Strategic Implementation of Mobile Health Clinics using Geospatial Analysis based Multi-Criteria Decision Making

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Introduction

The global healthcare system has been forced to tackle multiple issues affecting today's societies, including problems related to a growing disparity between privileged and more underserved communities. One of these issues relates to the mobility of disadvantaged communities, given the fact that a lack of access of freedom in transportation negatively impacts their financial, emotional, and physical wellbeing (Cass, N. et al. 2005). Even though COVID-19 has not been the sole cause for greater inequality between these communities, a healthcare crisis such as the COVID pandemic has emphasized the increased difficulty that vulnerable populations face in receiving affordable, accessible and comfortable medical attention.

Much of the issue of fragmented care in vulnerable areas is related to the increasing scarcity of medical centers, clinics, and hospitals within said neighborhoods (The University of North Carolina at Chapel Hill. 2020), due to the amount of resources and funding needed in order for them to function effectively. However, alternatives such as mobile health clinics have become more popular when it comes to addressing the medical needs of these communities. Mobile health clinics are movable healthcare units that are able to swiftly access more vulnerable and disadvantaged communities (Yu, S. et al. 2017), which more traditional healthcare facilities such as hospitals and clinics have a more difficult time reaching due to their stagnant nature (SJ, Poon, et al. 1970). Mobile health clinics (or MHC's) can range from repurposed commercial passenger vans to custom-made vehicles (Post, P. 2007), which allow for easier travel around neighborhoods and cities as opposed to a standard clinic. These mobile health clinics customarily specialize in preventative care, and have been proven to contribute to the physical and financial wellbeing of their patients by decreasing the number of avoidable emergency visits and decreasing the overall patient cost for medical attention (Commonwealth of Massachusetts, 2012) (Song, Z. et al. 2013). Even though they have been demonstrated to be valuable tools of intervention within the US healthcare system, there are still many logistical issues that relate to the implementation of these units in underserved communities (Atkins, E. et al, 2013).

Solving logistical issues behind the implementation of MHC's would not only make the healthcare system more resilient and adaptable to change, but would also have a significant impact on a plethora of communities and their members, an example being lower-income individuals with diabetic conditions. Diabetes is a chronic condition that is characterized by elevated levels of sugar in the body, currently affecting approximately 422 million people around the world (World Health Organization. n.d.) The primary challenge surrounding diabetes is that diabetic care calls for constant treatment and attention, which can become a burden for lower income, geographically isolated, underserved individuals due to the amount of money, time, and resources needed to seek and follow through with treatment (Girijala, R. et al. 2018). As a chronic condition, the fact that diabetes affects the lives of individuals for prolonged periods of time means that more privileged communities have access to medical services that are affordable and accessible for them. On the other hand, more marginalized communities are unable to constantly afford and access medical attention due to respective social determinants of health that complicate the attainability of healthcare. As a result of the health disparities present within diabetes care, disadvantaged communities currently experience a higher probability of not managing their conditions well, leading to a higher risk of acute complications such as lower-limb (or lower-extremity) amputations. Lower-extremity amputations (LEA) can gravely affect the emotional, financial, and physical wellbeing of an individual [], yet they are one of the most preventable outcomes of “uncontrolled lower limb ischemia,” or severe blockage of arteries in lower limbs, following diabetes mellitus or peripheral arterial disease (Post, P. 2007). Even though there is evidence that suggests that frequent testing and screenings could contribute up to a 39% decrease in amputation risk, the difficulty faced by underserved communities to access affordable, convenient, and quality medical care has caused vulnerable communities to be disproportionately affected by the negative impacts of diabetes (Higgins, T.F. 2010) . As a result, the implementation of innovative models of healthcare such as mobile health clinics could procure the prevention of drastic medical measures, such as amputations, by providing greater accessibility to healthcare.

On this premise, ensuring that mobile health clinics are implemented strategically within communities is crucial to providing equitable healthcare. By utilizing an interdisciplinary approach consisting of primary research, data interpretation, and observation of studies both related and unrelated to mobile healthcare, evidence-based suggestions could be made on how to best reach vulnerable communities. By establishing a general framework detailing the available tools needed to conduct an objective assessment of logistical planning, which would ideally by applicable to any type of MHC, greater coordination between mobile clinic programs could be achieved to reach a more democratied healthcare system. As a result, the purpose of this exploration is to determine a framework that allows for mobile clinics to decide where to best allocate their services and resources, by understanding the complexities behind the operation of MHC’s, and examining alternative systems that can allow for a more comprehensive understanding on how to overcome obstacles faced by mobile clinics.

Literature Review

It is imperative to first comprehend how mobile health clinics currently operate as a means of determining what are the largest issues that impact the outreach of this system. For one, there are currently over 1500 individual clinics within the United States alone (Hill, C. 2014], yet initiatives to implement these clinics around the world can also be seen in countries such as Mexico and the United Arab Emirates, and Canada (Garcia, D. el al. n.d.) (Center, I. n.d.). Mobile health clinics generally focus on providing preventative medical attention by treating patients through screenings, check-ups, or services related to chronic diseases such as hypertension (Yu, S. et al. 2017). However, services can also range from dental care to primary care to mammography services (SJ, Poon, et al. 1970).

Currently, mobile health clinics around the world are self-organized units in the sense that they are created, funded, organized and operated based solely on local needs. More specifically, most clinics are funded through philanthropy, and customarily result in the creation of routes and schedules that are focused on individual inclinations or agendas related to the overall mission and vision of their funding sources (SJ, Poon, et al. 1970). Examples such as the Family Van in Boston, Massachusetts and the AGAPE Family Health Center in Jacksonville, Florida operate by stationing their vehicle(s) in multiple areas around a city, with either set schedules with distinct hours and days of operation that include an established location, or a requesting procedure for the MHC to travel to a location desired by a patient (The Family Van. n.d.) (Agape Family Health, n.d.). One of the greatest appeals of mobile health clinics is the convenience of moving medical equipment across cities and neighborhoods with ease, but the ability to station these clinics is a crucial component of making such units convenient and reliable for their patients.

Even though the individualistic and modular approach of mobile health clinics can allow for greater autonomy over each MHC program, the fact that many MHC's struggle with communicating with each other effectively can lead to greater fragmentation in medical care within already struggling communities. Efforts to consolidate information and resources between MHC's can be most notably seen through initiatives such as the Mobile Health Map, where more than 700 US mobile health clinics have contributed with sharing their impact through said network (Mobile Health Map, n.d.). However, the most notable limitation present is that there are no consistent assessment parameters that dictate the selection of target areas, aside from the areas that have been pre-determined by funders.

On an even more local scope, many issues influence the implementation of mobile health clinics based regarding their necessity for resources to operate efficiently. For one, mobile clinics require a constant flow of electricity to keep their refrigeration systems cool for certain tools and medicines. In addition, they also need running water for medical practitioners to maintain personal hygiene and clean their utensils, as well as a stable Internet connection to collect and organize patient information (Centrone, W. 2009) As a result, clinics are faced with making stationing decisions that favor consistent access to crucial resources such as water or electricity, as opposed to choosing locations that are more convenient for their patients and thus maximizing their impact.

Finally, the process of onboarding prepared and capable staff can be challenging for some mobile health clinics, given that some individuals may feel uncomfortable with stationing in certain areas or neighborhoods (Song, Z. et al. 2014). Many MHC programs tackle staffing issues by onboarding medical students and external volunteers, as a means of recruiting individuals that are willing to gain experience and use their knowledge to address the needs of disenfranchised communities.

In short, the logistical challenge of mobile healthcare units is constituted by a series of multiple smaller problems that are interconnected in a manner resulting in the formation of a network of interdependent yet autonomous components. Complexity theory acknowledges healthcare system's challenges as belonging to a "complex adaptive system", which shares common principles and behaviors to other complex systems (or "CAS") (Hospital, A. 2001). Pioneers in the field of complexity science such as the Santa Fe Institute have utilized frameworks around complex adaptive systems to describe the intricacies of healthcare systems beginning in 1995 (Dooley, K. 1999), suggesting that a more comprehensive approach would be most effective in tackling greatly interconnected issues as in the field of medicine and healthcare.

By overcoming these challenges in a way that is user-centric and efficient, the healthcare system would become more resilient and adaptable to change. Furthermore, this essay will define the problems surrounding the logistics and operations behind mobile health clinics and explore current models and frameworks that can be implemented to solve some of the largest gaps in the operation of MHC's.

Section I: Consolidation of User Interviews

As part of this exploration, four interviews were conducted with organizers and staff from distinct mobile health programs across the US as a means of further comprehending the average gaps and challenges faced by MHC's across the country. Interviews were limited to individuals operating mobile health clinics in the United States to minimize miscommunication in the form of language barriers. The mobile health clinic programs contacted included the Pacific University Mobile Eye Clinic stationed in Oregon, the Morehouse School of Medicine's H.E.A.L. Clinic in Georgia, Bonnie's Bus Mobile Mammography Program in West Virginia, and the UTHealth School of Dentistry's Mobile Dental Van Program in Houston and East Texas.

Interviews conducted provided insight as to the common factors that currently contribute to the stationing and traveling of their mobile services, which were based on the type of medical attention provided on each clinic, the target patient audience, and geographic regions selected.

For one, interviews established that general target regions are usually determined by funders such as philanthropies, but some mobile clinic programs are able to select the locations and areas in which they choose to operate. The response as to the methodology behind the selection of regions was mixed, given the fact that the decision-making process was determined by a medley between available data of demographics and region, as well as consultation with local partners on identifying the most vulnerable populations. It was also established that some MHC programs serve more as capable support systems to their partners and other institutions, signaling that the decision-making process can also be redirected to external partners in the form of pinpointing the placement of services, selection of vulnerable populations in need of medical attention, and organization of patient appointments.

Subjects also suggested that partnerships constitute a crucial component of the logistics behind MHC's. Firstly, partnerships between health centers, educational institutions, or community centers enable the formation of connections between the MHC's resources and their target populations by working with such communities on a consistent basis. By doing so, not only do MHC's acquire an additional perspective on the behaviors and habits of their selected communities, but they also gain access to locations that are convenient for their potential users. As a result, many MHC's also utilize the parking lots outside of these centers in order to station and operate their vehicles. Establishing the proximity between MHC's and specifically healthcare centers can be especially useful for medical care that calls for follow-ups, as the ability of individuals to have reached a certain location in the past facilitates their ability to repeat now familiar pathways or travel routes. Some MHC models do not explicitly provide follow-up appointments, but they redirect patients to nearby medical centers and doctors that are capable of assisting individuals with their specific medical needs. As a result, MHC's such as Bonnie's Bus Mobile Mammography Program are allowed a broader range of mobility, as their vehicles are not incentivized to return to past locations and station there for hours at a time unless an appointment has been scheduled.

Over the course of the interviews conducted, a common theme that was established was that safety was a key component in the decision-making process for traveling and stationing. One interpretation of safety for MHCs would be the safety of the clinic itself, meaning the desire to maintain the integrity and quality of the vehicle.

Accessing vulnerable communities in both rural or urban regions usually translates to traversing poor road infrastructure, which can range from un-maintained asphalt roads filled with signs of distress (i.e. potholes, cracks, etc), to dirt roads as the only viable roads for travel. Poor road conditions can lead to damages to the vehicle itself or to medical tools kept in the MHC, which can translate to high costs in damage repair or crucial time that is wasted by MHC's as they wait for restorations or other services. From the interviews conducted it was established that mobile health clinics are delicate vehicles, and that avoiding areas that pose a threat to the physical integrity of their units is crucial to continue their regular operations.

In order to avoid these inconveniences, not only do mobile health programs consider the quality of the potential roads to use for their travel, but also consider the quality of surfaces for pathways in which the clinics would "ingress and egress" from their stationing. For example, parking lots with extremely poor and damaged entries and exits would be inconvenient for the mobile health clinic to travel across constantly, thus characterizing the potential stationing spot as less favorable. These decisions are currently made from physical assessments of the roads and suggestions from local partners, which call for in-person visits to the locations as a means of taking educated courses of action.

The remaining component of safety relates to the safety of the staff and patients. Mobile health clinics may attract the attention of individuals that desire medical equipment such as needles and syringes, especially within more rural communities given delicate situations in the US such as the opioid epidemic. Some mobile health clinics, such as the Pacific University Mobile Eye Clinic, have made efforts to curtail the potential risk of said encounters by posting signs outside their vehicle to communicate the absence of certain tools and items, due to the fact that the specific care provided on the vehicle does not call for such utensils. Local partnerships also tend to inform the mobile clinic programs of more high-risk areas in order to consider alternative locations. Regardless, the consideration of the willingness of staff to station in certain areas, as well as their well-being and that of their patients, is a significant component of mobile clinic programs' logistics.

In all, the consolidation of user interviews suggested that much of the logistical planning of MHC's rely on the degree of autonomy of each clinic, as well as specific nuances related to the type of medical care provided. Given the variety within the mobile healthcare system, establishing a common set of parameters that MHC programs can adapt to their operations could allow for a more efficient and secure implementation of their units within their target areas. As a result, the following section will explore the different ways in which data and technology can enable a more objective view of logistical planning.

Section III: Methodology

Based on the insight acquired through individual interviews and available literature on the mobile healthcare system, a suggestion on addressing the complexities behind the logistics of MHC's would be to determine a comprehensive framework on key factors that should be considered when deciding to implement a mobile health clinic. The nature of this framework should consist of region agnostic analysis and examples of practical applications, as a means of illustrating how certain data on a desired region could be interpreted to create more educated decisions. It is also important to note that the variation in staffing and recruitment for MHC's is a definite challenge for many mobile clinic programs, but this exploration will only focus on the barriers involving the physical location of a unit. For the purpose of this exploration, the overall approach of GIS-based multi-criteria decision analysis will be utilized to propose possible courses of action that mobile clinic programs can integrate in their logistics.

The proposed model consists of 3 main levels, each with distinct nuances and particularites that should be accounted for, in order to make informed decisions regarding the strategy of implementing mobile health clinics. This model is intended to be region-agnostic, and serve as a framework for any mobile health program around the world to search for and utilize relevant data that can serve as respective inputs.

A main approach for the creation of the model consists of the employment of a geospatial information system guided by multi-criteria decision making, or GIS-MCDA, in which multiple parameters can be standardized, weighed based on importance, and consolidated to inform the decision making process to decide the most optimal areas for interventions. GIS-MCDA has been most commonly applied in projects ranging from risk assessment of flood-prone regions (Feloni, E. 2019), to the determination of commercial services in new areas (Estoque, R. 2011), but has also been applied to assess planning in the public health sector (Tanser, F. 2006).

The traditional use of GIS-MCDA is commonly employed within private companies or commercial entities, in which decision-makers utilize the analytical hierarchy process (AHP) to troubleshoot spatial decision problems such as geographically allocating resources. AHP consists of constructing matrices with chosen criterions that have been assigned an arbitrary weight, either by ranking (i.e. from 1-9 based on importance) or rating (rating of factors using percentiles) (Estoque, R. 2001). Even though this is useful for private companies that have autonomy over their prioritization as entities and organizations, the arbitrary designation of weights can also become susceptible to corruption or subjectivity when applying the framework to more interconnected and layered problems. In order to ensure that GIS-MCDA can become of value when addressing social problems such as those within the mobile healthcare system, using data analytics tools that coincide with relevant data collection to the field and operations can facilitate the creation of objective processes.

A relevant exploration of the use of GIS-MCDA for primary healthcare assessment in rural areas is a 2006 study focused on the municipality of Hlabisa in South Africa, in which GIS data was used to determine the relationship between the physical access of clinics and usage based on geographic location (Tanser, F. 2006). The accessibility of healthcare facilitates for any given region within the municipality took into consideration a realistic average travel time of an individual in Hlabisa, as well as an analysis of predicted versus actual usage of clinics in the region (Tanser, F. 2006). The process of establishing the two aforementioned parameters consisted of calculating ideal or theoretical scenarios through assumptions on travel behavior and available statistics, calculating realistic scenarios based on insights from user interviews on usual travelling behaviors, and usage of aerial imaging and graph theory to calculate quickest paths based on existing road infrastructure. Applying a similar methodology would facilitate the visualization of regions outside of South Africa, based on accessibility to healthcare services for included communities. Also, the fact that mobile health clinics have the ability to station in areas that do not exclusively offer medical care means that applying GIS-data to assess more specific locations, in a similar fashion to the Hlabisa study, could result in greater freedom of using data-driven decision making to maximize the impact of these MHC units.

With the following framework being proposed, GIS-MCDA would be utilized to assess determined areas in terms of greatest need of diabetes-related care, and establish the locations that would maximize the usage of MHC units to ensure that efforts are being made to provide accessible and quality medical attention for marginalized communities. As of writing this exploration, GIS-MCDA hasn't been integrated thoroughly into the logistical planning process of healthcare systems, making this framework a unique application of GIS-tools that allow for the determination of efficient placement of services down to a hyper-local level.

Section IV: Development of Framework

Determination of Region

The scope for the determination of the region relates to the understanding of vulnerability of geographic areas based on multiple parameters to determine specific regions in the greatest need of medical intervention. By using a geospatial information system guided multi-criteria decision making (GIS-MCDA), multiple variables pertaining to the social determinants of health of certain communities can be compared to establish logical implementation. A strategic and data-driven approach such as the application of a GIS-based MCDA framework can contribute to better understanding the geographic and social behavior factors that impact a certain population, which has shown to be especially useful for healthcare implementation in rural regions (Arcury, T. et al. 2005).This section will elaborate on the relevant parameters that should be considered when designing for mobile clinic programs, and explore distinct tools that can facilitate the process of region determination through geospatial analysis.

The initial conditions of this first level of the framework are influenced by the degree of autonomy of the determined mobile clinic program, which can be a result of the involvement and individual agendas of funding sources and local partnerships. For more context, the fact that some mobile clinics are given a certain state or city to operate in, as a result of requirements from philanthropic organizations, individual donors or certain anchor institutions that fund their projects, translates into MHC programs having less freedom to select the most vulnerable populations that would be most benefited from alternative healthcare interventions such their own. Regardless, ideal situations to increase the certainty of logical and strategic implementation would be for MHC programs to have autonomy of deciding broader boundaries such as target state, and begin narrowing to the municipality or county level based on established parameters and measures.

<u>Prevalence and Incidence of Condition</u>

In regards to mobile healthcare programs, one of the first parameters to consider would be the prevalence or incidence rate of the condition being addressed by the MHC program, for being core principles within the epidemiology field that are able to illustrate the impact of a condition or disease based on geographic location (Center for Disease Control and Prevention. 2012). Prevalence rates are used to best describe chronic conditions such as hypertension or diabetes for being gradual and prolonged in nature, and are influenced by the density of cases in a predetermined region, as well as the respective population (Center for Disease Control and Prevention. 2012). The utilization of prevalence rates also avoids skewing of data, since the standardization of the amount of cases per capita prevents more densely populated regions to be directly categorized as most impacted. The challenge of this parameter is that the data can be misleading, since publicly available data also accounts for middle and upper class communities with easy access to treatment, medical staff and healthcare facilities due to high quality opportunities and infrastructure for treatment.

Socio-economic Factors

Given the fact that the barriers surrounding providing equitable access to healthcare also involve socio-economic factors of the communities involved (Girijalam R. et al, 2018), incorporating these factors into consideration are able to provide answers as to the vulnerability of the communities being observed, as well as the eventual impact of the implementation of these MHC' programs. On this premise, geospatial analysis can be used to illustrate publicly available data such as poverty rates or vulnerability index by social need by municipalities.

Accessibility of Health Centers

The final parameter relates to the accessibility of health services for each involved community, which involves the feasibility of receiving convenient and affordable medical attention for any given individual. The first consideration is to determine the current density of health services in an area, as to understand the current resources being allocated in the overall region. Studies showcase a positive correlation between the density of health services and usage of healthcare facilities, even though additional factors such as the individual clinic's "care intensity" or capacity also play a role in clinic usage (Léonard, C. et al. 2009).. Conversely, finding the regions with the least amount of available healthcare resources can be an initial indicator to determining gaps in medical attention.

The outcome of the first level of the framework is to establish the municipalities or counties chosen for intervention, in order to concentrate efforts of strategically stationing MHC's in manners that are most appropriate for the spatial and social behaviors of individuals within the area. The following step would be to establish the most appropriate approach of providing accessible medical care through user-centric logistical design.

Stationing and Safety Logistics

The following component of the framework would be to establish the specific stationing of MHC's in the determined target regions, resulting in the decision-making being finalized at the hyper-local level. As in previous parts of the decision-making process, the degree of freedom in choosing potential stationing sites can be influenced by already established partnerships with other organizations, yet the following section will explore overall suggestions that any MHC can take into account if their planning allows it. The purpose of this level would be to determine specified locations that would ultimately maximize the impact of the stationed MHC's in terms of greater usage.

Firstly, insights from interviews and research showcase that mobile clinics experience greater patient turnout in locations such as community centers, smaller clinics focused on disenfranchised communities, or even universities around the region, as they are able to facilitate the redirection of patients in the case that their facilities are already affiliated with medical resources and staff. As convenience is a great factor in ensuring that patients follow through with appointments between their varied and complicated schedules, locations that already interact with target populations can contribute to greater ease of access for potential MHC visitors. Not only would this allow for both MHC staffing and patients to feel safer in more public areas, but it can also translate to better maintained roads or parking lot surfaces that MHC's have to take into consideration when moving their vehicles. In terms of scalability, establishing partnerships with larger and more widespread centers could also allow for faster and easier expansion of resources, which should be considered for MHC programs when looking for stable partners that are able to ensure greater outreach.

Once potential partnerships or locations have been determined, categorizing selected locations as most or least impactful, in terms of usage of services provided, should be an important process that should be completed to objectively decide on most effective locations. The following two examples showcase the usage of technological tools to visualize the predicted impact of implementing new activities in different locations, serving as inspiration for possible methodology of translating findings from both examples into the healthcare scenario. Even though the direct transferring of methods would be filled with assumptions due to the difference in target populations, observing the type of information collected clarifies questions on how data can be used to determine optimal placement of units.

Ideal circumstances would be to determine the most densely populated hubs of individual mobility for underserved communities, with the most illustrative examples being CityScience's CityScope Champs-Élysées project at the MIT Media Lab, in which agent-based modelling was used to mimic the standard mobility behaviors of individuals along one of Paris's most transited avenues (MIT CityScience. n.d.). However, the aforementioned effort can be difficult to translate over to the current issues surrounding mobile healthcare, as it can be troublesome to illustrate the mobility habits of underserved and marginalized populations due to the inclusion of average travel times as well as the decision of visualizing well-maintained roads and avenues.

Regardless, an example of the application of data and geospatial analytics can be seen in site planning efforts for food trucks within the US. Even though food trucks are unrelated to the mobile healthcare industry, the similarities in their modular nature, as well as their objective of increasing usage as a manner of maximizing impact, can be comparable to the purpose of efficiently stationing MHC's.

A 2018 study completed by CARTO consisted of using their team's specialty in spatial analysis to assess and determine the most profitable areas for the stationing of a local food truck in New York City (Murray, P. 2018). The process consisted of aggregating one month's worth of data of usage and sales for 10 individual food trucks, and "using proportional circles reflecting revenue amounts for each location across Manhattan and Brooklyn" (Murray, P. 2018). Census data on demographics based on area was also utilized to segment target population response, as it was noted that census data could be misleading based on the mobility behaviors of their specific customers, as well as the fact census data was not especially useful for largely commuter populations (Murray, P. 2018).

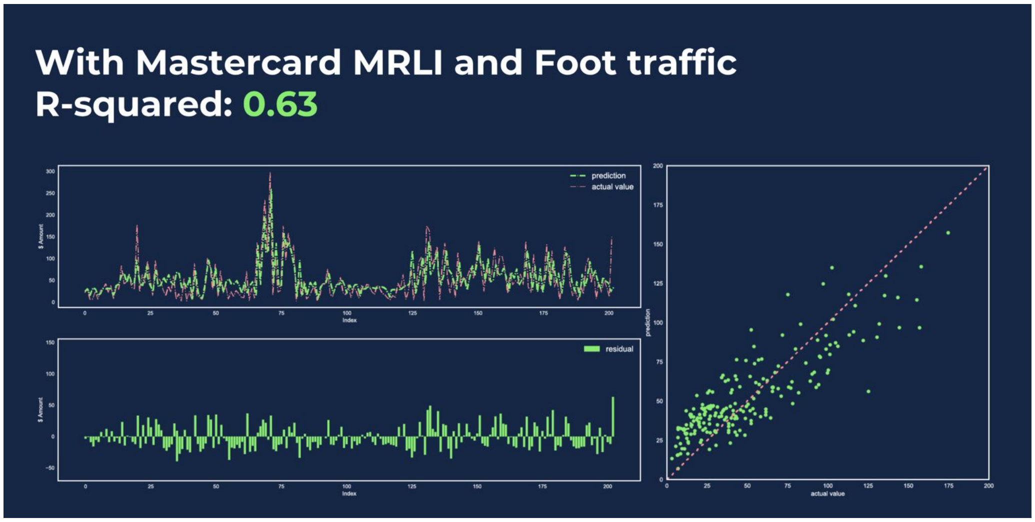

Figure 1: Gradient boosted regression model with two data layers to determine strategic placement of NYC food truck (CARTO, 2018)

After visualizing historical data of the local food trucks' engagement, the more refined iteration of the data analysis consisted of using a **gradient boosted regression model** (Grover, P. 2019) in order to make accurate predictions and decisions on which factors were most influential in the engagement of each food truck (Murray, P. 2018). In the image shown above, gradient boosted modelling (GBM) was utilized to predict the outcome of potential stationing and compare with actual values of usage, and was later combined alongside multiple data layers to determine the most impactful parameters that contribute to increased revenue of their units. Based on the data collected, it was determined that the proximity of their units in relation to densely populated or highly trafficked areas contributed to greater sales.

In regards to mobile clinics, the increased revenue would be translated into increased visits to the units as means of providing more equitable healthcare. In addition, the fact that MHC's focus on more vulnerable communities that differ from the average populations also signals that geographic population density would not be the most indicative of accessibility for target individuals, but it would be the overall convenience for people to reach said clinics. In comparison to CARTO's usage of gradient boosted modelling, MHC programs would be able to use their own historical records on clinic usage and location, and utilize analytical tools in the form of GBM to predict and discern the most beneficial parameters that contribute to the success of their clinics. In short, GBM would be used to validate the assumption that proximity to centers or more densely populated areas serve as better options for future stationing.

Road and Travel Path Assessment

After the selection of areas that are deemed as most vulnerable in terms of lacking accessibility of basic needs and health services, as well as the potential sites for stationing, the feasibility of safe and efficient travel can be analyzed based on geospatial analysis. As indicated through user interviews and available literature, barriers in convenient and accessible transportation and mobility is a large contributor in the usage of health services of disadvantaged populations (Jolly, R. et al. 1966). On this premise, ensuring that the implementation of MHC units coincides with typical spatial behavior of said individuals is crucial in providing sensible and considerate healthcare services.

Within the scope of this exploration, the integration of health services would be deemed accessible and convenient if it coincides with the target population's mobility behaviors, in the sense that reasonable distance and time from their usual trajectories. As by this stage multiple locations have been considered to be possible stationing areas through the use of their parking lots, assessing the potential impact of MHC units by using statistics on average travel time and distance based on region can be of value to apply to the mobile healthcare sphere.

Publicly available information on average travel time and distances can be misleading for including all individuals in an area, regardless of socioeconomic status (Buor, 2003; Kohli et al., 1995). As this can lead to multiple assumptions regarding the actual methods of transportation for underserved communities, available statistics should be used with caution. However, using those values can serve as baselines for a method of visualization called isochronic mapping, in which a contour map is created to illustrate the range of distance that can be covered in a determined time limit by choosing a center point. Isochronic maps are especially useful when showcasing geographic accessibility that can be a cause of poor road infrastructure, changes in topography, or simply high traffic rates, and thus provide a more realistic representation of potential mobility within a region (Dovey, K. et al. 2017). In an ideal setting, national databases would include information on most common methods of transportation based on socio-economic status or specific demographic, as well as their average commute times to serve as the determined time frame for an isochronic map. This would be due to the fact that marginalized communities are more susceptible to having longer commute times (National Equity Atlas, n,d.), as a result of underlying inequities that impact their degree of mobility as it has been stated throughout the exploration. In order to resolve this issue, using average wait times could serve as a goal time estimate, in order to predict the minimum amount of area covered based on patient mobility. By covering greater areas in shorter periods of time, the implementation of MHC's would translate into greater coverage of populations around municipalities; consequently, MHC's should be strategically spaced so that the least amount of overlap occurs between MHC units in order to optimize the accessibility factor of their medical services. After using isochronic maps to visualize the coverage area of potential locations, categorizing them based on geographic accessibility, or the ease of access for both the MHC's and patients, would be the final step in determining optimal stationing.

As mentioned earlier, observing the geographic accessibility in terms of the conditions of the potential sites' surroundings is an integral component of selecting vehicle placement. In order to determine whether roads are safe to travel over, while still using objective and data-driven methodologies as a means of minimizing bias, many technological tools can be utilized to harness the power of today's geospatial tools.

Currently, there are sophisticated technologies that allow for a detailed assessment of road structures and conditions, which utilize AI to recognize the presence of distresses such as potholes, cracks, or overall deterioration that can negatively impact the integrity of many vehicles (Quillen, A. 2020; OpenRouteService, n.d.).These tools can be incredibly useful for urban planning or commercial logistics; however, it can be inconvenient and unsafe for the parties involved if they have limited time and resources to asses the region, or if there is an underlying risk of damage if the area has been affected by natural disasters (Neis, P. n.d.).

In order to carry out a detailed and accurate assessment of desired road networks, aerial imaging can be utilized as a similar method to analyze the integrity of possible pathways. Even though aerial imaging is normally used for high-fidelity road detection using neural networks and AI tools in similar fashion to the sophisticated technologies mentioned earlier (Mnih, V. Hinton, G. n.d.), there are existing applications of aerial and satellite imagery to assess different types of road including unpaved roads. The inclusion of unpaved roads in certain applications render themselves useful as some technologies are limited to analyzing solely asphalt or paved roads, which can become a complication at the moment of analyzing road networks of rural communities that might only have unpaved, gravel or dirt roads (Quillen, A. 2020).

An exploration on the different methods on road network and condition analysis also discussed the possibility of utilizing aerial and satellite imaging as an efficient method to assess regions possessing a lack of information on their road networks or general infrastructure. Options such as Google Earth were discussed for being greatly accessible, yet it was suggested that the combination of lesser-quality images that are not always updated consistently could translate into misleading or inaccurate results when used as the only source (Workman, R. et al. 2016) However, the fact that decision making can also be influenced by more experienced partners and stakeholders, which ultimately possess more knowledge on the current integrity of roads and surroundings, means that Google Earth and Google Maps are accessible tools for many MHC programs to consult.

By completing this final level of the framework, MHC programs should have a clear understanding of the available locations that can be consulted for partnerships and agreements, in order to ensure that the locations are easy for patients to visit, as well as easy for MHC staff to "ingress and egress" their units safely if their specific unit has to be moved to another location. It is important to note that by choosing optimal locations, this does not exclude the possibility for MHC's to consult other areas in the case of visiting for appointments, but the goal is to make the most user-centric decisions on stationing through the use of available data. Even though much of the framework once again relies on the flexibility of each MHC program, the overall approaches and parameters from the framework could be taken into consideration to devise most appropriate logistical plans.

Section V: Mexico Case Study

As the purpose of this exploration is to determine an evidence-based model on strategic implementation of mobile health clinics, applying the proposed model on a real geographic region can help illustrate the process of utilizing and interpreting the proposed decision-making framework. The scope of the following example pertains to the implementation of a *new* mobile health clinic program in the country of Mexico, with a specific focus on providing diabetic care for underserved communities. For the purpose of this case study, there will be no constraints based on funding sources, partnerships, or political circumstances, given the fact that it would be based on the MHC program's individual partners at the time of other MHC programs applying the proposed model.

<u>Understanding the problem of access to diabetic care in Mexico</u>

In the country of Mexico, the growing rate of diabetes diagnoses has become an increasingly prevalent topic in the nation's public health sphere, as "only 24% of people with diabetes in Mexico have diabetes-related outcomes that are considered under control" according to a 2019 study (Ingram, M et al. 2019). As recent studies showcase an increasing number of diabetes cases, alongside a stagnation in the number of new medical centers capable of providing preventative care, the development of avoidable amputations have already begun disproportionately affecting underserved communities. Due to the prolonged nature of creating new clinics and hospitals, the development of LEA in the country of Mexico is currently at alarmingly high rates that cannot be addressed by the current amount of prosthetic clinics. As of writing this paper there are currently over 900,000 amputees in the country (Ascencio-Montiel, I. 2018), signalling that thousands of Mexican citizens struggle with receiving constant medical services that could have avoided the development of amputations. It is also important to note that Mexico possesses a centralized healthcare system to provide medical services across the nation (Secretaría de Salud, 2008), but vulnerable populations mostly depended on a national insurance program called *Seguro Popular* until it was replaced by a new program called Instituto de Salud Para El Bienestar (INSABI) (Institute of Health and Wellbeing) (Secretaría de Salud, 2008).

In response to the current situation surrounding diabetes care in Mexico, alternative methods such as MHC programs could be beneficial to decreasing the burden that individuals face due to the worsening of their diabetes conditions.

Application of the Framework

The first component of the decision-making process would be to establish the target region, as a result of utilizing geospatial analysis tools and publicly available data to make evidence-based decisions.

Based on the particular objective of providing preventative diabetes-related care to underserved communities, as a means of preventing the worsening of conditions leading to lower-extremity amputation, observing the density of prevalence based on geography would be the most indicative of severity of diabetes around Mexico. The prevalence of diabetes by region would not include the amount of untreated or undiagnosed cases, and would also consolidate information of all diabetes cases regardless of socio-economic status. However, the direct correlation between the prevalence of diabetes and difficulty in receiving access to healthcare facilities signals that visualizing prevalence can be an initial step to strategic selection of target regions. This information would be paired alongside the vulnerability index of each region, which can also be determined using publicly available datasets. In the case of Mexico, the country's Instituto Nacional de Estadística y Geografía (INEGI) (National Institute of Statistics and Geography) can serve as a source for both diabetes and vulnerability indexes based on county (Instituto Nacional de Estadística y Geografía, 2018).

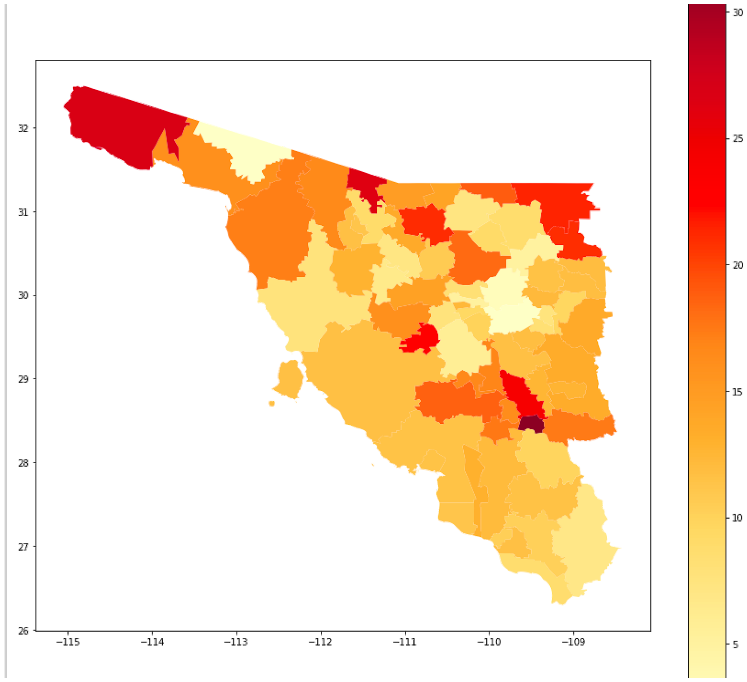

Figure 2: Heat map using simple linear regression, Geopandas, and Python to assess diabetes prevalence and socio-economic factors in Sonora, Mexico (Ackerman, Liam. 2020. [Manuscript in preparation]. Biomechatronics Lab at the MIT Media Lab.)

The Biomechatronics Group at the MIT Media Lab has begun visualizing the aforementioned parameters through the use of GIS-modelling, specifically using simple linear regression and software tools such as Geopandas and Python to color code Mexico states based on multiple data layers including prevalence, health insurance status, median income, and access to healthcare (MIT Biomechatronics Lab, n.d.). "Heat map" style visuals showcase deeper darker colors as indicative of worse conditions, highlighting the increased need of alleviating the burdens brought by a lack of accessible healthcare.

After preliminary assessment of a state-level "heat map" focusing on the necessity of healthcare services in Mexico, one state that could be seen benefited from the implementation of MHC's would be Sonora. From a county-level perspective, publicly available data has also detailed the severity of vulnerability and prevalence indexes for the chosen state. Using the same methodology as with the state-level map, one potential municipality, or county, can be chosen by determining the deepest colored regions as shown through the model. Based on currently available data and assessment of the heat map, the chosen municipality will be San Luis Rio Colorado (pictured below), and the following would be focused on the samely named city within the municipality.

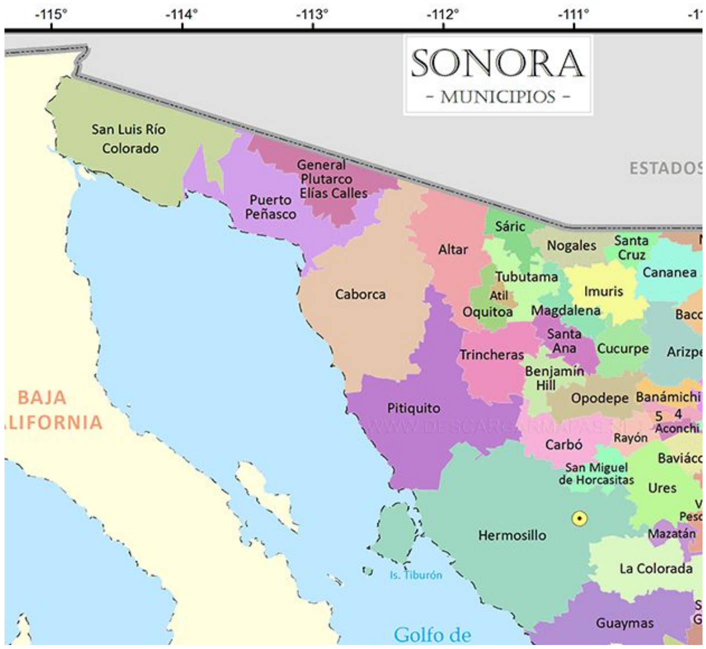

Figure 3: Map of Sonora including San Luis Rio Colorado Municipality ([Digital image]. (n.d.). Retrieved from https://descargarmapas.net/mexico/sonora/mapa-estado-sonora-municipios.png)

Once the target region has been determined, the next step would be to determine potential stationing placements based on the mobility behaviors and capabilities of disenfranchised communities in Mexico.

As mentioned in previous sections, partnering with healthcare providers or smaller health centers can be beneficial ways to quickly and easily establish relationships between patients and medical practitioners. For this exploration, locations of primary health care facilities in the region of San Luis Rio Colorado were labelled using a custom MyGoogleMaps. When mapping the location of potential hosting sites for MHC's, five out of six of the locations were focused on the upper region of the municipality. Assuming that all six clinics would be capable of providing care, the clustering of the clinics in the upper region of the municipality means that the lower boundaries would most likely be excluded due to travel times embedded in the mobility behaviors of vulnerable populations. In order to ensure that more equitable access to healthcare is being provided, looking at alternative locations such as community centers could be of value to consider as potential locations.

As mentioned in a previous section, strategically choosing locations such as community centers can be useful when determining sites that are culturally appropriate and convenient for underserved communities. In the case of Mexico, an idea would be partnering with DIF centers (Sistema para el Desarrollo Integral de la Familia) (System for Integral Family Development) across the municipality, which are one of the most widespread community centers around the country (Sistema Para el Desarrollo Integral de la Familia de la Ciudad de México, n.d.). Even though one of their largest focuses is to provide support for children and adolescents in disenfranchised communities through different programs and offerings, they also provide medical services, educational programs, and recreational activities to members of their community of much older ages (Sistema Nacional DIF, 2020). Due to the comprehensive nature of services that DIF centers are able to provide, considering these sites as hubs of individuals that could benefit from MHC services could be an initial step to considering user-centric locations. As demonstrated in the image below, traditional clinics and DIF centers have been mapped to visualize the amount of healthcare services in the area.

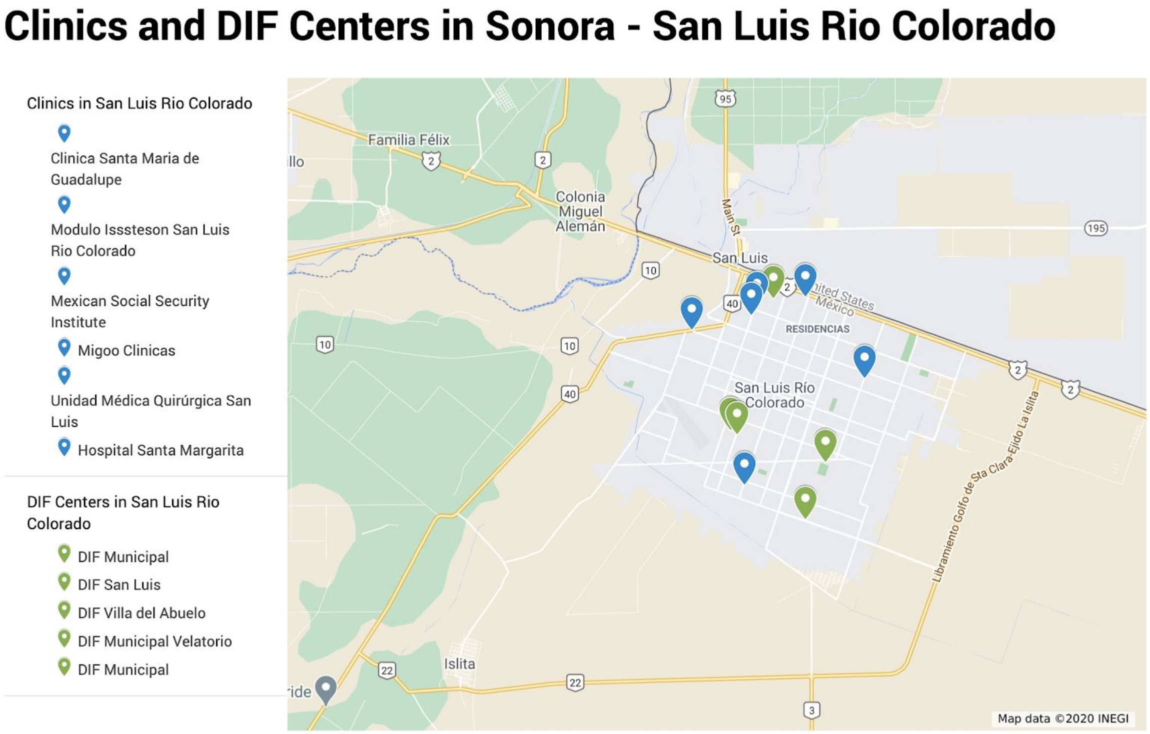

Figure 4: Custom MyGoogleMaps created to visualize clinics and DIF centers in San Luis Colorado, Sonora, Mexico; December 2020

As potential locations have already been identified, the next step would be to create isochronic maps based on mobility behaviors of communities in San Luis Rio Colorado. As mentioned in previous sections, using national databases or national statistics can be potential sources to gain a general understanding of average commute times and transportation methods. Using INEGI's most recent data on mobility and transportation habits by state, the average commute time in Sonora is 26 minutes, and the most common methods of transportation are commercial vehicles, followed by "truck, taxi, 'combi' or 'colectivo'", or essentially shared passenger vehicles (Instituto Nacional de Estadística y Geografía, n.d.). Given the fact that marginalized communities on average have greater commute times than more financially stable individuals, using the average travel time of 25-30 minutes, as well as using motor vehicles as plausible means of transportation, would be the parameters applied for the chosen municipality in Mexico.

Using an isochronic map generator (Iso4App. n.d.), an initial, layered isochronic map detailing the degree of mobility within a 30-minute radius using motor vehicles was created in response to national data for the state of Sonora, using four potential DIF center locations. As seen in the map picture below, great overlap in all four locations signals that the assumption of potential patients using motor vehicles to move around the city, meaning that less MHC units could be used in the case that the target population validates that aforementioned assumption.

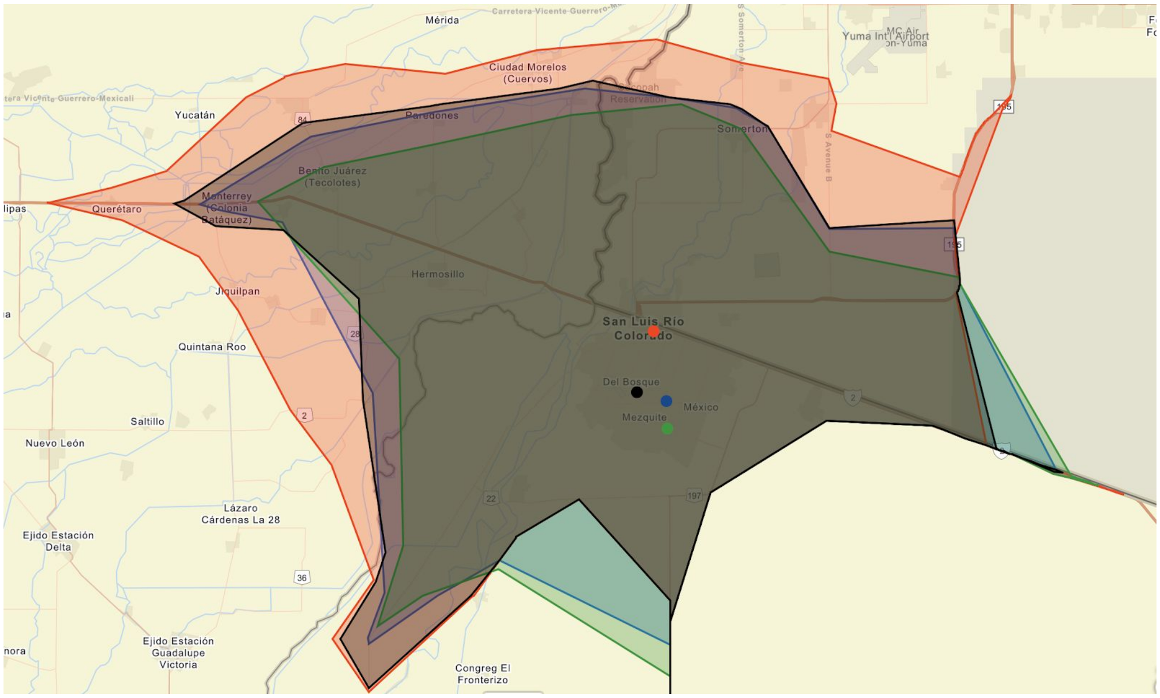

Figure 5: Custom 30-minute isochronic maps using motor vehicles as mode of transportation in San Luis Rio Colorado, Sonora, Mexico; December 2020

In the case that the boundaries of the outreach of mobile clinics would be tested by using other parameters, an isochronic map was also created showcasing the coverage area of four DIF centers using a 30-minute radius, but walking as the mode of transportation. As expected the coverage area would be much smaller, but isochronic maps as the one pictured below can be useful for MHC programs to determine realistic coverage areas of their units, and also plan accordingly if resources need to be added or relocated if certain locations should be targeted.

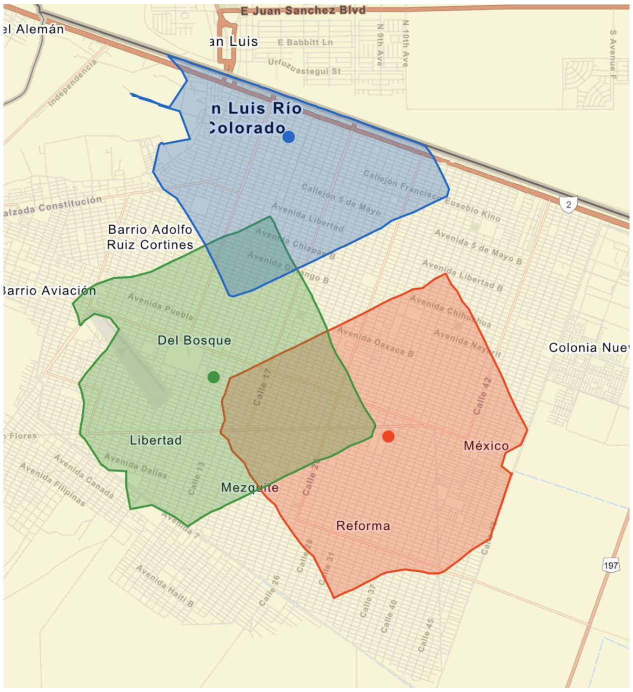

Figure 6: Custom 30-minute isochronic map using walking as mode of transportation in San Luis Rio Colorado, Sonora, Mexico; December 2020

Finally, using Google Maps to assess the surface integrity and surroundings of potential locations would be one of the final uses of technological tools to inform the decision-making process. As shown in Figure 7 below, closer views of the surrounding rows and parking spaces can be convenient for MHC staff to quickly assess the integrity of roads, but issues surrounding the lack of updated images (as indicated on the bottom right corner with the image capturing date of September 2009) causes complication in actual evaluations of the current environment. As a result, aerial photographs as shown in Figure 8 can be used as blueprints for external GIS or CAD software tools to use for the detection of distress in selected roads, as the AI methodology applied by the University of Toronto (Mnih, V. Hinton, G. n.d.).

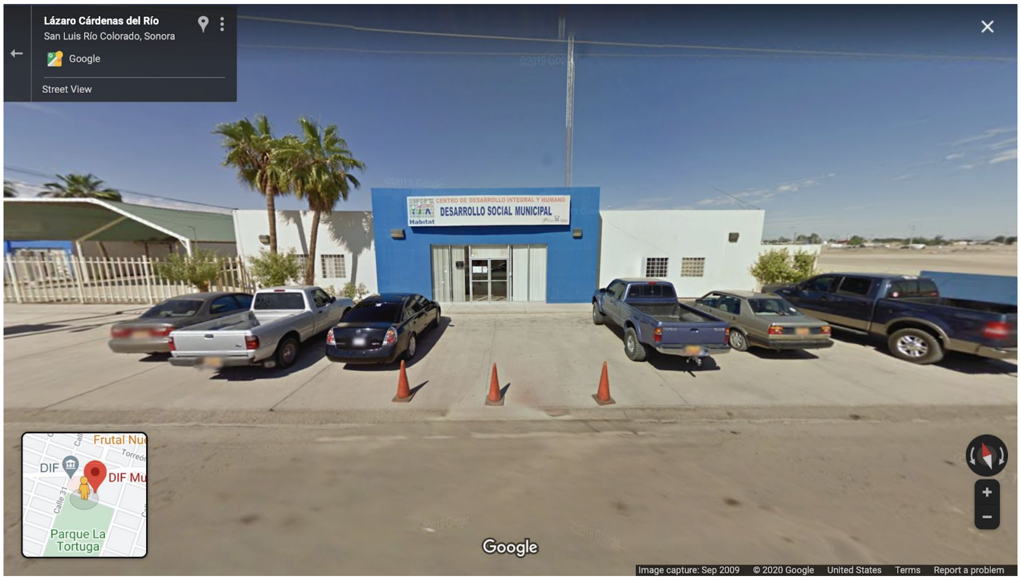

Figure 7: Google Maps image capture of DIF center in San Luis Rio Colorado, Sonora, Mexico (Google. (n.d.). [DIF Municipal]. Retrieved from https://www.google.com/maps/place/DIF+Municipal/@32.4344079,-114.7564024,330m/data=!3m1!1e3!4m5!3m4!1s0x0:0xab46d4272cbe6a72!8m2!3d32.4342887!4d-114.7563643)

Figure 8: Google Maps aerial image capture of DIF center in San Luis Rio Colorado, Sonora, Mexico (Google. (n.d.). [DIF Municipal]. Retrieved from https://www.google.com/maps/place/DIF+Municipal/@32.4344079,-114.7564024,330m/data=!3m1!1e3!4m5!3m4!1s0x0:0xab46d4272cbe6a72!8m2!3d32.4342887!4d-114.7563643)

By applying various components of the proposed framework to San Luis Rio Colorado, a new MHC program wishing to provide diabetes-related medical care to any region in Mexico could utilize the interdisciplinary suggestions discussed in this exploration to inform their decision-making process. Within this preliminary proposal of the conceptual model, there is still much room for MHC staff to utilize their preferred methods of data collection and visualization, as well as different sets of tools based on the amount of complexity that would be desired. As the suggested model was applied to a new MHC program with no historical data, gradient boosted modelling would be used after initial trials of placement and stationing in different areas, including information of summary of patient visits, time and date of visits, travel time to visit, and proximity to relevant sites. After consistently gathering data on the habits of MHC users, GBM would be utilized by having each parameter as a data layer, and thus mimic the methodology of CARTO's exploration to determine the most important consideration for future implementations of MHC's. By doing so, a feedback loop can be created to predict maximized impact for individual units, thus continuing the process of informing decision-makers in the case that the MHC program should reassess findings based on updated geospatial data.

Section VI: Limitations:

The proposal of the model is in its preliminary stages, with much room for technological development, as well as practical applications to multiple regions around the world based on the focus of rural or urban areas. Given the technological capacities today, the framework should serve as a foundation for MHC's to find data and tools that fit their niche in the healthcare and medicine market, as well as understand the degree of freedom in decision-making based on the influence of funding sources and partnerships. As mobile healthcare and geospatial analysis become increasingly more prevalent topics in the spheres of medicine and technology, it is also important to note that the need for user-friendly platforms is to be an integral component of ensuring that data-driven decisions can be massly implemented in different MHC programs. As of writing this paper, there are currently no accessible platforms available in order to perform high-fidelity geoanalytics in the humanitarian healthcare sphere, signalling a current gap in the market that has the potential of affecting the public's understanding of the impact behind geographic location and logistics. By creating dashboards and services that consolidate efforts in a similar fashion to MobileHealthMap [], as well as facilitate the update of information to showcase growth in access to healthcare around the world, more communication across MHC's can be established for the future.

Section VII: Conclusion

After completing an interdisciplinary exploration of the application of GIS-MCDA using available technological tools and abstract concepts, a conceptual framework was developed that allows for a hyper-local determination of the implementation of healthcare services such as mobile health clinics. By understanding patterns in behavior of potential users, being both experienced staff and MHC patients, insights can be determined to select best courses of action based on the type of care being offered. At the time of writing this paper, the efforts of using technological tools and data-driven decisions to strategically implement mobile health clinics focused on diabetic care will be continued at the Biomechatronics Lab at the MIT Media Lab, as part of the comprehensive project focused on providing quality care for diabetic patients and diabetes-related amputees in Mexico and other regions. Through the use of innovative tools, validated methodologies, and collaborative efforts between stakeholders and MHC programs, alternative healthcare systems are to have more potential of alleviating some burdens that disenfranchised populations face in any community, and provide medical services that are focused on the user's necessities as patients seeking resources.

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