Local Resources for Urban Climate Research and Education at ASU

A Scorching Divide: Optimizing Cooling Center Placement and Scheduling to Improve Heat-Risk Coverage for Vulnerable Populations

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Introduction

With extreme heat becoming more frequent and severe, cooling centers have emerged as a critical intervention to reduce heat-related health risks (Widerynski et al., 2017). Cooling centers are typically located within facilities such as community centers and libraries. They provide air-conditioned spaces for respite during extreme heat events.

Cooling centers are often visited by heat-vulnerable populations, including elderly people and people experiencing homelessness. Despite their importance, access to centers remains uneven. Previous studies have examined centers' spatial distribution and accessibility; *however*, limited attention has been given to temporal variations in operating schedules and their alignment with peak heat-exposure-risk periods.

Research Objectives

To develop spatial optimization models that simultaneously identify:

1. **Optimal cooling center locations based on the locations of vulnerable populations**
2. **Optimal operating schedules that prioritize coverage during periods of elevated heat-exposure risk**

Methodology

We developed a set of ***Cooling Center Location Problems (CCLPs)*** to identify the optimal candidate cooling center sites that maximize service provision for heat-vulnerable populations. The CCLPs explicitly account for temporal variability in service availability by jointly optimizing facility locations and daily operating schedules over a defined planning horizon. Maximum daily operating hours and the maximum number of operating days were incorporated as constraints in all CCLPs to reflect current real-world practices.

We considered three scheduling types representing different levels of operational flexibility, and a separate model was constructed for each:

1. ***Flexible operating hours (FlexOH)*** - Each selected candidate site can have its own operating schedule, which may vary across days within the planning period (*Figure 1*).
2. ***Fixed operating hours (FixOH)*** - Each selected candidate site maintains its own operating schedule. However, a selected site's daily schedule remains consistent throughout the planning period, except on non-operating days.
3. ***Fixed operating hours with no Sunday operations (FixOH-NS)*** - Each selected site follows a consistent daily schedule throughout the planning period, and all sites remain closed on Sundays. This scenario represents a special case of the CCLP for FixOH.

Decision Variables

$x_{jdt} = \begin{cases} 1 \text{ if candidate site } j \text{ is selected that starts operating at time } t \text{ on day } d \\ 0 \text{ otherwise} \end{cases}$

$u_{jdt} = \begin{cases} 1 \text{ if candidate site } j \text{ is selected that operates during time } t \text{ on day } d \\ 0 \text{ otherwise} \end{cases}$

$y_{idt} = \begin{cases} 1 \text{ if demand } i \text{ is served by a cooling center during time } t \text{ on day } d \\ 0 \text{ otherwise} \end{cases}$

$z_{jd} = \begin{cases} 1 \text{ if candidate site } j \text{ is selected that operates on day } d \\ 0 \text{ otherwise} \end{cases}$

$\pi_j = \begin{cases} 1 \text{ if cooling center site } j \text{ is selected to operate} \\ 0 \text{ otherwise} \end{cases}$

Parameters

i : Index of demand locations
j : Index of candidate cooling center sites
d : Index of days
t : Index of hours
T : Total number of hours in a day
U : Maximum number of days a center can operate over a planning period
$\lambda_{ij} = \begin{cases} 1 \text{ if demand } i \text{ is covered by candidate site } j \\ 0 \text{ otherwise} \end{cases}$
$N_i = \{j \mid \lambda_{ij} = 1\}$
q_t : Priority score of coverage during time t in a day
R_j : Maximum operating hours per day for candidate site j
p : Number of candidate sites to be selected

The CCLP-FlexOH is formulated as follows:

Maximize $\sum_i \sum_d \sum_t q_t y_{idt}$ (1) - Maximize overall coverage of demand while considering the intra-day temporal variation in heat risk within a day

Subject to

$\sum_{t=0}^{T-R_j+1} x_{jdt} \le 1 \; \forall j, d$ (2) - Restrict each cooling center to a single opening time a day
$\sum_{t=0}^{T} u_{jdt} \le R_j \; \forall j, d$ (3) - Specify the maximum number of operating hours for each site per day
$\sum_d z_{jd} \le U \; \forall j$ (4) - Limit each candidate site to operating no more than U day(s) within the planning period
$\sum_j \pi_j \le p$ (5) - Determines the total number of selected sites over the planning period
$\pi_j \ge z_{jd} \; \forall j, d$ (6) - Ensure that a cooling center can operate daily only if it is selected for the period
$\sum_{j \in N_i} u_{jdt} - y_{idt} \ge 0 \; \forall i, d, t$ (7) - Ensure that demand at location i during time t on day d cannot be considered covered ($y_{idt} = 1$) if no nearby candidate site j is operating during the same time period ($u_{jdt} = 1$)
$u_{jdk} \ge x_{jdt} \; \forall j, \forall d, \forall t < T - R_j + 1, \; \forall k \in \{t, t+1, \ldots, t + (R_j - 1)\}$ (8) - Establish the linkage between the start-time decision variable with the hourly operation variable
$\sum_{t=0}^{T} u_{jdt} \le R_j \sum_{t=0}^{T-R_j+1} x_{jdt} \; \forall j, d$ (9) - Specify that a candidate site operates on a given day only if a start time is selected for that day
$u_{jdt} \le z_{jd} \; \forall j, d, t$ (10) - Ensure that service hours can be assigned to a site only if it is open on that day
$\sum_{t=0}^{T} u_{jdt} \ge z_{jd} \; \forall j, d$ (11) - Define that if a site provides service on a given day, that day is designated as an operational day
$x_{jdt}, u_{jdt} = \{0, 1\} \; \forall j, d, t$ (12) - Impose binary requirements on the decision variables
$y_{idt} = \{0, 1\} \; \forall i, d, t$ (13) - Impose binary requirements on the decision variables
$z_{jd} = \{0, 1\} \; \forall j, d$ (14) - Impose binary requirements on the decision variables
$\pi_j = \{0, 1\} \; \forall j$ (15) - Impose binary requirements on the decision variables

Figure 1. Formulation of the CCLP-FlexOH

Case Study

The CCLPs were applied to *the Phoenix Metropolitan Area* (hereafter referred to as "***Phoenix***"), Arizona, as a case study. The locations of individuals experiencing homelessness were incorporated as demand points to maximize the spatial coverage of candidate cooling center sites (*Figure 2*). In addition, hourly heat-related 911 call data were used to prioritize opening sites during periods of elevated heat risk.

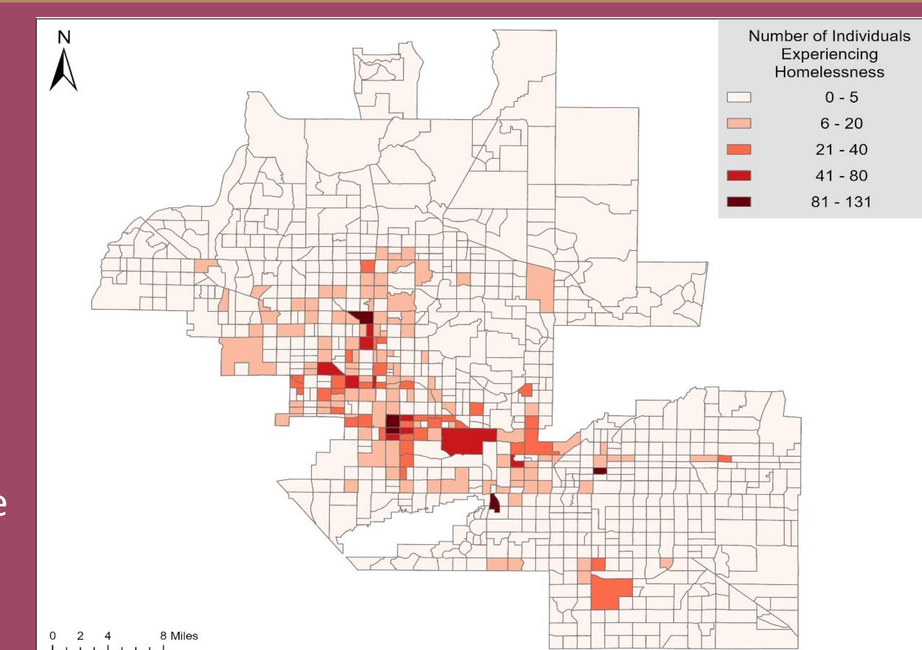

Figure 2. Number of Individuals Experiencing Homelessness at the Census Tract Level in Phoenix

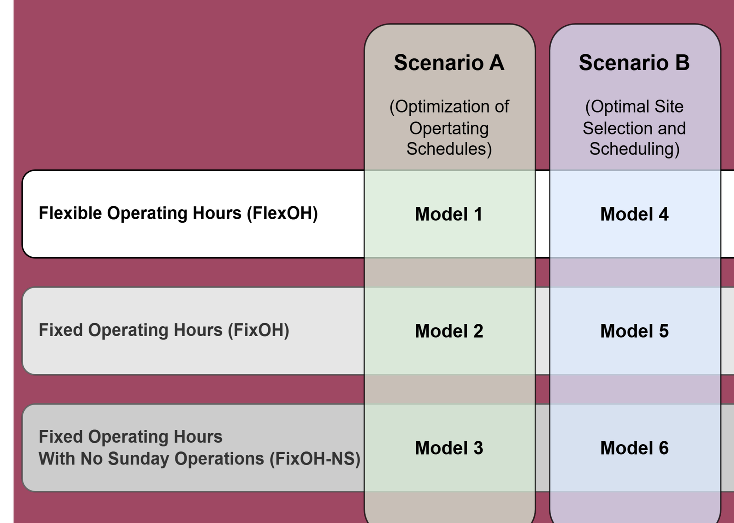

Figure 3. Model for Each Scenario and Scheduling Type

We introduce the following two scenarios to optimize cooling center coverage:

1. ***Scenario A***: Optimize the weekly operating schedules of *existing cooling centers (cooling and respite centers)* to maximize service coverage (*n = 95*)
2. ***Scenario B***: Identify optimal cooling center locations from candidate sites (existing centers in scenario A, hydration stations, and religious centers) and determine their weekly operating schedules.(*n = 250*)

Results

In scenario A, the CCLPs improved the hourly heat-exposure-risk-weighted coverage of homeless individuals by up to 15% (*Table 1*) from the current operations. *Figure 4* shows that homeless individuals are covered for longer hours on average after optimized schedules between 12 pm and 8 pm, when the heat-exposure-risk greatest in a day.

Table 1. Objective Function Values of the CCLPs in Scenario A

	Objective Function (Time-Weighted Coverage)	
	Value	% Increase from Current Operating Hours
Current Operating Hours	8,293.46	0
Model 1 (Flexible Operating Hours)	9,552.53	15.2
Model 2 (Fixed Operating Hours)*	9,318.34	12.4
Model 3 (Fixed Operating Hours + No Sunday)	8,876.03	7.0

* We set the optimality gap to 3% due to the large problem size.

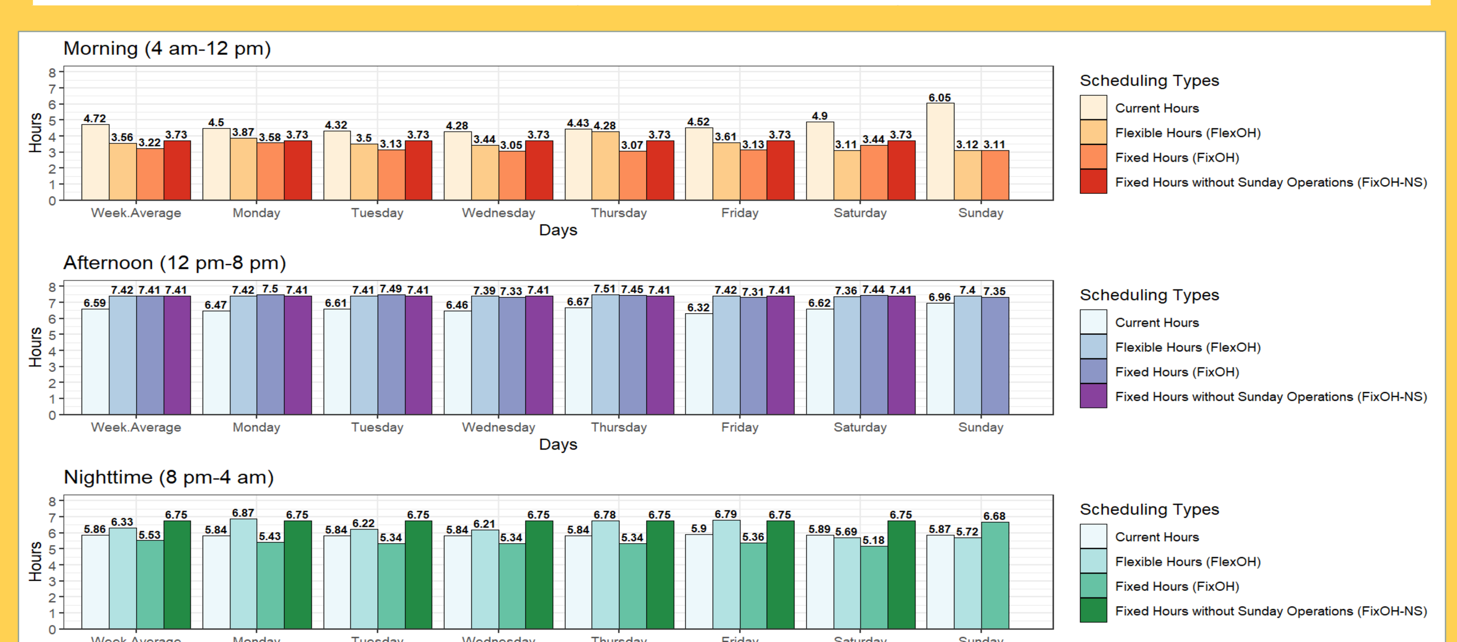

Figure 4. Average Hours of Coverage by Time Block Under Each Scheduling Type in Scenario A

Table 2. Objective Function Values of the CCLPs in Scenario B

	Objective Function (Time-Weighted Coverage)		Covered Homeless Individuals (Total: 3,773)		Number of Selected Centers Per Day (Existing Centers)						
	Value	% Increase from Existing Centers	Number	% Increase from Existing Centers	Mon	Tue	Wed	Thu	Fri	Sat	Sun
Existing Centers (n = 95)	8,293.46	0	1,723	0	89	92	92	89	86	66	32
Model 4 (FlexOH)*											
85	14,004.57	68.9	2,356	36.7	78 (22)	72 (22)	72 (20)	68 (22)	74 (24)	71 (19)	75 (21)
95	14,343.95	73.0	2,426	40.8	80 (24)	84 (24)	80 (22)	80 (21)	78 (21)	81 (21)	82 (23)
105	14,653.34	76.7	2,452	42.3	85 (27)	92 (28)	96 (27)	89 (30)	93 (31)	85 (26)	90 (29)
Model 5 (FixOH)*											
85	-	-	-	-	-	-	-	-	-	-	-
95	13,453.42	62.2	2,421	40.5	79 (24)	87 (26)	85 (23)	83 (25)	85 (23)	84 (21)	67 (14)
105	-	-	-	-	-	-	-	-	-	-	-
Model 6 (FixOH-NS)											
85	12,926.00	55.9	2,404	39.5	85 (25)						N/A
95	13,204.66	59.2	2,451	42.3	95 (27)						N/A
105	13,419.56	61.8	2,481	44.0	105 (33)						N/A

* Due to the large problem sizes, the optimality gap was set to 2% for Model 4, and 12% for Model 5, repectively. Also, "–" indicates results not yet computed.

In scenario B, the CCLPs identified the *85*, *95*, and *105* optimal locations from the candidate sites and their operating schedules under each scheduling type. The hourly heat-exposure-risk-weighted coverage increased by up to 70% compared to current schedules (*Table 2*).

Similar to Scenario A, *Figure 5* shows that individuals are covered for longer hours on average in the afternoon under the optimized schedules in Scenario B. In addition, the optimized solutions indicate that 95 selected sites tend to concentrate around the center of the study area across all CCLP models, whereas existing centers are more evenly distributed in the current placement (*Figure 6*).

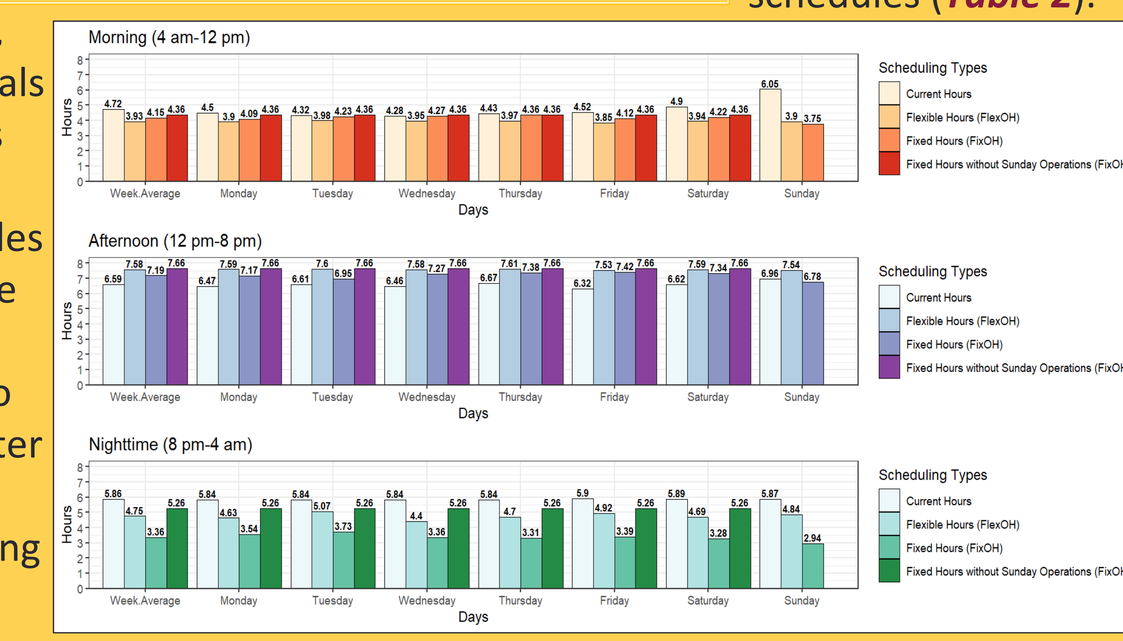

Figure 5. Average Hours of Coverage by Time Block Under Each Scheduling Type in Scenario B (95 Selected Sites)

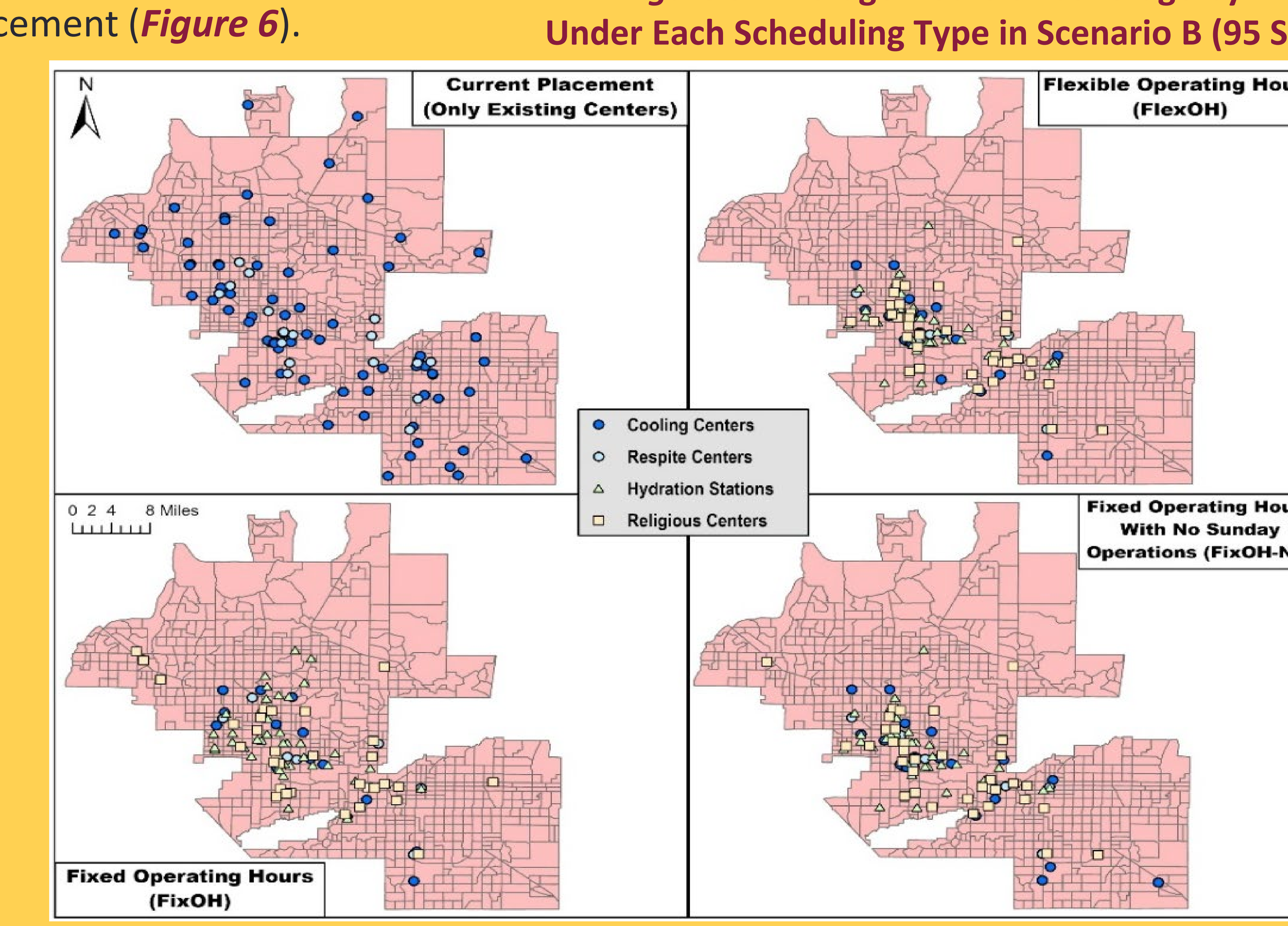

Figure 6. Locations of Existing Centers and 95 Selected Sites in Phoenix Across Scheduling Types in Scenario B

Discussion and Conclusion

Findings from Scenario A suggest that cooling centers in Phoenix could serve more individuals experiencing homelessness during the hottest periods of the day, even without adding new locations. In addition, results from Scenario B show that identifying optimal locations from candidate sites and determining their operating schedules can significantly improve coverage while meeting operational constraints, even when the number of candidate sites is the same as in the current system.

This study contributes to the literature by incorporating temporal dimensions into the optimization of cooling center coverage. Moreover, the proposed CCLPs provide a scalable decision-support framework that enables municipalities to better protect vulnerable populations during extreme heat events.

References
Widerynski, S., Schramm, P. J., Conlon, K. C., Noe, R. S., Grossman, E., Hawkins, M., Nayak, S. U., Roach, M., & Hilts, A. S. (2017). *Use of cooling centers to prevent heat-related illness: Summary of evidence and strategies for implementation.* Centers for Disease Control and Prevention. https://stacks.cdc.gov/view/cdc/47657