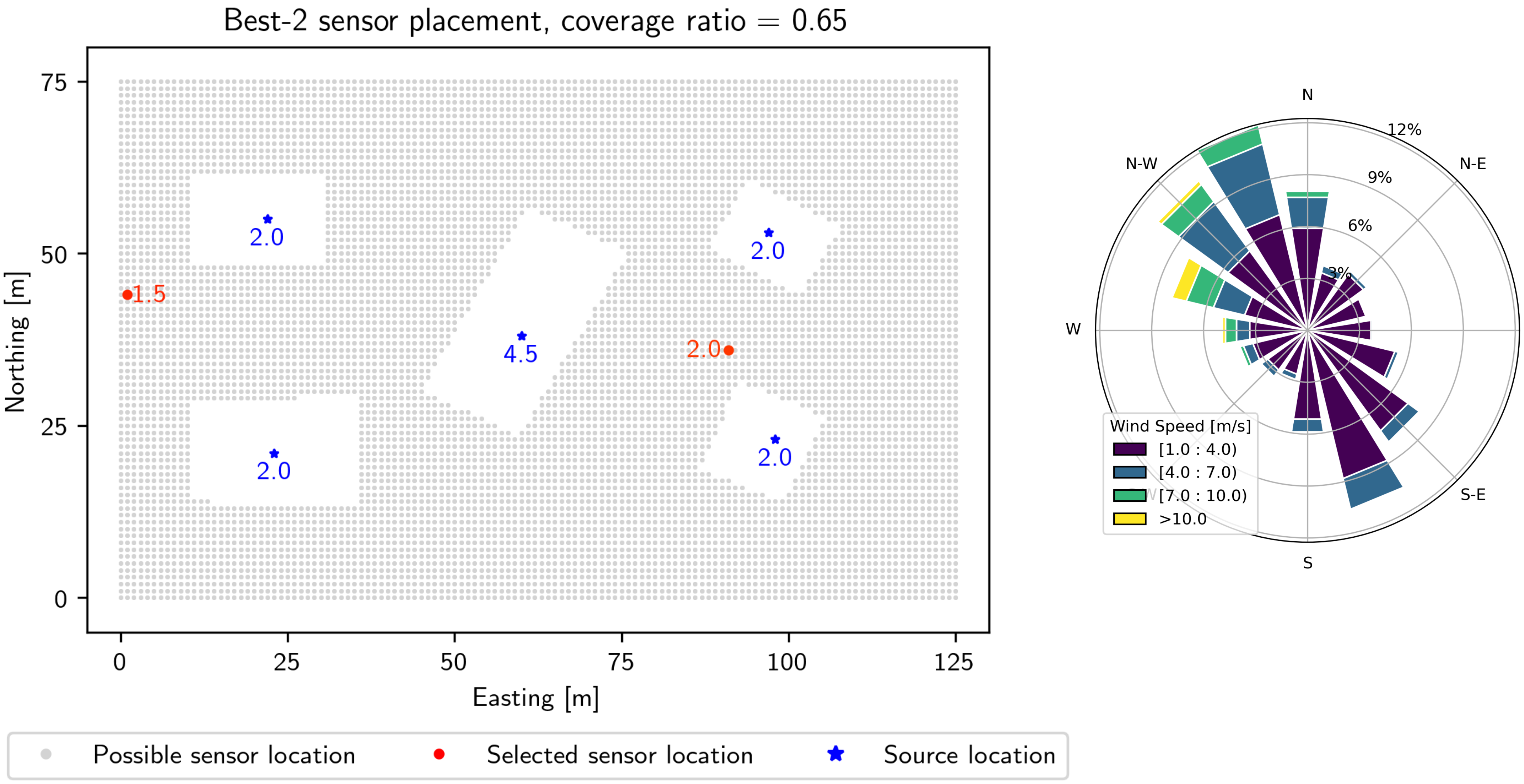


Best-1 Sensor Placement

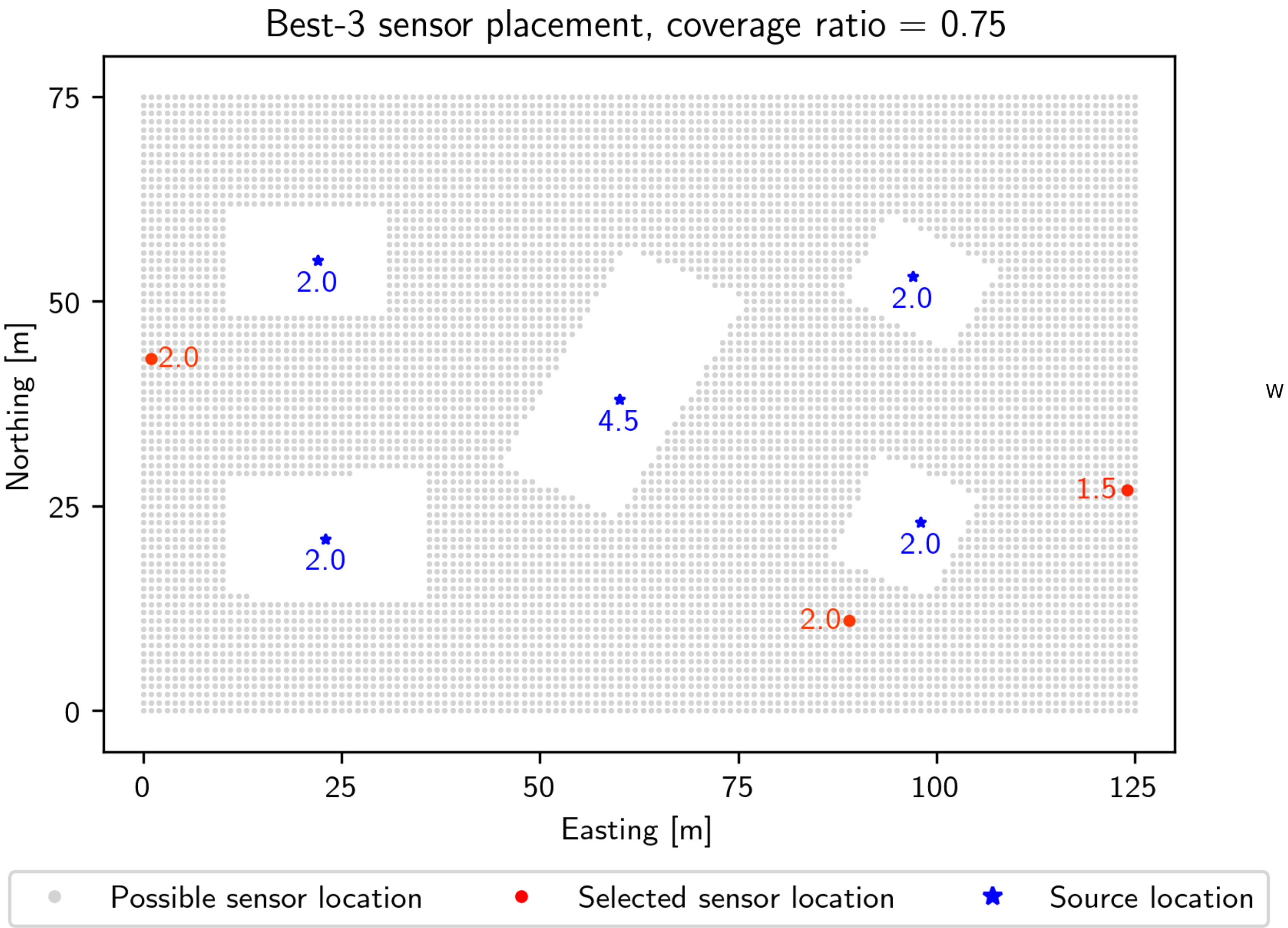


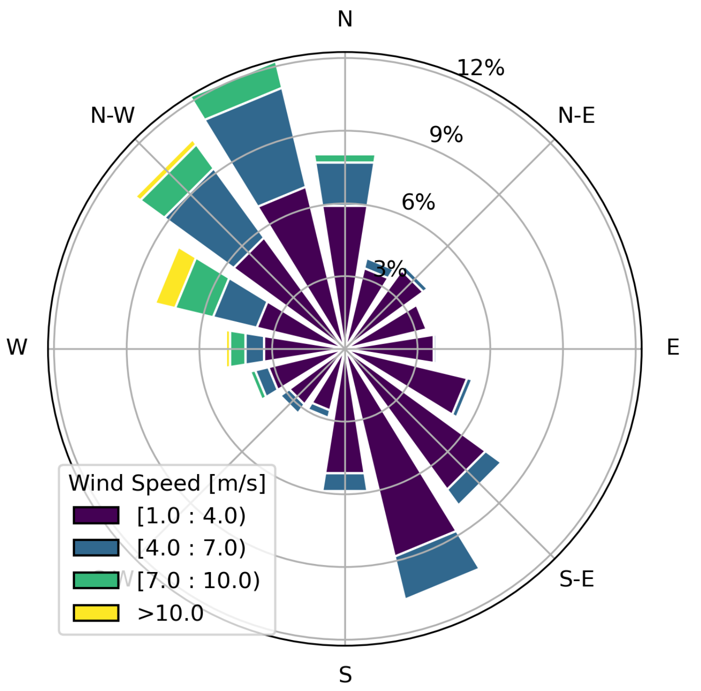


Best-2 Sensor Placement

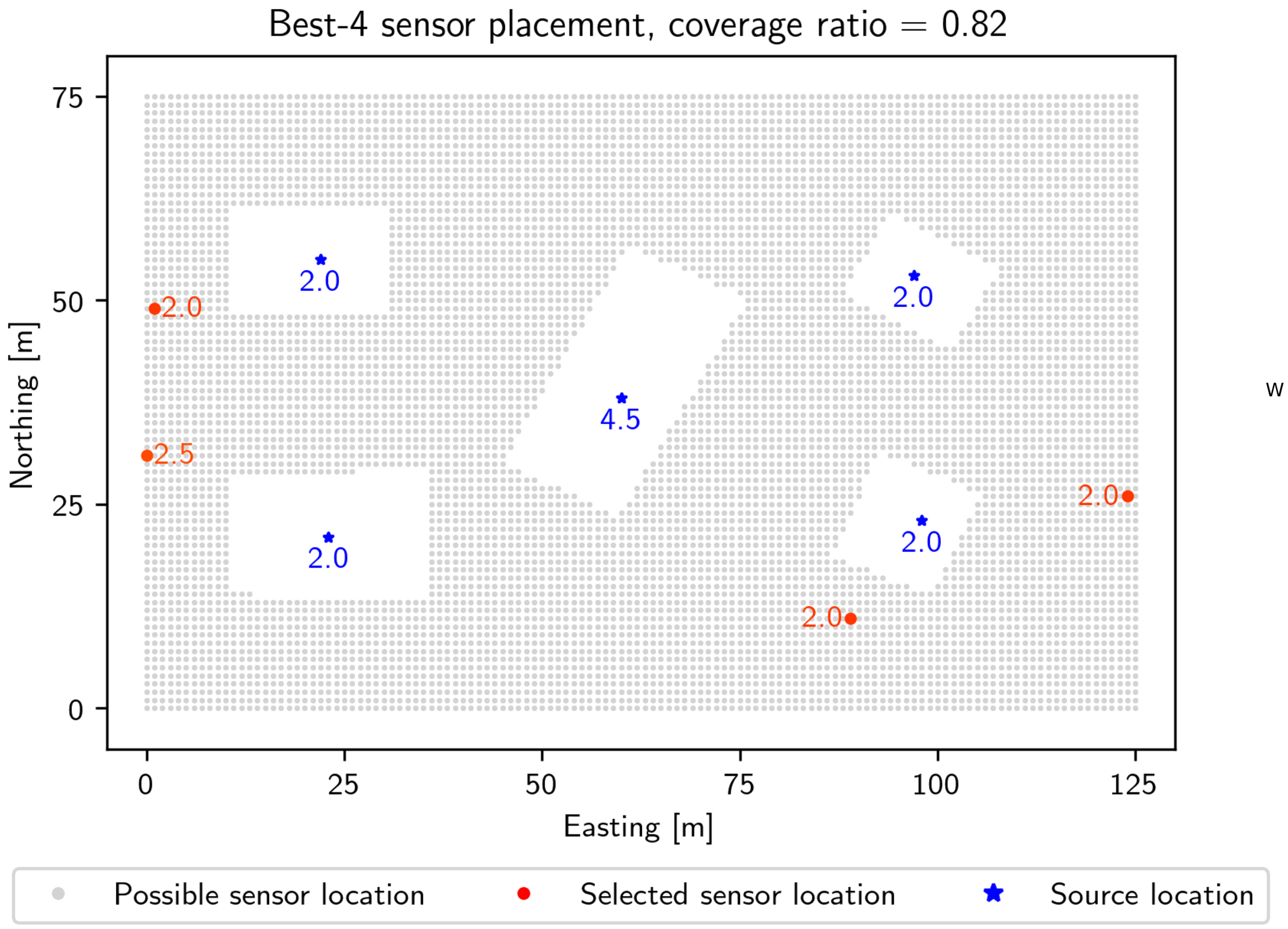


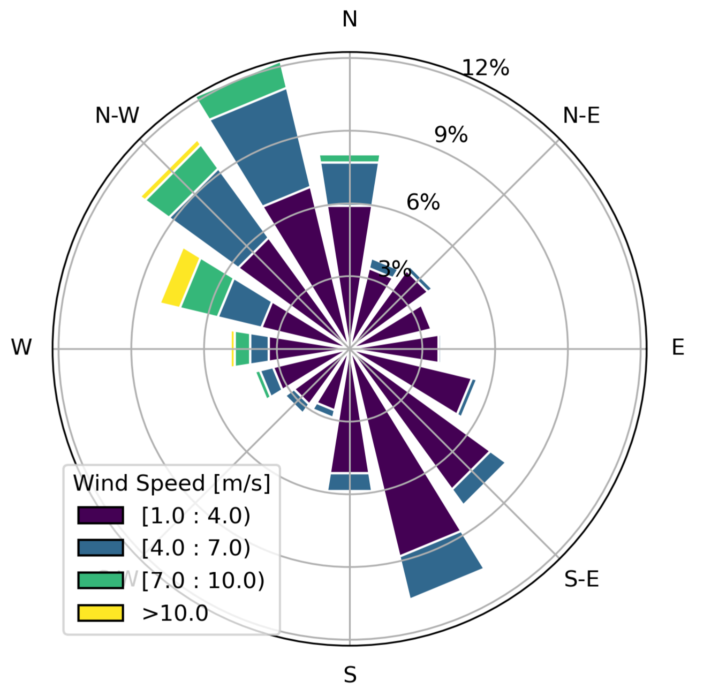
Best-3 Sensor Placement



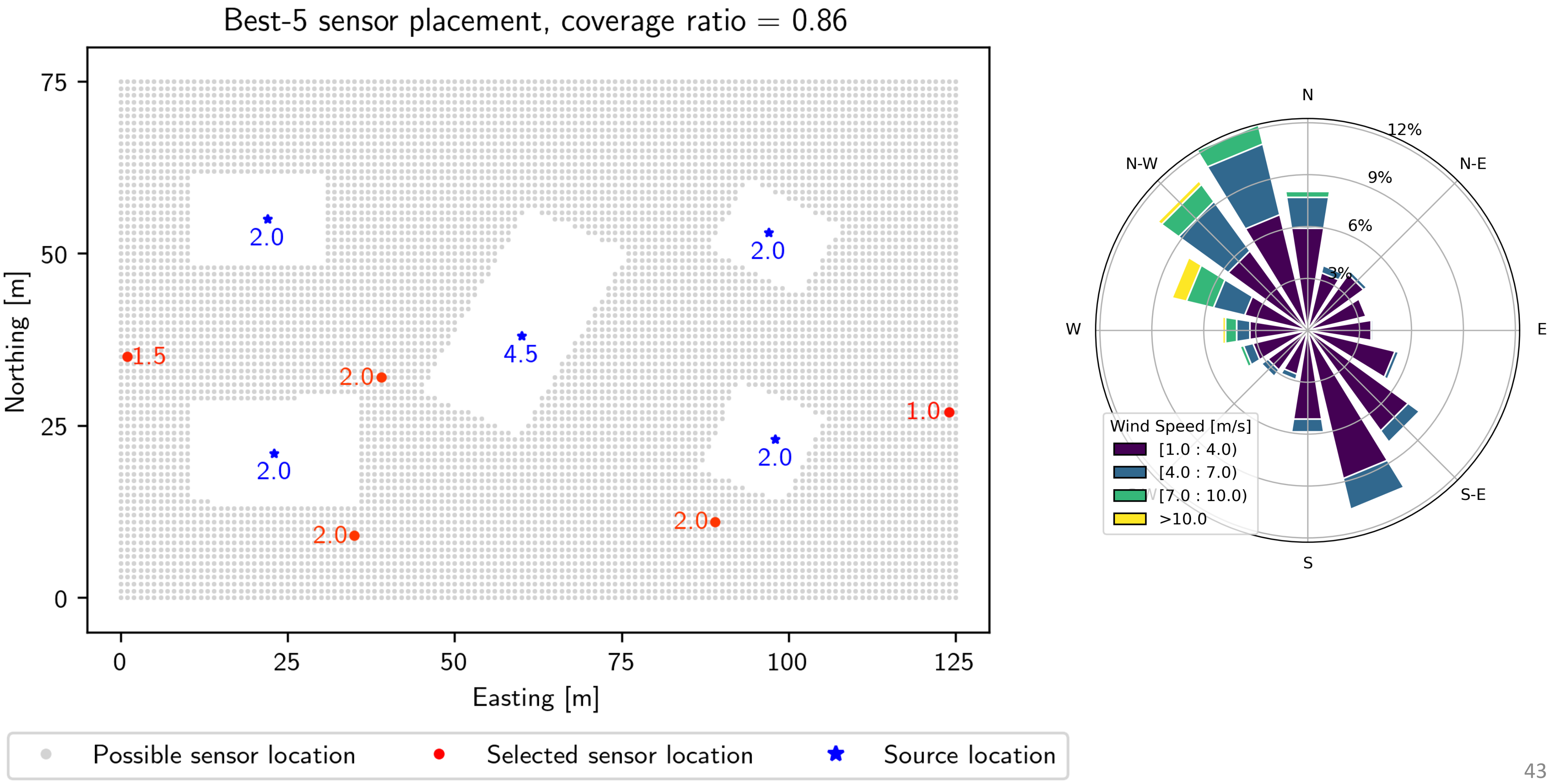


Best-4 Sensor Placement

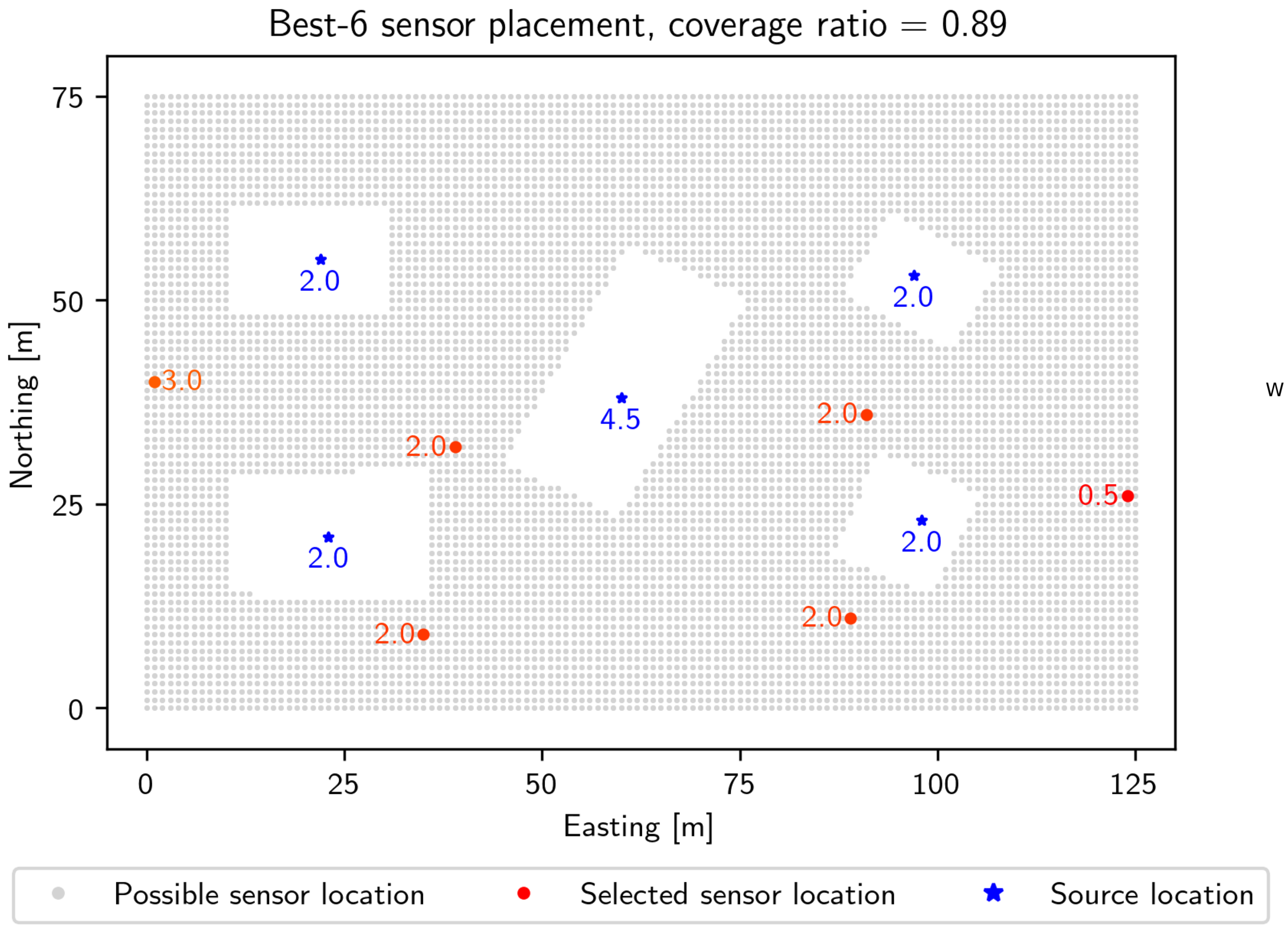


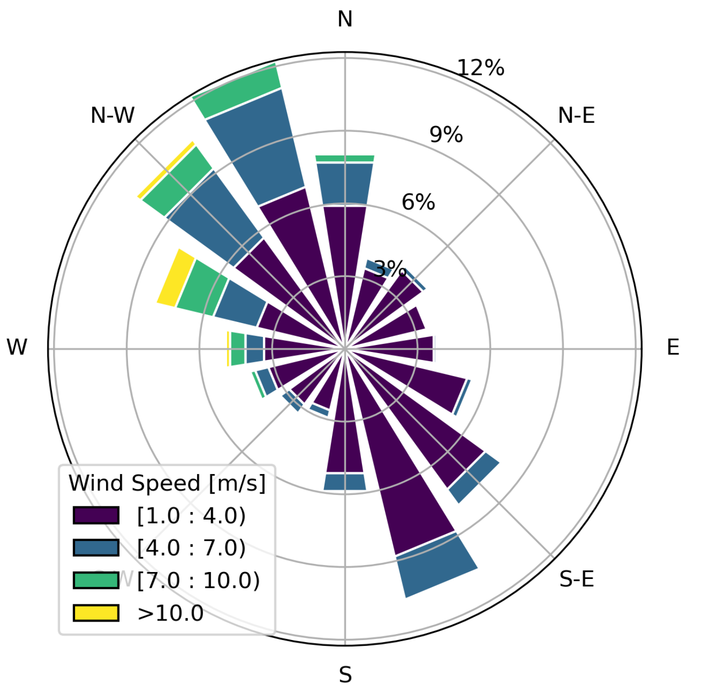


Best-5 Sensor Placement

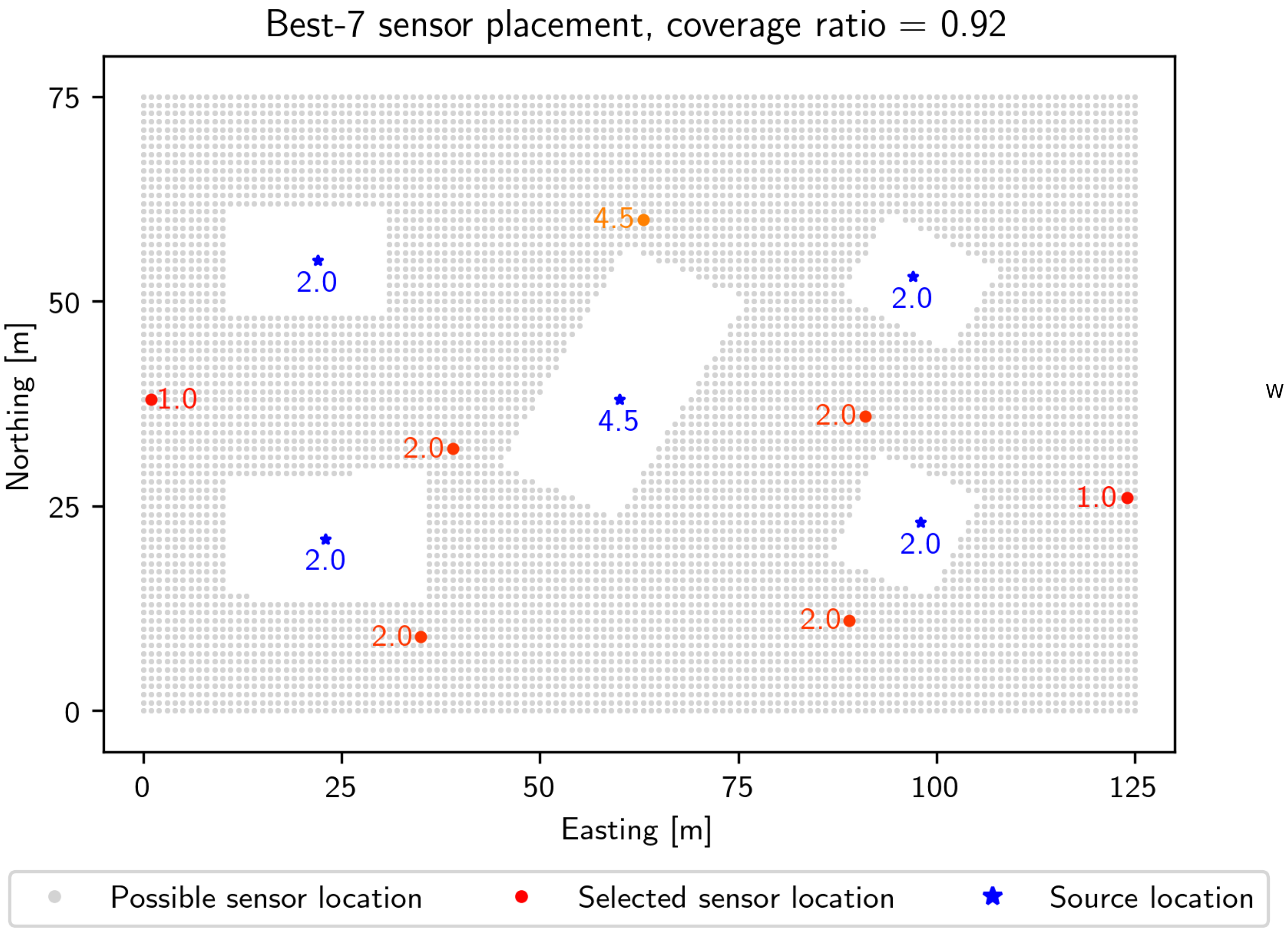


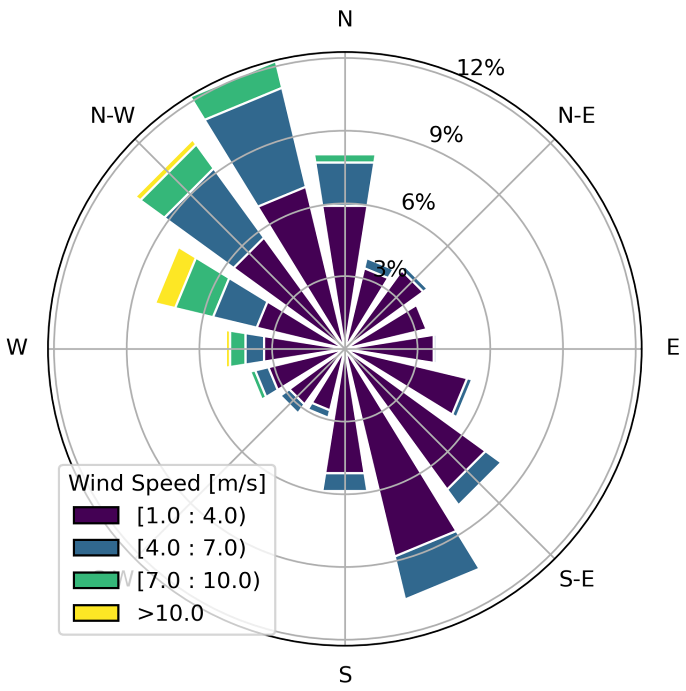
Best-6 Sensor Placement



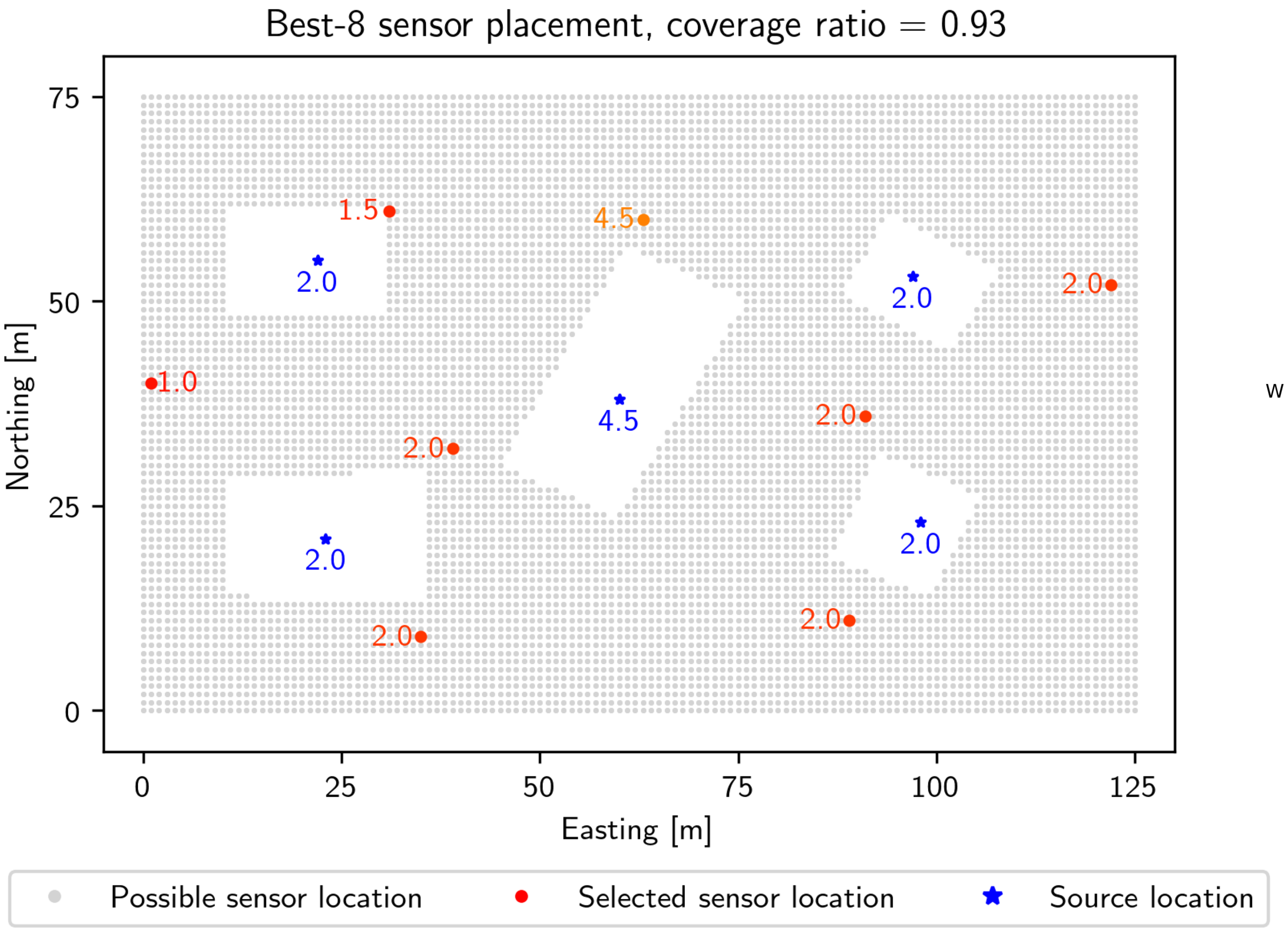


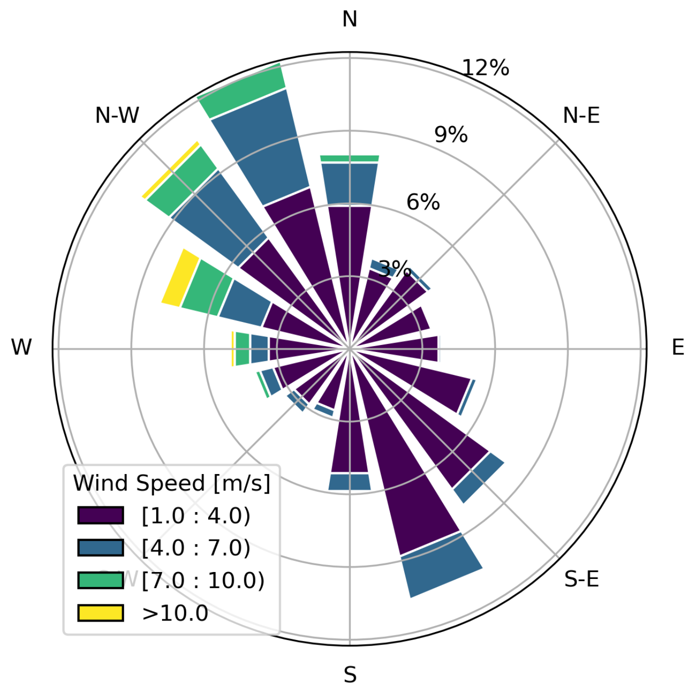
Best-7 Sensor Placement



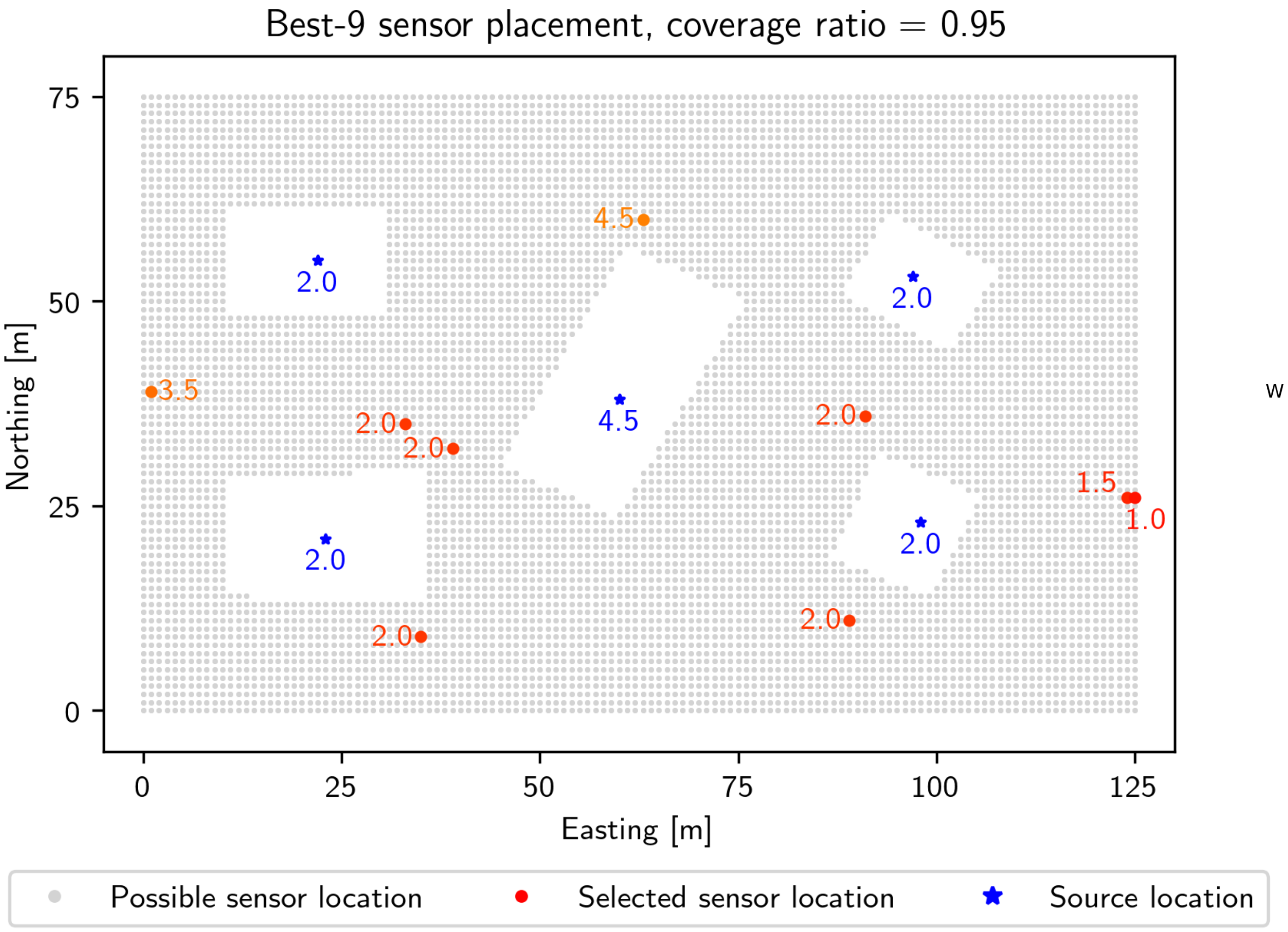


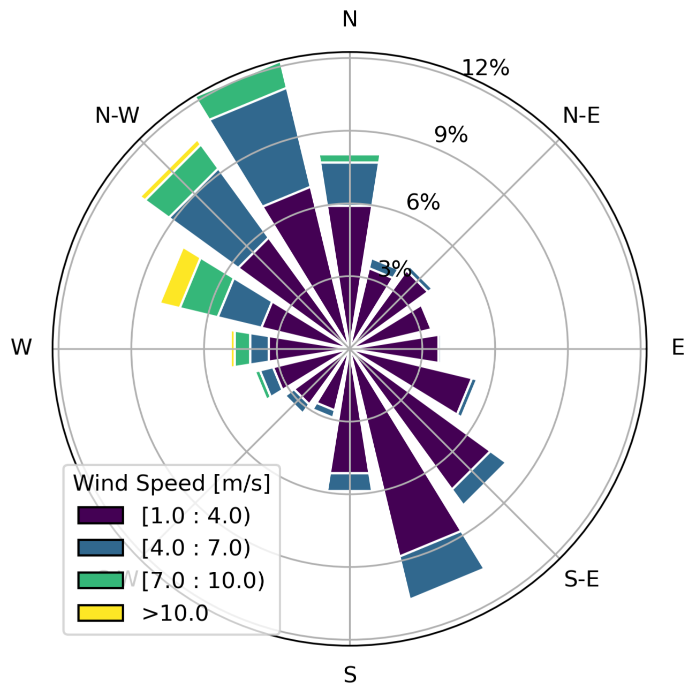
Best-8 Sensor Placement





Best-9 Sensor Placement





Best-10 Sensor Placement