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PSU Student Research from the TRB 2022 Annual Meeting: Drone Facility Location Considering Coverage Reliability: Application to Emergency Medical Scenarios

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DRONE FACILITY LOCATION CONSIDERING COVERAGE RELIABILITY: APPLICATION TO EMERGENCY MEDICAL SCENARIOS

Darshan Rajesh Chauhan

PSU Friday Transportation Seminar
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OUTLINE

- Emergency services
- Modeling coverage reliability
- The drone facility location problem
- Other considerations
- Results
- Conclusions

EMERGENCY SERVICES

Need to maintain high level of service:

- US Fire: 90% response rate in 4 minutes response time[a]
- US EMS Act 1997: 95% response rate in 10 minutes[b]
- UK NHS: 75% and 95% response rates in 8 and 14 minutes[c]
- Medical drone applications active in the US: Nevada, North Carolina, North Dakota[d]

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[a] National Fire Protection Agency, 2020. NFPA 1710.

[b] Lutter, P., Degel, D., Büsing, C., Koster, A.M. and Werners, B., 2017. Improved handling of uncertainty and robustness in set covering problems. European Journal of Operational Research, 263(1), pp.35-49.

[c] Budge, S., Ingolfsson, A. and Zerom, D., 2010. Empirical analysis of ambulance travel times: The case of Calgary emergency medical services. Management Science, 56(4), pp.716-723.

[d] FAA, 2021. UAS BEYOND. https://www.faa.gov/uas/programs_partnerships/beyond/

MODELING SERVICE RELIABILITY

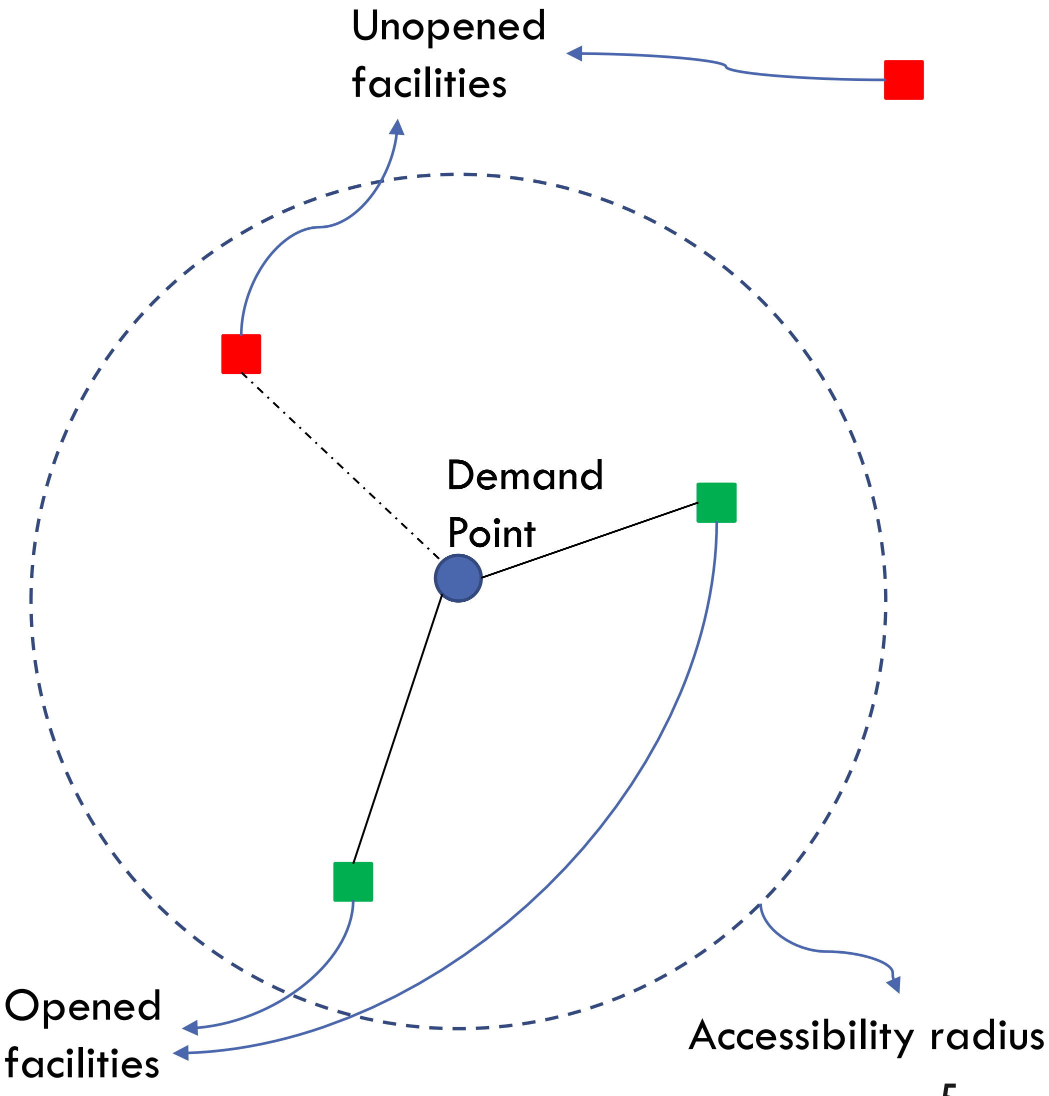
- S_i : Set of open facilities that can access demand point i
- p_{ij} : probability of failing to reach demand point i from location j
- a_{ij} : 1, with probability $(1 - p_{ij})$, and 0 with probability p_{ij}
- α : reliability standard (e.g., 90%)

For demand point i to be covered:

$$Prob\left(\sum_{j \in S_i} a_{ij} \geq 1\right) \geq \alpha$$

Assuming independence:

$$Prob\left(\sum_{j \in S_i} a_{ij} \geq 1\right) = 1 - \prod_{j \in S_i} p_{ij} \geq \alpha$$



A BASIC FACILITY LOCATION MODEL (SP-D)

Objective: Maximize Coverage

$$Max_{x,y} \sum_{i \in I} c_i x_i$$

Coverage Reliability Constraints for each demand point $i \in I$

$$\prod_{j \in S_i} (p_{ij})^{y_j} \leq (1 - \alpha)^{x_i}$$

Facility Opening Constraint

$$\sum_{j \in J} y_j \leq q$$

Variable definitions

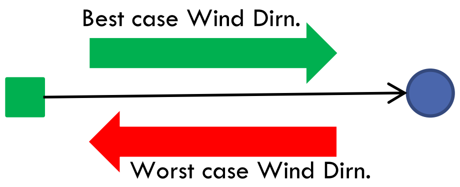
$x_i, y_j \in \{0,1\}$

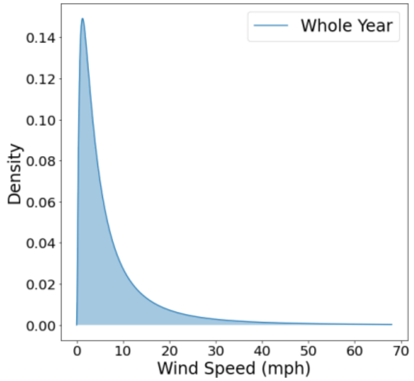
c_i defines importance of covering a demand point $i \in I$. Therefore, it is a composite metric and can include factors like:

- Population and demographics
- Emergency calls history
- Equity considerations
- others…

HOW ARE LOCATION DECISIONS AFFECTED?

Initial Information





Monte-Carlo Sampling

Estimating Failure Probabilities

$\bar{p}_{ij}$ is weighted average of p_{ij}^{best} and p_{ij}^{worst}.

Weights are decided by the proportion of time wind direction is aligned with delivery direction.

SP-D assumes $p_{ij} = \bar{p}_{ij}$

Facility Location Model

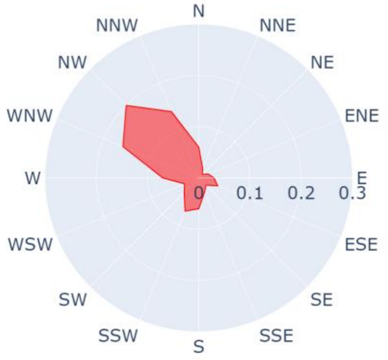
Final Output

Selected locations for drone operations

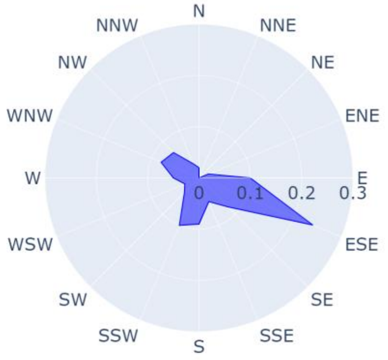
Demand Locations that would be “reliably” covered

OTHER CONSIDERATIONS

Seasonality in Wind Directions



Summer Months
(Apr – Sept)



Winter Months
(Oct – Mar)

Captured using multiple periods.

Allows opportunity to model changes in facility locations between periods

Whole Year

Failure Probability Estimation Uncertainty

Assuming $p_{ij} \in [p_{ij}^{best}, p_{ij}^{worst}]$, instead of $p_{ij} = \bar{p}_{ij}$

Use Robust Optimization framework

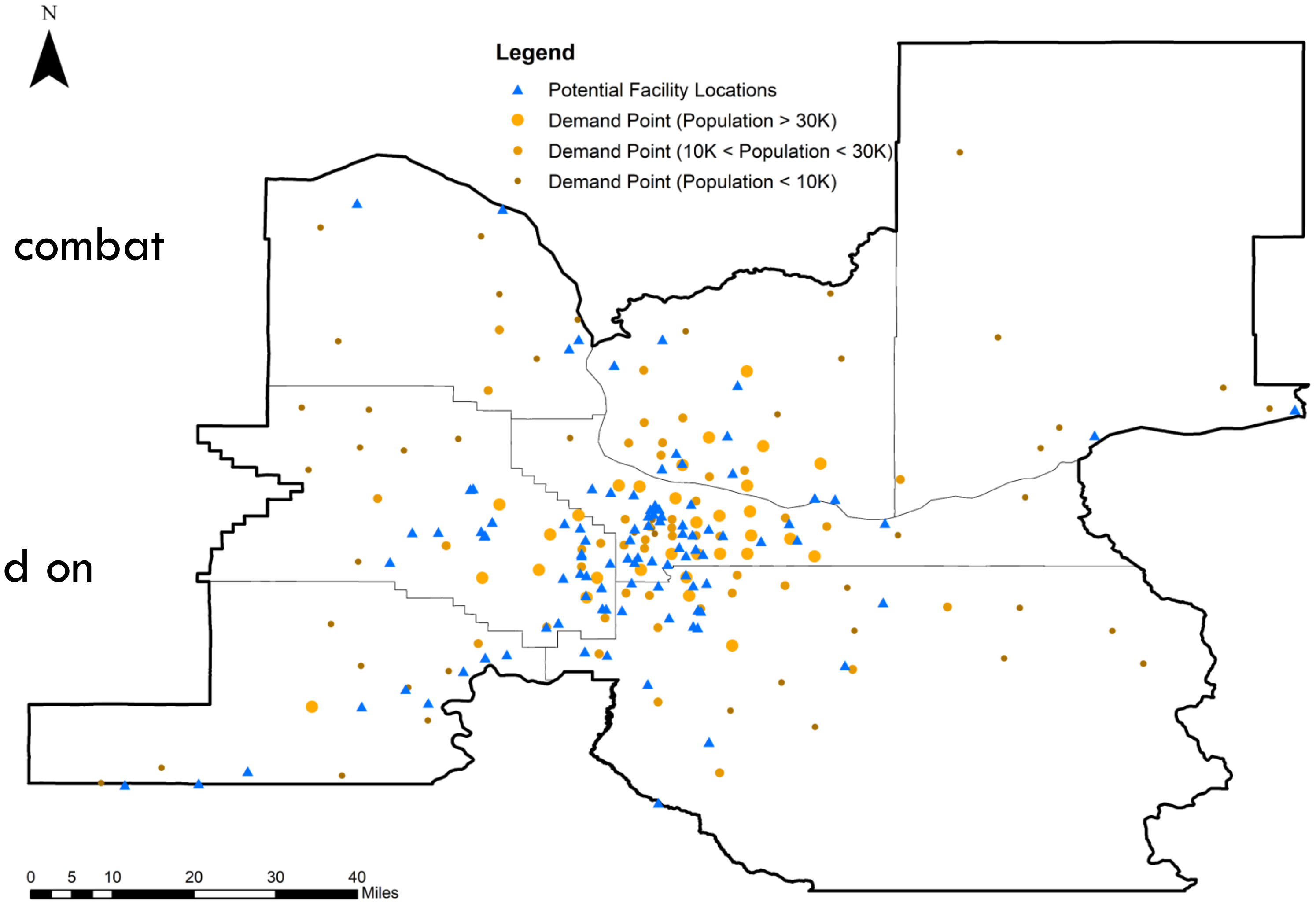
Conservatism induced by capturing uncertainty is controlled using parameter Γ

New facility location models developed that capture:

- Seasonality only: MP-D
- Uncertainty only: SP-R
- Both seasonality and uncertainty: MP-R

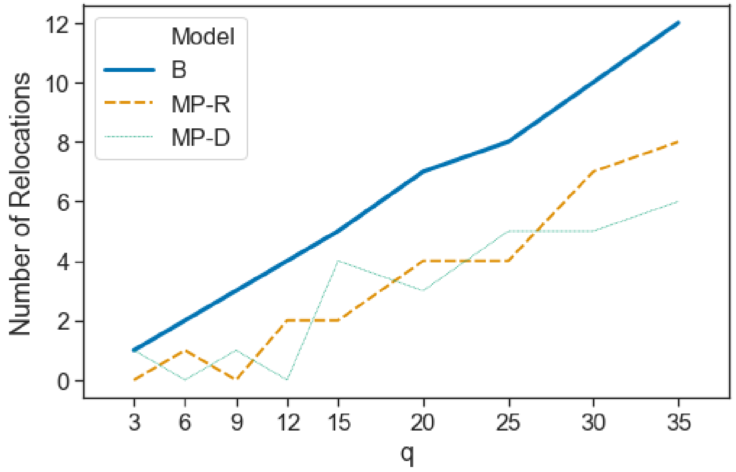
CASE STUDY

- Deploy AED-enabled drones to combat out-of-hospital cardiac arrests
- 122 demand locations
- 104 potential facility locations
- Coverage importance (c_i) based on normalized population
- Two Service Standards:
  - SS1: providing 90% coverage reliability in 4 minutes
  - SS2: providing 95% coverage reliability in 10 minutes

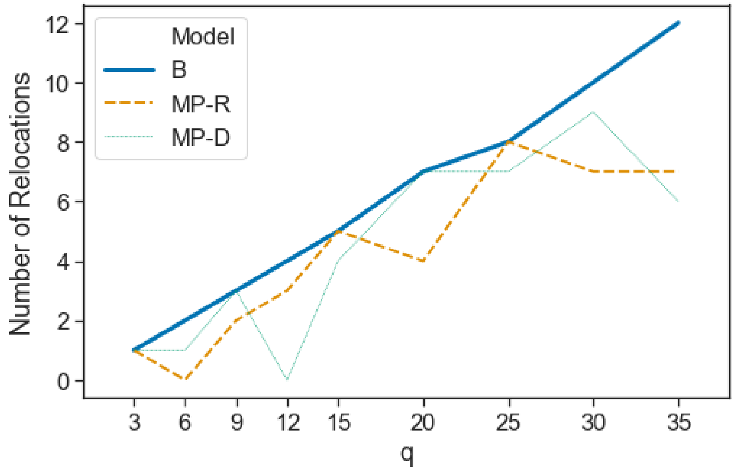


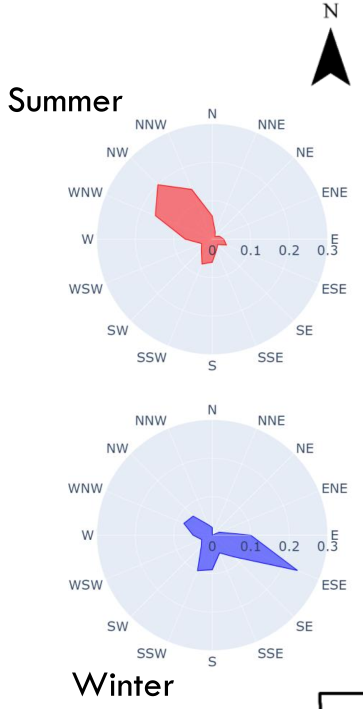
EXTENT OF FACILITY RELOCATION

SS1

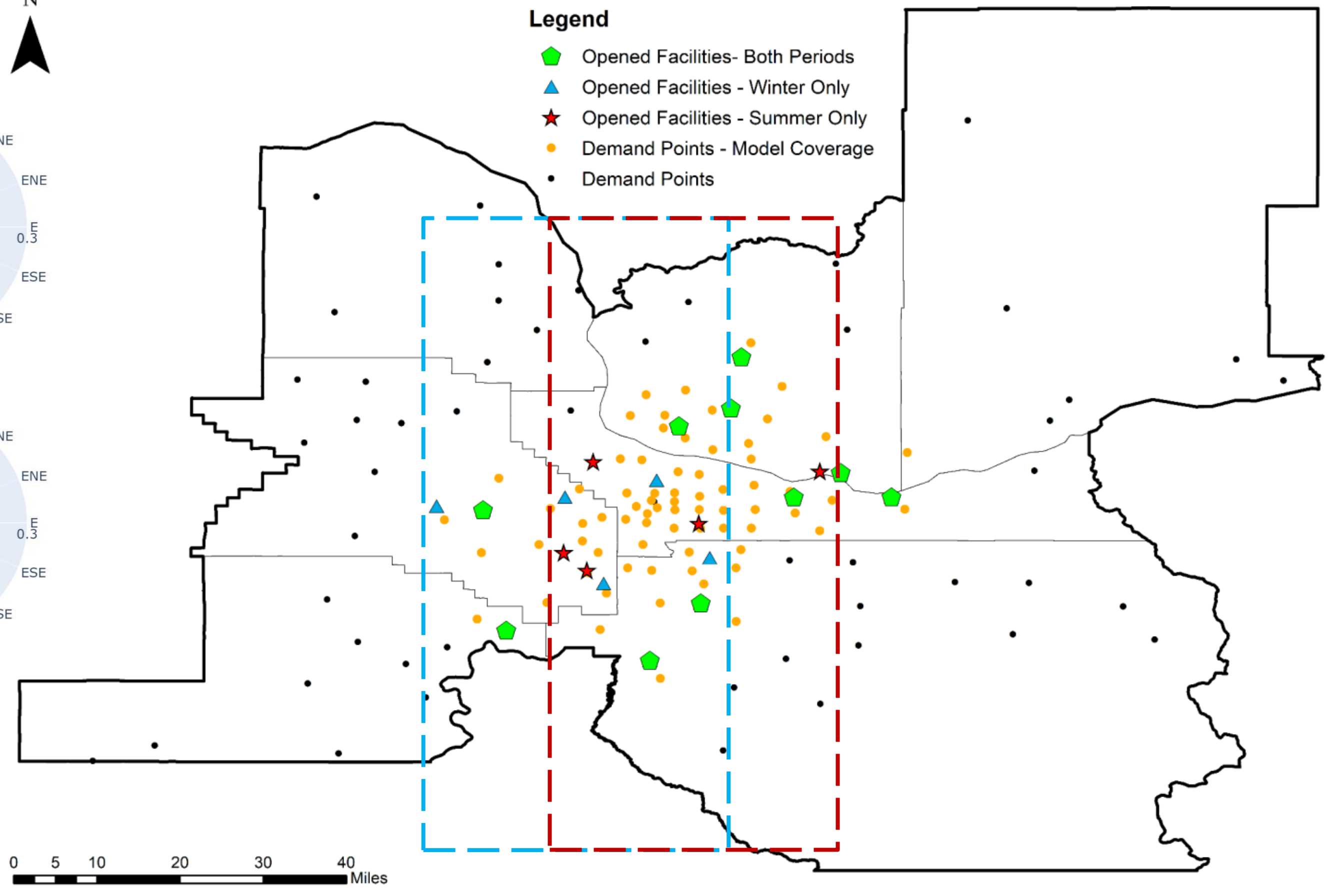


SS2



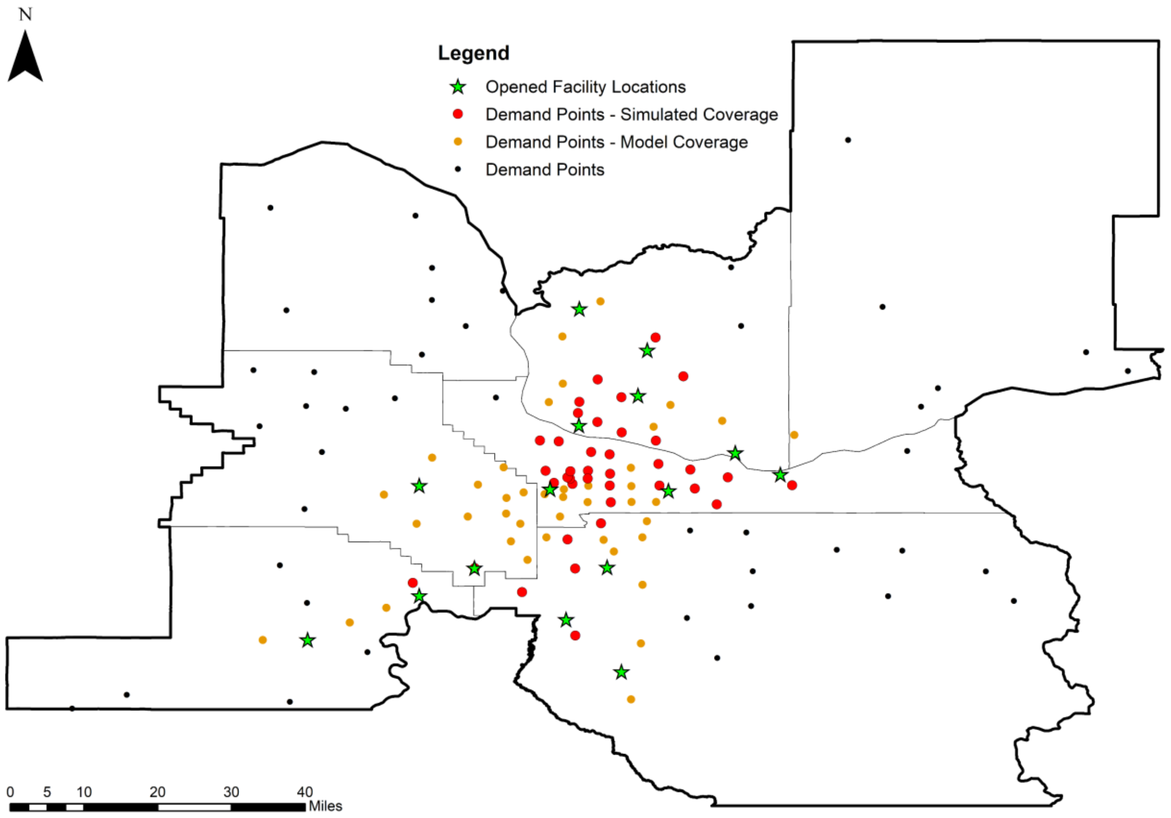


MP-R with Γ=1; SS2; q=15; at most 5 facilities can change locations between Summer and Winter

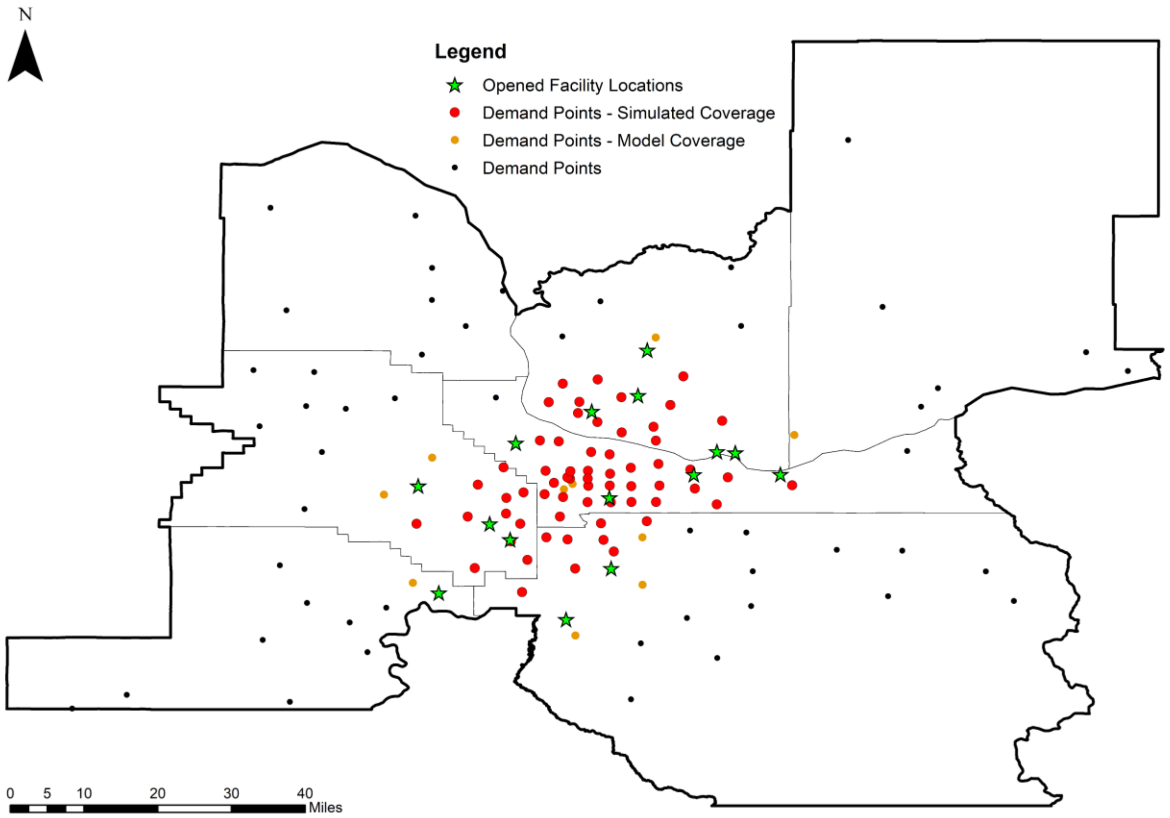


IMPROVEMENTS IN COVERAGE RELIABILITY

SP-D



MP-R with Γ=1



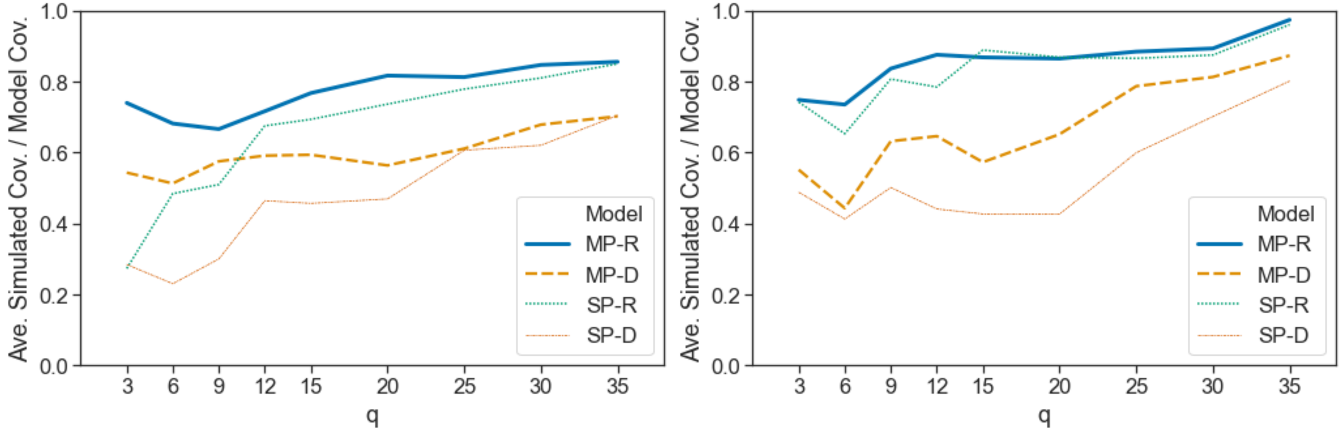
SS2 (95% reliability in 10 minutes); q=15

REDUCING THE GAP BETWEEN MODEL AND SIMULATED COVERAGE VALUES

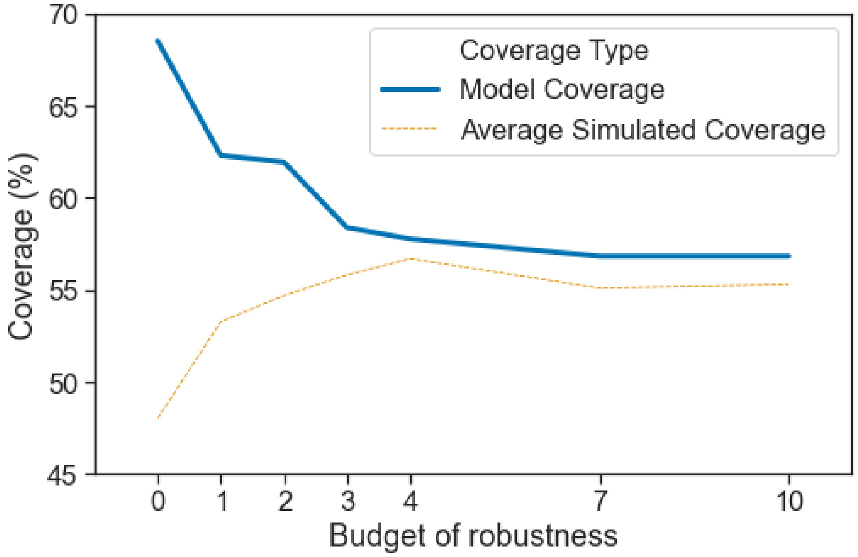
Increasing the number of opened facilities (q)
(robust models use Γ_i^t=1)

SS1

SS2



Increasing decision conservatism
(MP-R; SS1; q=35; B=12)



CONCLUSIONS

- Facility location problem considering coverage reliability is modeled. The model uses multiple periods to capture seasonality and robust optimization to capture uncertainty in estimation of failure probabilities.
- Capturing both seasonality and uncertainty improves simulated coverage values by 57% (or, 0.57 times), on average.
- Capturing both seasonality and uncertainty are required for best decisions when travel time threshold is small (SS1), while just capturing uncertainty would suffice when travel time thresholds are long (SS2).
- Capturing uncertainty consolidates facilities in the urban core to improve reliability.
- The performance gap between model coverage and simulated coverage can be reduced by either increasing conservatism in decisions, or by opening more facilities.

THANK YOU!

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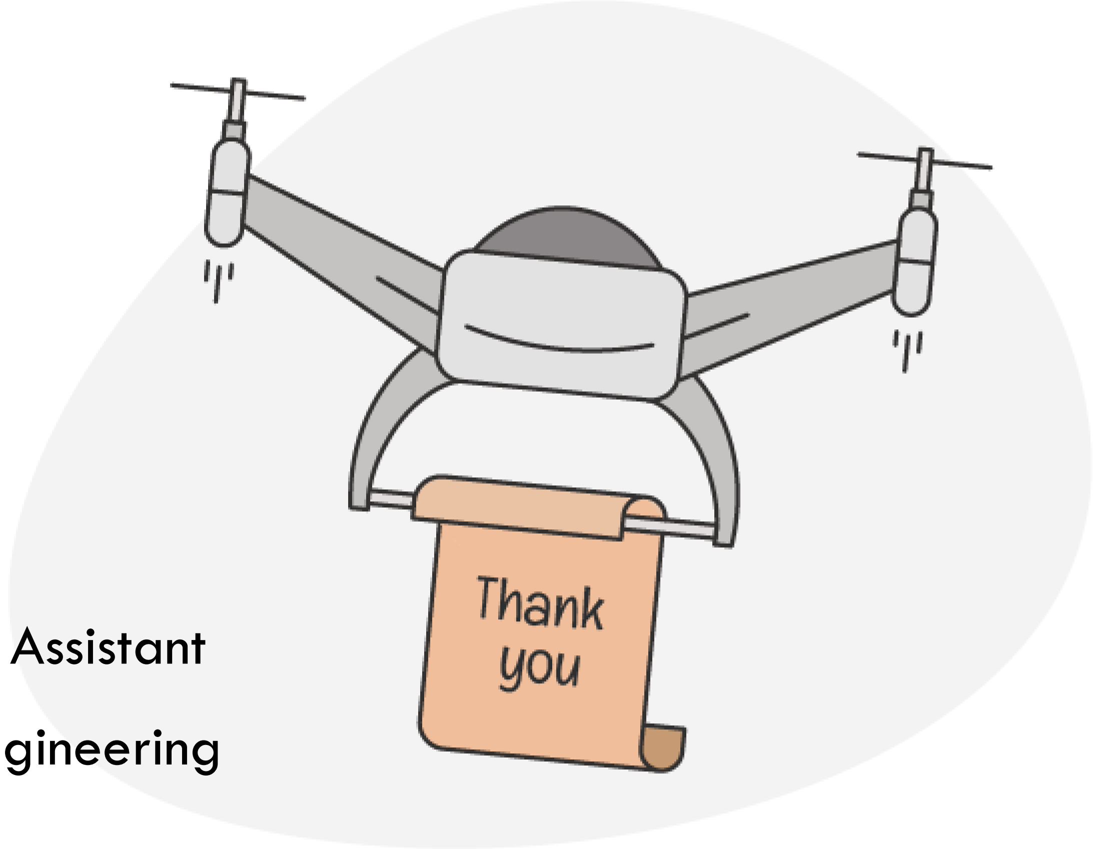

Image credits: Drone by Anoop Kumar (https://dribbble.com/shots/3187144-Drone)

SUPPLEMENTARY MATERIAL

MULTI-PERIOD ROBUST (MP-R) FORMULATION

Objective:

$$Max_{x,y,z} \sum_{i \in I} c_i x_i$$

Coverage Reliability Constraints for each demand point $i \in I$ and time period $t \in T$

$$Max_{\{U \subseteq S_i, |U| \leq \Gamma\}} \left[\prod_{j \in U} (p\_worst_{ij}^t)^{y_j^t} \cdot \prod_{j \in S_i \setminus U} (\bar{p}_{ij}^t)^{y_j^t} \right] \leq (1-\alpha)^{x_i}$$

Facility Opening Constraint for each time period $t \in T$

$$\sum_{j \in J} y_j^t \leq q$$

MULTI-PERIOD ROBUST (MP-R) FORMULATION

Facility Relocation Budget Constraint

$$\sum_{t\in T\setminus\{1\}}\sum_{j\in J}\sum_{k\in J} f_{jk}^{t} z_{jk}^{t} \leq B$$

Facility Relocation Logical Constraints

$$\sum_{k\in J} z_{jk}^{t} = y_{j}^{t-1} \quad \forall j \in J, t \in T\setminus\{1\}$$

$$\sum_{j\in J} z_{jk}^{t} = y_{k}^{t} \quad \forall k \in J, t \in T\setminus\{1\}$$

Variable Definitions

$$x_i, y_j^t, z_{jk}^t \in \{0,1\}$$

MODEL PERFORMANCE RESULTS

- SS1: service standard of providing 90% reliability in 4 minutes

Computational time increment by:

- Adding multiple periods: 37 times
- Adding robustness (Γ=1): 5.2 times

- SS2: service standard of providing 95% reliability in 10 minutes

Computational time increment by:

- Adding multiple periods: 49.5 times
- Adding robustness (Γ=1): 24.5 times

MODEL PERFORMANCE RESULTS

- SS1: service standard of providing 90% reliability in 4 minutes

Improvement in average simulated coverage for SS1:

- Adding multiple periods:
  - Deterministic model: 0.41 times
  - Robust model ($\Gamma=1$): 0.29 times
- Adding robustness ($\Gamma=1$)
  - Single period: 0.28 times
  - Multiple period: 0.14 times
- SP-D to MP-R: 0.60 times

- SS2: service standard of providing 95% reliability in 10 minutes

Improvement in average simulated coverage for SS2:

- Adding multiple periods:
  - Deterministic model: 0.24 times
  - Robust model ($\Gamma=1$): 0.02 times
- Adding robustness ($\Gamma=1$)
  - Single period: 0.51 times
  - Multiple period: 0.23 times
- SP-D to MP-R: 0.54 times

WIND SPEED AND DISTRIBUTION DATA

Available openly at https://github.com/drc1807/RMP-MCFLP-CR