Identifying priority areas for expanding mental health facilities with mixed integer linear programming

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Abstract

This research attempts to estimate the unmet mental health services demand at a census tract level and identify new mental health facility locations to maximize the number of new individuals with serious mental illness (SMI) who get covered. Using estimates of the capacity of existing facilities, unmet demand in each census tract, and the distance between each census tract center, we built a mixed integer linear programming model to maximize coverage of newly opened facilities. We found that among the total of 765,304 individuals with SMI in Ohio, 469,549 (61.4%) perceive an unmet need for mental health services due to the lack of geographic access and limited service capacity. The model suggests 10 new potential mental health facilities could provide geographic access to 418,228 new patients, about 89.1% of the total SMI population that currently has unmet mental health services demand in Ohio. The findings of this research could make recommendations for identifying hot spots for individuals with SMI and priority areas for expanding mental health facilities.

1 Introduction

In contemporary society, due to various risk factors including "psychiatric illness, previous suicide attempts, substance misuse, acute interpersonal stressors, partner-relationship disruption, and history of sexual abuse" (Yuodelis-Flores & Ries, 2015), people are getting more and more vulnerable to developing psychological disorders and mental illness. Serious mental illness (SMI) is defined as a diagnosable mental, behavioral, or emotional disorder that causes serious functional impairment that substantially interferes with or limits one or more major life activities (Evans et al., 2016). It was reported that about 14.2 million people (5.6% of the US population) were diagnosed to have SMI among adults aged 18 or older in 2020. Within the diagnosed population, 9.1 million (64.5% of the diagnosed population) have received mental health services, while an estimated 7 million (49.7% of the diagnosed population) perceived an unmet demand for mental health services (Substance Abuse and Mental Health Services Administration, 2021a). While some patients may have received limited treatment or counseling services, they were not satisfied due to various factors including unaffordable service costs and geographic limitations. SMI is an important issue to study because of the burdens on families and stigma on patients themselves. The effects of stigma include perceived, experienced, anticipated, and self-stigma (Dubreucq et al., 2021). The consequences of these stigmas include low quality of life, suicide risk, life dissatisfaction, and non-effective personal recovery (Dubreucq et al., 2021). Additionally, it is proposed that individuals with SMI are both more likely to cause criminal offenses and to be arrested for displaying psychiatric symptoms (Junginger et al., 2006).

The major diagnosis of SMI includes schizophrenia, bipolar disorder, major depression, and other non-affective psychosis and affective disorders (Walsan et al., 2019). Among all the diagnoses of serious mental illness, mental health treatments are usually a combination of therapy and prescriptions. Most people with schizophrenia are treated by community mental health teams (CMHT) that provide day-to-day support and treatment while ensuring patients' independence as much as possible (National Health Service, 2022). For people with bipolar disorder, seasonal affective disorders, or major depression, most treatments are a combination of different medications like mood stabilizers, treatment for the major symptoms of depression and mania, psychological treatment, and lifestyle advice.

Access to mental health facilities is essential for individuals with SMI to attain treatment services. More research on the accessibility of mental health facilities in various areas has been conducted over the past ten years. A previous study evaluates the accessibility of health services in southwest Montreal (Ngui & Vanasse, 2012). They marked the postal code of psychiatric hospitals, psychiatric clinics, and community mental health facilities on the map and measured the travel distance between these places and had a valuable result in the field of spatial accessibility to healthcare. The accessibility to mental health facilities in Florida has also been evaluated based on different age groups (Ghorbanzadeh et al., 2020). They stated that most of the rural areas in Florida have poor access to mental health facilities, and this is because opening facilities in urban areas are always profitable and accessible, but it ignores the geographic accessibility in rural areas. The Department of Health and Human Services State Standards for Access to Care in Medicaid Managed Care published the standards for distance and travel time for urban and rural areas and the commute distance to primary care providers should be limited to 30 miles (Department of Health and Human Services, 2014). Meanwhile, a previous study also evaluated the access differences between higher-income areas and lower-income areas (Wang & Ariwi, 2021). By conducting research in the city of Toronto, they found that there are more mental health facilities located in lower-income neighborhoods.

Previous studies have used mathematical models to examine geographic access to treatment

providers. The geospatial buffering model was used by Langabeer et al. (2020) to estimate the treatment access for buprenorphine providers nationally. Rosenblum et al. (2011) investigated the commuting patterns among 23,141 patients enrolling in 84 OTPs in the US and predicted the distance traveled to the treatment program by individuals by using linear mixed model analysis. Bonifonte & Garcia (2022) studied opioid overdoses by adapting optimization models that maximize the new clients served and minimize the travel distance for existing clients. This research adapts these methods to find the optimal locations for mental health facilities and maximize the geographic coverage of serious mental illness patients.

This research aims to identify priority areas for expanding mental health facilities to maximize the number of SMI patients who can be provided geographic access. In section 2 we describe the methods adopted for cleaning data, estimating facility capacity, unmet demand, the distance between census tracts, and building the optimization model for new potential facilities. The optimization model maximizes the number of new individuals with SMI that can be covered. In section 3 we describe the data sources that are used in the whole process, including the geographic information of existing facilities, census tract data, the number of people diagnosed with SMI and received treatment, and the radius k that is used for limiting commuting distances. In section 4 we present descriptive results including visualizations and modeling output. Finally, in section 5 we discuss the implications and limitations of this research. Since opening new facilities is normally costly and highly depends on local policies, the results and decisions from this research could be regarded as a recommendation for facility location planning and an example of building models to optimize the geographic locations of facilities.

2 Data Collection

2.1 The geographic information of existing facilities

Existing outpatient mental health facilities that provide services for patients with SMI were identified from the National Substance Use and Mental Health Services Survey (N-SUMHSS) 2021 directory conducted by the Substance Abuse and Mental Health Services Administration (Substance Abuse and Mental Health Services Administration, 2022b). The longitude and latitude of each address were geocoded using the data from Open Street Map. For those addresses that cannot be found using the geocoder, they were located and collected using Google Maps.

2.2 Census Tract Data

Census tract data including the geographic information and population was gathered from the Bureau (2018). The 2019 American Community Survey 1-Year Estimates was used for the population. Census tract centers were defined as the mean center of the population within each tract based on the 2010 census.

2.3 The total number of people diagnosed with SMI

The total number of people with SMI for each census tract is obtained by multiplying the total number of people of each census tract and the average percentages of people with SMI in different substate regions. The substate estimates are collected from National Survey on Drug Use and Health (NSDUH) 2018 - 2020 directory conducted by the Substance Abuse and Mental Health Services Administration (Substance Abuse and Mental Health Services Administration, 2022a).

2.4 The number of people with SMI who have received treatment

The total number of people with SMI who have received treatment in the United States was acquired from the National Mental Health Services Survey (N-MHSS) 2020 directory conducted by the Substance Abuse and Mental Health Services Administration (Substance Abuse and Mental Health Services Administration, 2021b). Both the nationwide estimate and state estimates are contained in the report and used in this study, and the estimates are cumulative over the year.

2.5 The cutoff radius r

The threshold that patients are considered to be having access to the services in this research is set at $r = 30$ miles. This is based on the Department of Health and Human Services State Standards for Access to Care in Medicaid Managed Care (Department of Health and Human Services, 2014). These standards are set to ensure care access within a reasonable distance from residence to care providers. While the guidelines vary from state to state and only 32 states limit the travel distance, the average longest drive distance to primary care in urban areas is 30 miles. It is assumed that those individuals with SMI beyond a 30 miles radius of a mental health facility cannot be served because it would be time-consuming to travel a long distance to acquire services, especially since those mental health services are normally counseling services and it always takes hours for a complete service.

3 Methods

3.1 Facility capacity

In this work, we only focus on outpatient treatment facilities. We assume that individuals with SMI have geographic access to mental health facilities if the centers of their residence census tracts are within a specified radius r of facilities with treatment capacity. To estimate the capacity of the facilities, we first record the number of diagnosed SMI population in Ohio. Then, we obtain the number of people with SMI that have received treatment by multiplying by a nationwide percentage of who received treatment. We make this proportionality assumption because there is no state-specific data on SMI treatment populations. Finally, we divided this estimated population by the number of existing facilities in Ohio to estimate average facility capacity.

3.2 Estimating unmet demand

In this work, the radius r is set to be 30 miles according to the Department of Health and Human Services State Standards for Access to Care in Medicaid Managed Care.

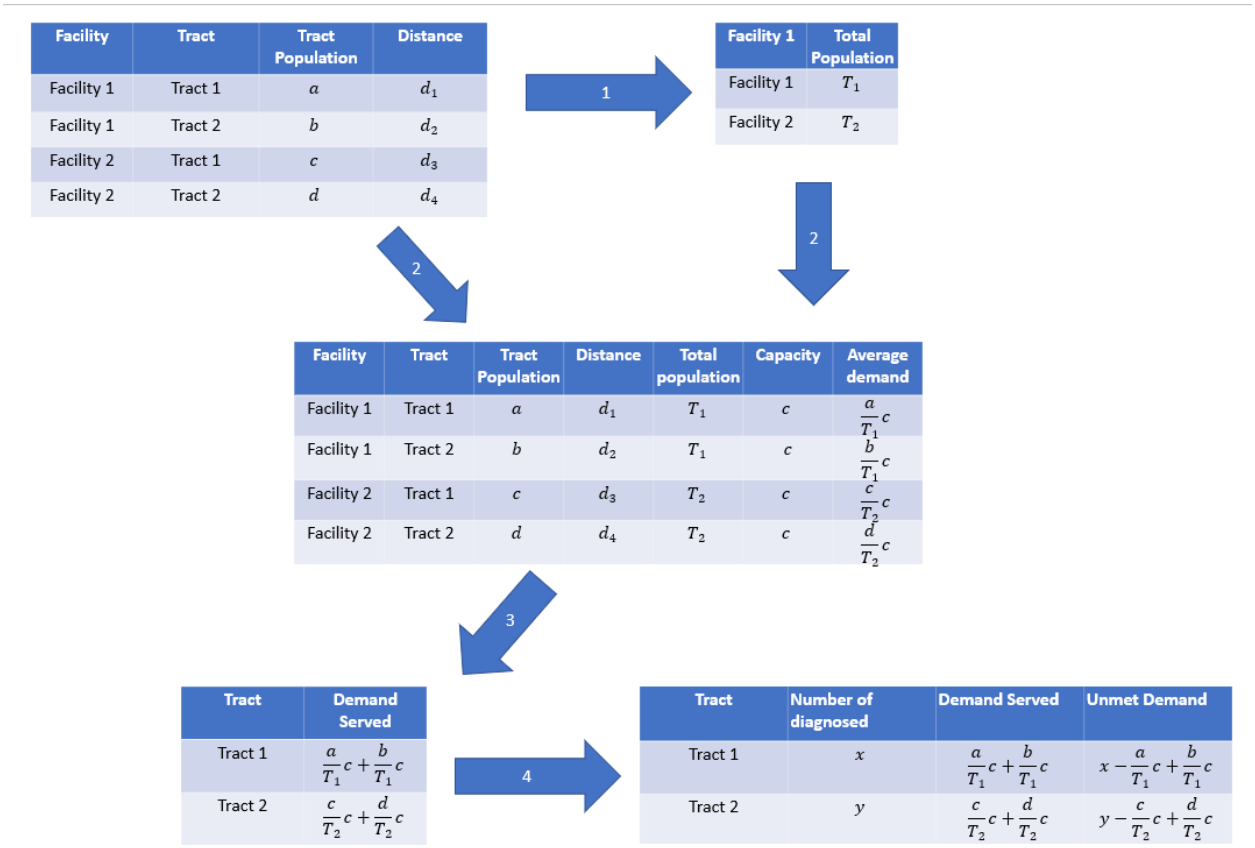

Figure 1: Procedure of estimating unmet demand

Figure 1 above briefly shows the procedure for obtaining the unmet demand data. To estimate the unmet demand for mental health services, we first identified and filtered out those census tracts that are not within the radius by calculating the Euclidean distances between facilities and the center of each census tract. The geographic information of facilities including latitude and

longitude are geocoded using the data from Open Street Map. We then aggregated the number of census tracts covered by each facility and assigned each census tract with demand served based on the percentage of the tract population. We noted some tracts might be covered by multiple different facilities. We then aggregated the census tracts and summed up the demand served for each tract. Based on the SMI percentage estimate by substate regions, we obtained the number of people diagnosed with SMI by multiplying it with the population of each census tract. Subtracting the demand served from the total number of diagnosed people generates the unmet demand, which represents the number of people with SMI that are currently not receiving any mental health treatment. We assume that every individual diagnosed with SMI needs mental health services, ignoring it will have tremendous negative consequences for the individual and communities.

3.3 Estimating the distance between each census tract

In this research, we used the Euclidean distance between census tract centers to define the set of underserved individuals with SMI and help optimize the number of newly covered people with SMI. For computational feasibility, we assume that facilities are opened in the geographic center of tracts.

3.4 Prescriptive Model

Notation	
U	The set of census tracts with currently unmet demand (demand $> c$ or distance to nearest facility $> r$)
N	The set of potential new facilities
k	Number of new facilities to open
u_i	Currently unsatisfied demand of tracts, $i \in U$
$d_{i,j}$	Distance from tract i to facility j, $i \in T, j \in A$
c	The capacity of existing facilities
r	The distance used as a threshold, set to be 30 miles (48.3 km)
Variables	
$y_{i,j}$	Newly served SMI people from tract i served by facility j, $i \in U, j \in N$
z_j	1 if we open the facility, $j \in N$

Table 1: Notation and Decision Variables

Table 1 shows the notation and decision variables used in this study. There are two types of decision variables that were used in the optimization model. $y_{i,j}$ is a continuous variable that represents the number of clients with unmet demand from census tract i that is served by potential new facility j. z_j is a binary variable representing whether to open facility j. By our assumption of facility capacities met by existing demand, all underserved clients can only be served by new potential facilities.

The optimization model is given by:

$$max \sum_{i \in U} \sum_{j \in N} y_{i,j}$$

subject to:

$$\sum_{j \in N} y_{i,j} \leqslant u_i, \forall i \in U \tag{1}$$

$$\sum_{i \in U} y_{i,j} \leqslant c z_j, \forall j \in N \tag{2}$$

$$\sum_{j \in N} z_j \leqslant k \tag{3}$$

$$y_{i,j} = 0, \forall i \in U, j \in N : d_{i,j} > r \tag{4}$$

$$y_{i,j} \geqslant 0, z_j \in \{0, 1\} \tag{5}$$

The objective function above maximizes the number of individuals that currently lack geographic access to mental health facilities that can be covered with newly opened facilities. Constraint (1) says that the number of newly met demand cannot surpass the unsatisfied demand. Constraint (2) ensures that demand can only be served by newly opened mental health facilities; when $z_j = 1$, the unmet demand in the range can be met; when $z_j = 0$, no demand can be served at facility j. Constraint (3) limits the number of new facilities that may be opened to the specific parameter k. Constraint (4) indicates that the newly covered SMI people can only attend the facilities within the radius r of them. Lastly, Constraint (5) ensures that the number of newly covered SMI people to be a continuous variable and cannot be negative, and z_j to be a binary variable.

4 Results

According to our estimates, the capacity of each existing facility is 1,837 over one year based on the cumulative estimates of the population that have received treatment. In Ohio, there are about 765,304 people diagnosed with serious mental illness, which is about 6.55% of the total population in Ohio. These individuals account for about 5.4% of the total nationwide population that has been diagnosed with SMI (14.2 million), while the population of Ohio is only 3.54% of the whole population of the United States. Among the 765,304 people with SMI in Ohio, 469,549 (61.4%) are estimated with an unmet demand for mental health treatment due to the lack of geographic access or facility capacity, while among the 14.2 people with SMI, it is reported that 49.7% (about 7 million people) were perceived with unmet demand for mental health services.

4.1 The distribution of the existing facilities and the number of diagnosed SMI patients

For our preliminary step, we plot out the distribution of the existing facility locations and the SMI patient population. Figure 2 below shows the map of facility locations and the number of people diagnosed with SMI at the census tract level. Each gray dot indicates one existing facility, and the census tracts with darker colors represent those tracts with a larger SMI population. According to the map, the majority of the facilities concentrate in popular cities including Columbus, Cleveland, Cincinnati, Dayton, and Toledo, while the others are scattered evenly over the east part of Ohio, and the distribution of the number of individuals with SMI is fairly evenly spread. The facilities have covered most of the state, however, the capacities keep them from being sufficient in offering services to all the diagnosed individuals with SMI, and it should be noticed that there are no facilities opened around Findlay in northwest Ohio, even though there is a fair amount of demand around there. Based on our preliminary findings, we expected to see more facilities open outside of the major cities, especially the areas around Findlay.

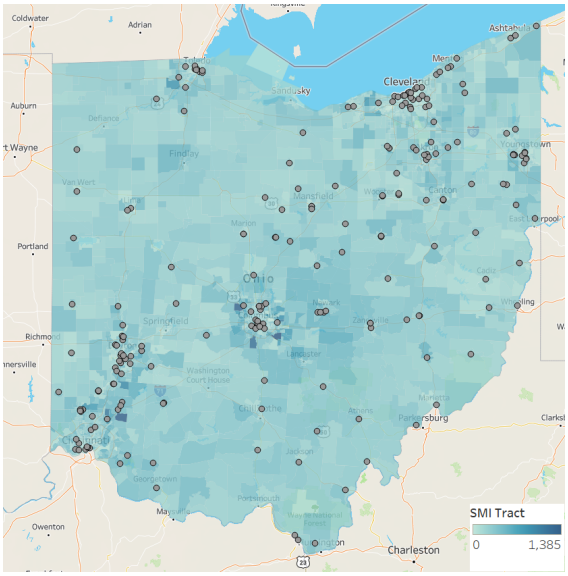

Figure 2: Existing facilities and the heat map of diagnosed SMI population for each tract

4.2 Estimated Unmet Demand

Figure 3 below shows the comparison of the demand for mental health services that have been served by existing facilities and the unmet demand. Compared with our map of existing facilities and diagnosed SMI, the heat map of demand served appears to be similar because most of the served demand concentrates at major cities like Cleveland, Columbus, Cincinnati, Dayton, and Toledo, while all those areas that are distant from big cities rarely have large demand served, which perfectly corresponds to the distribution of the existing facilities. On the contrary, we see similar patterns in the unmet demand map because of urban density and facility capacities. Therefore, even though those big cities have a large number of existing facilities and have already served a huge amount of the SMI population, there still exists a fair amount of unmet demand in these areas. Meanwhile, it can be still seen that rural areas have unmet demand and may be in need of additional facilities to address the demand there. One modeling challenge is, if we were to consider capacity on newly opened facilities, the optimization model would place these facilities only in big cities because of their large unmet demand, even for large k values. In this situation, we will not open any new facilities in rural areas despite their unmet demand. To avoid this outcome, we do not consider capacity on newly opened facilities and instead identify areas that could provide maximal coverage to within their radii.

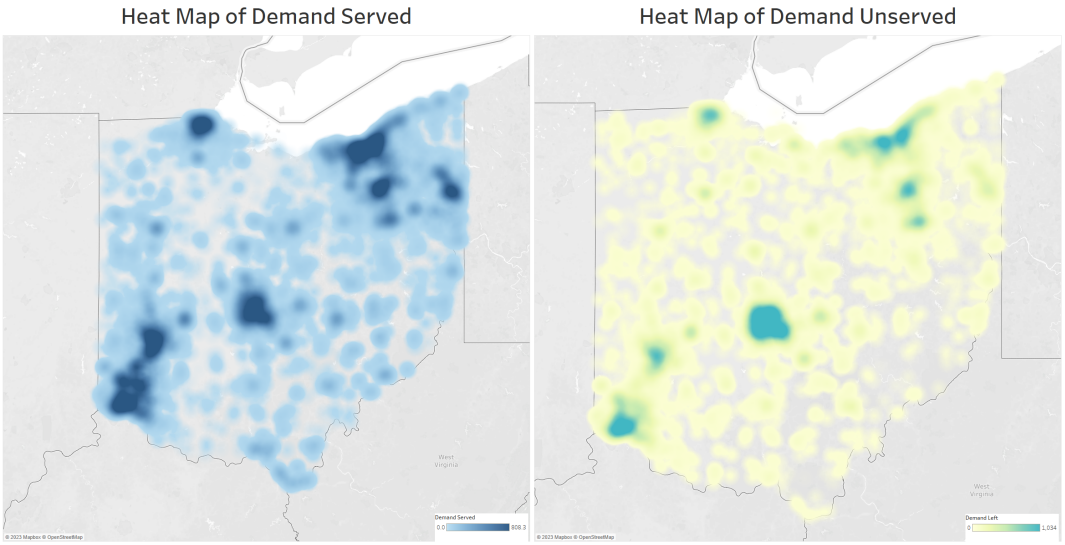

Figure 3: The heat map of demand served by existing facilities and unmet demand

4.3 New patients served

Figure 4 below shows the change in the total number of new patients covered and the percentage of statewide demand met with different k values. As we increase the k values, more patients can be covered and it reaches 418,228 patients in total if we open 10 new facilities in Ohio, representing 89.1% of the total SMI population that are perceived with an unmet demand for mental health services. As expected, we observe decreasing marginal returns in the number of patients covered by each facility with more facilities opened.

Table 2 below shows the number of new individuals with SMI and the major city served by the newly opened facilities with $k = 10$ in Ohio. Recall that for reasons discussed in Section 4.2, our

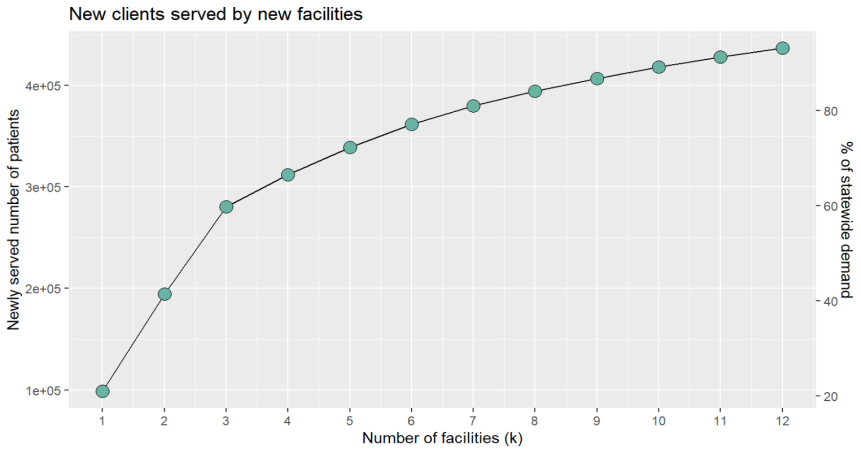

Figure 4: Number of new patients served with different k values

optimization model doesn't limit the capacity of newly opened facilities so these results represent the geographic coverage of newly opened facilities and not demand that could be served by one new facility. Meanwhile, we are not proposing the exact facility locations, these new potential facility locations can be used to address the patient flow identified in nearby cities.

Facilities	**City Served**	**New patients covered**
Facility 1	Delaware	92,016
Facility 2	Mason	78,329
Facility 3	Cleveland	75,949
Facility 4	Warren	36,046
Facility 5	Troy	30,143
Facility 6	Bowling Green	29,287
Facility 7	Berlin	25,206
Facility 8	Willard	20,421
Facility 9	New Lexington	18,047
Facility 10	Washington Court House	12,783

Table 2: New patients served when $k = 10$

4.4 Facility Locations

Figure 5 below shows the 10 new potential mental health facilities in Ohio suggested by the optimization model. As we expected, the new facilities suggested by the model cover (the orange circles) most of the hot spots (shadowed with green). Rather than opening facilities in the city centers of Columbus, Cincinnati, and Akron, the model suggests to open them in the suburban areas nearby. The reason behind this may involve greater coverages by skewing slightly off-center of major metropolitan areas to better capture dense suburbs. As suggested from the map, Columbus in central Ohio is the area most in need of additional treatment facilities, with over 90,000 individuals within 30 miles not receiving sufficient treatment. Cleveland and Cincinnati each have over 70,000 individuals nearby needing treatment. The other facilities on the map cover underserved individuals in suburban and rural areas, and ten new facilities cover most of the regions in Ohio. We note

this is a planned $k = 10$ systemwide optimal solution, whereas a greedy solution may pick different locations for various k.

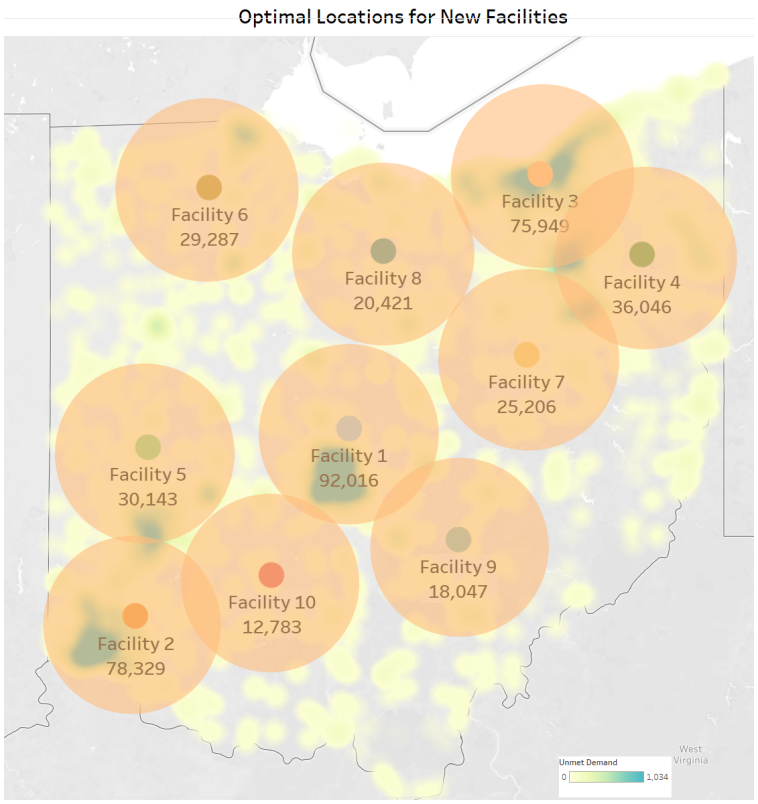

Figure 5: Optimal locations for mental health facilities

5 Discussion

5.1 Discussion of findings

One of the major objectives of this research is to estimate the number of SMI patients with unmet demand for mental health services. In Ohio, based on our estimates, there are about 765,304 people that have been diagnosed with serious mental illness, 6.55% of the total population in Ohio. The number of SMI patients in Ohio is about 5.4% of the total population that has been diagnosed with SMI in the US (14.2 million), while the population of Ohio is 3.54% of the whole population of the United States. Among the 765,304 people with SMI, 469,549 (61.4%) are estimated with an unmet demand for mental health treatment due to the lack of geographic access or facility capacity, while it is reported that in the US 49.7% (about 7 million) people were perceived unmet demand for mental health services among the 14.2 million people with SMI. These estimates emphasize the importance of this research due to the higher proportion of the SMI population and unmet demand for mental health services in Ohio and demonstrate the need for improving geographic accessibility to mental health facilities for serving as many new SMI patients as possible.

Another major objective of this research is to identify the optimal facility locations to maximize the number of new individuals with SMI that can be covered in Ohio. As expected, the recommended new potential mental health facilities are suggested to be in the regions that are most in need of the services. For example, figure 5 shows 10 new potential mental health facilities when $k = 10$. These new facilities could cover up to 418,228 individuals with SMI, which is about 89.1% of the total individuals with SMI that are perceived with an unmet demand for mental health services in Ohio. Many of the new potential facilities are suggested to be in suburban or rural areas near major cities that have hot spots.

While this work considers a system-wide perspective, in real-world implementation, facility construction would be done in a greedy consecutive way, as opening new facilities can be costly and time intensive. The facility locations change each time when solving for different k values. As we increase the k value, more facilities will be suggested to open in Columbus, Cincinnati, and Cleveland because of the hot spots there, and more facilities will also open in rural areas to address the unmet demand there. However, the computational time for large k values can be limiting, taking for $k = 10$, six and a half hours for $k = 11$. And over twelve hours for larger values. In this research, we only focused on 10 new potential facility locations for computational reasons.

While opening new mental health facilities is largely based on local policies, especially for those public mental health service centers heavily relying on government funding, the approach and results of this research could be considered as the recommendation for future implementation of facility location problems. Since the large cities have many mental health facilities and serve diagnosed people in the surrounding census tracts, considering the geographic accessibility and estimating unmet demand in different regions would widen the service coverage.

5.2 Limitations

There are several limitations to this research. From the modeling perspective, we have assumed that the new potential mental health facilities can only be opened at the center of census tracts. It reduces the computation difficulty because we do not need to consider all possible spots to be potential locations on the map. Furthermore, we have assumed that the distribution of demand served is the same as the population distribution of census tracts and not accounted for variability in facility capacities. This assumption could be relaxed if more detailed data on the distribution of the served population were available. Because of our objectives and approach, we have considered capacity on existing facilities for distributing met demand but did not consider newly opened facility

capacities. Finally, we have also assumed the maximum travel distance is 30 miles for all patients for modeling purposes, whereas we acknowledge there exists individual variability in willingness to travel.

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References

Bonifonte, A., & Garcia, E. (2022). Improving geographic access to methadone clinics. *Journal of Substance Abuse Treatment*, 108836.

Bureau, U. (2018). American community survey single-year estimates. *The United States Census Bureau. Retrieved July 15, 2022, from https://www. census. gov/newsroom/press-kits/2019/acs-1year. html*.

Department of Health and Human Services. (2014). *State standards for access to care in medicaid managed care*. Office of Inspector General.

Dubreucq, J., Plasse, J., & Franck, N. (2021). Self-stigma in serious mental illness: A systematic review of frequency, correlates, and consequences. *Schizophrenia bulletin*, *47*(5), 1261–1287.

Evans, T. S., Berkman, N., Brown, C., Gaynes, B., & Weber, R. P. (2016). Disparities within serious mental illness.

Ghorbanzadeh, M., Kim, K., Ozguven, E. E., & Horner, M. W. (2020). A comparative analysis of transportation-based accessibility to mental health services. *Transportation research part D: transport and environment*, *81*, 102278.

Junginger, J., Claypoole, K., Laygo, R., & Crisanti, A. (2006). Effects of serious mental illness and substance abuse on criminal offenses. *Psychiatric Services*, *57*(6), 879–882.

Langabeer, J. R., Stotts, A. L., Cortez, A., Tortolero, G., & Champagne-Langabeer, T. (2020). Geographic proximity to buprenorphine treatment providers in the us. *Drug and alcohol dependence*, *213*, 108131.

National Health Service. (2022). *Treatment - Schizophrenia*. National Health Service.

Ngui, A. N., & Vanasse, A. (2012). Assessing spatial accessibility to mental health facilities in an urban environment. *Spatial and spatio-temporal Epidemiology*, *3*(3), 195–203.

Rosenblum, A., Cleland, C. M., Fong, C., Kayman, D. J., Tempalski, B., & Parrino, M. (2011). Distance traveled and cross-state commuting to opioid treatment programs in the united states. *Journal of environmental and public health*, *2011*.

Substance Abuse and Mental Health Services Administration. (2021a). *Key substance use and mental health indicators in the united states: Results from the 2020 national survey on drug use and health*. Substance Abuse and Mental Health Services Administration.

Substance Abuse and Mental Health Services Administration. (2021b). *National mental health services survey (n-mhss): 2020*. Substance Abuse and Mental Health Services Administration.

Substance Abuse and Mental Health Services Administration. (2022a). *2018-2020 national survey on drug use and health substate tables, percentages*. Substance Abuse and Mental Health Services Administration.

Substance Abuse and Mental Health Services Administration. (2022b). *National directory of mental health treatment facilities 2022*. Substance Abuse and Mental Health Services Administration.

Walsan, R., Mayne, D. J., Pai, N., Feng, X., & Bonney, A. (2019). Smi diagnosis groups and icd 10 codes included in the study [data retrieved from Public Library of Science, https://plos.figshare.com/articles/dataset/SMI_diagnosis_groups_and_ICD_10_codes_included_in_the_study_/11326769].

Wang, L., & Ariwi, J. (2021). Mental health crisis and spatial accessibility to mental health services in the city of toronto: A geographic study. *International Health Trends and Perspectives*, *1*(2), 191–213.

Yuodelis-Flores, C., & Ries, R. K. (2015). Addiction and suicide: A review. *The American journal on addictions*, *24*(2), 98–104.