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The Optimal Location of Ambulance Stations in a Regional Area: The Case of Mackay

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Abstract: The provision of efficient and effective emergency service such as ambulance service is a task faced by most cities and major regional centres. The emergency medical service is very necessary and plays a vital role in reducing death or serious complication from life threatening health incident. Over the years, there have been several major initiatives to improve the access to and quality of emergency care in Queensland. In 2009-2010, public hospital Emergency Departments (ED) in Australia covered about 7.4 million emergency cases of which there were over 3 million ambulance incidents.

Mackay is a regional city in Queensland, Australia's east coast. The Mackay Metropolitan which comprises of 24 suburbs is prone to natural disasters such as cyclones and flood. The Mackay region depends highly on emergency services especially during disasters. The current ambulance locations in the Mackay Local Ambulance Service Network (LASN) are significantly underperforming with regard to not meeting the target response time according to Queensland 2014 ambulance report. Early response to emergency calls is important and crucial for human survival. The response time is a function of the distance between the emergency facility and emergency demand. It is therefore important to locate emergency facility such that the distance to be travelled by an ambulance in response to emergency call is minimized.

The *p*-median problem finds the location of *p* facilities to minimize the demand weighted average or total distance between demand or population and their closest facility. The objective of this study is to discuss the importance of the application of the *p*-median model to locate emergency stations. We compare existing ambulance stations with the optimal solutions proposed by the *p*-median location models in the Mackay region. We determine the cost of assessing the facilities that are located using the *p*-median model and showed the cost saving of the model when optimal locations are compared with locations when facilities are added to the existing ambulance locations optimally.

Keywords: *Optimal, emergency, ambulance, cost*

1. INTRODUCTION

The accessibility to ambulances during emergency situations is an important aspect of health care delivery in most cities and major regional centres. It is vital for health care to be provided within a short time during any life-threatening emergency situations. There have been several major initiatives to improve the access to and quality of emergency care in Queensland. In 2009 and 2010, public hospital Emergency Departments (ED) in Australia dealt with about 7.4 million services. This is equal to 331 services per 1000 people. In Queensland the utilization rate is 350 services per 1000 people which is above the national average. People in regional areas in 2007-2008 were 1.7 times more likely to use Emergency Departments than the major cities. In Queensland 512 per 1000 used the Emergency Departments over the same period. The number of ambulance incidents recorded in Australia in 2009 and 2010 is over 3 million while the ambulance utilization rate in Queensland is 169 incidents per 1000 people. The demand for ambulance is constantly rising in Queensland for the period of ten years from 2000 to 2010 (Toloo *et al.*; 2011).

Mackay is a regional city in Queensland, on Australia's east coast. The Mackay Metropolitan area has 24 suburbs with the population of 76,069 reported in 2011. Mackay region is prone to natural disasters such as cyclones as evidenced by cyclone Debbie in the area just recently. It is therefore crucial for proper location and adequate number of emergency facilities for effective response during those natural disasters. The latest report for the period of July 2016 to March 2017 for the Mackay region indicates that 50% of the life threatening emergencies are responded within 8.3 minutes while 90% of the life threatening events are responded within 18 minutes which is higher than the state average of 16.8 minutes. There have been 90 ambulance incidents for which 73 of them have been transported by road. This is about 81% of the incidents which were transported by road for 9 months (July 2016 to March 2017). The average current cost of ambulance usage in Queensland per incident is $645 as reported in the 2013-14 ambulance service performance report.

The major problem is to determine the optimal location of the ambulances for effective health care delivery. The *p*-median problem finds the location of *p* facilities to minimize the demand weighted average or total distance between demand or population and their closest facility. The objective of this study is to discuss the importance of the application of the *p*-median model to locate ambulance stations in Mackay. We consider Mackay for the study because apart from Queensland ambulance report, the study on Mackay ambulance location is very limited. We also learnt from 2013-14 ambulance service performance report that Mackay LASN is under performing so we are motivated to conduct a research on Mackay to investigate that claim. We compare existing ambulance stations with the optimal solutions proposed by the *p*-median location models in the Mackay region. We determine the cost of assessing the facilities that are located using the *p*-median model. We compare the optimal locations with the locations resulting from adding facilities optimally to the existing ambulance locations. The paper is organized as follows. We briefly discuss the characteristics of ambulance locations in rural and urban areas in Section 2. In Section 3, we present the mathematical formulations of the *p*-median problem. We also discuss the *p*-median problem in terms of distance and transportation cost in Section 3. We discuss Mackay metropolitan area and present Mackay data in Section 4. Computational results obtained from Mackay data is presented in Section 5 and conclusion in Section 6.

2. AMBULANCE LOCATIONS IN RURAL AND URBAN AREAS

The ambulance care provided by rural emergency care is not different from the care provided by urban and suburban emergency workers. The operational mode is however difficult in the rural settings than the urban areas. The challenges that are faced in the rural areas include; the distance from the patient to an essential service and the level of infrastructure etc. Mackay metropolitan is surrounded by a number towns and remote mining areas hence the importance of the discussion on rural ambulance location. Moreover, a study by Busko (2008) stated that emergency delivery for population smaller than 250, 000 have not been reliable which is one of the major problems that are encountered in rural areas. Mackay with a population of 76,069 falls into this category. We can therefore state that the services in the major cities in Australia are more reliable than the regional areas (see Hamilton *et al.,* 2010 and Leeuwenburg and Hall, 2015).

A study by Barneveld *et al.* (2015) indicated that a reduction of one ambulance busy or not available in rural area is more noticeable in rural areas than in an urban area because of the limited number of ambulances in rural areas. The ambulance coverage in urban areas is uniform while it is not uniform in rural areas as population in rural area is not uniformly distributed. There is also greater area to be served in the rural or semi-urban area therefore the average response time is longer in the rural than the urban area. The road conditions and longer distances to be travelled in rural areas also contribute to longer response time. There are number of studies (Goodman *et al.*; 1997) that have stated that increased demand and better managed care occur in urban areas. In terms of cost, the per capita cost of providing ambulance in rural areas is general higher compare to urban densely populated areas.

The models to be used to locate facilities in less densely populated areas such as regional or rural areas are debatable. Chanta *et al.* (2014) stated that traditional covering models do not favour rural or semi-rural areas or less densely populated areas. They stated that using covering models will result in longer response times for patients in less densely populated areas. A study by Lee stated that the ambulance locations in rural or semi urban areas are designed based on distance from a fixed service (Lee; 2014).

In Australia, the paramedics who work in the rural areas in Australia experience stress according to the study by Hamilton *et al.* (2010). Pyper and Paterson (2016) also stated that rural and regional ambulance personnel in Australia experience high levels of fatigue and emotional trauma at work. The paramedics at the rural areas have to transfer a large proportion patient from small rural health facilities to urban medical care. There is therefore larger workload for Australian rural paramedic as compared to the paramedics in the urban areas.

3. THE *P*-MEDIAN PROBLEM

The objective of the *p*-median problem is to find the locations of *p* facilities to minimize the demand weighted total cost between each demand node and the nearest facility. For the *p*-median problem the cost of serving demands at node *i* is the product of the demand at node *i* and the distance between demand node *i* and the nearest facility to node *i.* The demand is proportional to the population at node *i*. The *p*-median problem in general is concern with the performance of the whole network instead of trying to solve only a particular problem in the network.

I = the set of demand nodes indexed by i

J = the set of candidate facility locations, indexed by j

p = the number of servers to be deployed or facilities to be located

a_i = the population at the demand node i

d_{ij} = distance between demand node $i \in I$ and candidate sites $j \in J$

$$Y_{ij} = \begin{cases} 1, & \text{if demands at node } i \in I \text{ are assigned to a facility at candidate site } j \in J \\ 0, & \text{otherwise} \end{cases}$$

$$X_j = \begin{cases} 1, & \text{if we locate at candidate site } j \in J \\ 0, & \text{otherwise} \end{cases}$$

$$\text{Minimize} \quad \sum_i \sum_j a_i d_{ij} Y_{ij} \tag{1}$$

subject to

$$\sum_{j \in J} Y_{ij} = 1 \,, \quad \forall i \in I \tag{2}$$

$$\sum_{j \in J} X_j = p \tag{3}$$

$$Y_{ij} \le X_j \,, \quad \forall i \in I, j \in J \tag{4}$$

$$Y_{ij} \in \{0,1\}, \quad \forall i \in I, j \in J \tag{5}$$

$$X_j \in \{0,1\}, \quad \forall j \in J \tag{6}$$

The objective (1) is to minimize the total cost from customers or clients to their nearest facility. Constraint (2) shows that the demand of each customer or client must be met. From constraint (3), the number of facilities to be located is *p.* Constraint (4) shows that customers must be supplied from open facility. Constraints (5) and (6) present the problem as a binary integer programming. The above formulation assumes that the potential facility sites are nodes on the network. Hakimi (1964) showed that allowing facilities to be located on the arcs of the network instead of the nodes would not reduce total travel cost.

A number of authors have used the *p*-median model to locate or relocate emergency facilities. These include Berlin *et al.* (1976); Carson and Batta (1990); McAleer and Naqvi (1994) Serra and Marianov (1998); Caccetta and Dzator (2001, 2005); Dzator and Dzator (2013, 2015). Recently, Dzator and Dzator (2016) relate the use of *p*-median problem to locate facilities to development.

3.1 The *p*-median problem and the cost of accessing facilities

The *p*-median problem is simply to minimize the transportation cost between the facility and the allocated customers. We may state the problem basically as a combinatorial optimization problem as:

$$\min_{F \subseteq J} \{ \sum_{i \in I} \min_{j \in F} d_{ij} : |F| = p \} \text{ (Using the same notation)} \qquad (7)$$

The transportation cost can also be referred to as the connection cost between a customer or patient and the facility. The cost depends on the number of facilities that is accessible and the travel distance. According to Daberkow and King (1977) emergency ambulance service is considered to be price and income inelastic. That is emergency service is an essential service that would be acquired at almost any cost however, the closer the facility is to the customer or patient the better it is for the provider and the patient. The cost of accessing the facility increases as the distance between the facility and the customer increases. We assume that customers or patients will only use their closest facility.

In the siting of emergency facilities the facilities are located such that customers or patients are assigned to the facilities to minimize the total cost. The connection cost from the facility to the demand or patients is directly related to the distance between the facility and the patients. That is the longer the distance the higher the cost in accessing a facility assuming that all other variables in relations to the facilities located are the same. If we assume that the only variable cost in using the facilities is the transportation cost then the cost saving is related to how long it takes to get access to the facilities. We also assume that each potential facility has the same fixed cost for locating a facility and the facility do not have capacities on the demand that they can serve.

For the *p*-median problem as stated by Daskin and Maas (2015) the demand weighted cost or distance decreases with the addition of each subsequent facility. If the previous facilities that are located is optimal then adding the next facility at any potential site that does not have a facility will decrease the demand weighted total cost or distance.

The total cost is determined by summing the weighted distances from each node to each of the proposed facilities. The objective of facility location problems is to locate facility to minimize the total setup cost and the total transportation cost. For this paper we will consider only transportation cost because we assume that the cost of locating the facilities is the same. For uniform setup cost minimizing the transportation cost is the way to effectively locate facilities.

Caccetta and Dzator (2005) stated that the response time depends on the distance between emergency facilities and the patients. The solutions to the *p*-median are efficient since they bring the emergency facilities into closer proximity of the users. This will result in the reduction of the response time if we assume that all other variables remain constant. The *p*-median model also considers everyone in the community when facilities are located unlike other basic location models such as the *p*-centre model and the maximal covering location models (MCLP) which aims at maximizing the population that is covered or served. The *p*-median model therefore evaluates the performance of the whole network instead of just solving a particular problem within the network.

4. MACKAY METROPOLITAN AREA

The Mackay metropolitan comprises of 24 suburbs and it has two ambulance stations located at Mackay City and North Mackay. There is one major public hospital in Mackay. We will discuss below how we obtained the data for the study.

Data

For this study the distance matrix from node to node is determined by distance data developed by Travelmate Company. This distance is the road network among the various suburbs in the Mackay metropolitan area. Hence the distance values are the shortest road travel distances (equivalent to distance on a road map) between the origin and the destination.

We weighted the distance by taking into consideration only the population of the origin suburb since we can also weigh by considering the nature of the road. The fact is that the better the road network the easier it is for a vehicle to move from one suburb to another. The weighted distance is thus the product of the population at the origin suburb and the distance between the origin suburb and the destination suburb. We note that the larger the population the larger the weight. This weighted distance is calculated for each of the twenty-four suburbs in the Mackay Metropolitan region. This calculation is done by noting the distance from a suburb to all other suburbs and each value is multiplied by the weight of the origin suburb. This is repeated for every suburb and values are recorded as a column matrix representing Mackay Metropolitan area. The population for the suburbs which was used for the weight for each node ranges from 38 for a suburb of Cremorne to 9372 which corresponds to Andergrove and this shown in Table 1 below. The minimum weighted distance for the Mackay Metropolitan area is 76 km and the maximum value is 178,068 km.

Table 1. Names of suburbs in Mackay Metropolitan Area and their Population from 2011 Census Data

Node	Suburb	Population	Node	Suburb	Population
1*	Mackay City	4072	13	Erakala	351
2	East Mackay	3636	14	Glenella (with Foulden)	4633
3	West Mackay	6507	15	Mackay Harbour	733
4*	North Mackay	6597	16	Mount Pleasant	4751
5	South Mackay	7416	17	Ooralea	2601
6	Andergrove	9372	18	Paget	360
7	Beaconsfield	4934	19	Racecourse	242
8	Blacks Beach	2871	20	Richmond	505
9	Bucasia	4257	21	Rural View (with Nindaroo)	3324
10	Cremorne	38	22	Shoal Point	1086
11	Dolphin Heads	398	23	Slade Point	3859
12	Eimeo	3309	24	Te Kowai	217

5. COMPUTATIONAL RESULTS

We used the SITATION software (Daskin; 1995) to determine the results for the existing locations and the optimal locations. The first two existing locations are known so we determined their objective values using the SITATION software. Facilities are then added optimally to existing locations using the SITATION software and we noted the objective value for the locations. The optimal locations were determined by the implementation of the Lagrangian relaxation in the SITATION software (Daskin; 1995).

Table 2. The Existing Location and the *P*-Median Locations with Total Population Weighted Distance (TPWD)

Number of Facilities	Existing Locations - TPWD	Optimal Location - TPWD
2	{1, 4} - 855120	{10 , 22} - 7106
3	{1, 4, 10} - 7600	{8, 10, 22} - 6498
4	{1, 4, 10, 22} - 6919	{8, 10, 11, 22} - 5928
5	{1, 4, 8, 10, 22} - 6308	{8, 9, 10, 11, 22} - 5396
6	{1, 4, 8, 10, 11, 22} - 5738	{8, 9, 10, 11, 12, 22} - 4864
7	{1, 4, 8, 9, 10, 11, 22} - 5206	{8, 9, 10, 11, 12, 22, 24} - 4370

Table 3. Distance Cost for Existing Location (EL), Optimal Location (OL) and Average Cost Per Person

Number of Facilities	EL Cost	OL Cost	Average Cost - EL	Average Cost - OL
2	855120	7106	11.241	0.093
3	7600	6498	0.100	0.085
4	6916	5928	0.091	0.078
5	6308	5396	0.083	0.071
6	5738	4864	0.075	0.064
7	5206	4370	0.068	0.057

Table 4. Distance Cost for Existing Location (EL), Optimal Location (OL) and Average Cost Per Incident for Nine Months (July 2016 to March 2017)

Number of Facilities	EL Cost	OL Cost	Average Distance Cost for EL	Average Distance Cost for OL	Average Percentage Cost Increase
2	855120	7106	11713.97	97.34	11934.08
3	7600	6498	104.11	89.01	16.96
4	6916	5928	94.78	81.21	16.70
5	6308	5396	86.41	73.92	16.89
6	5738	4864	78.60	66.63	17.96
7	5206	4370	71.31	59.86	19.13

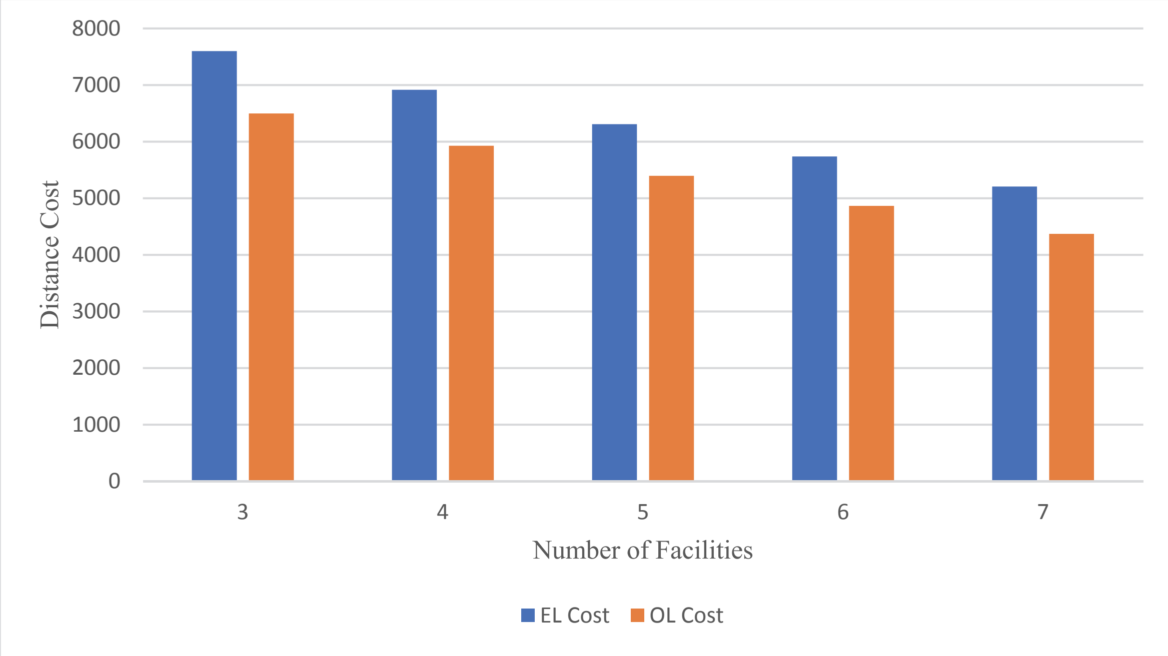

Figure 1. Distance Cost for Additional Existing Location (EL) and Optimal Location (OL)

Table 2 shows the existing and optimal locations when locating 2 to 7 ambulance stations. Currently, we have ambulance stations at node 1 (Mackay City) and node 4 (North Mackay). We located additional stations using the two existing stations as a constraint which should be in the final solution. In practice that is what happens when for example we have fixed facilities and we are expected to add new facilities to the existing ones. The TPWD for the two existing ambulance stations is 855120 and the optimal value is 7106. Table 2 and Figure 1 show TPWD for 2 to 7 and 3 to 7 ambulance stations for the EL and OL respectively. The cost of using the existing location or the optimal location is the distance cost of accessing the facilities.

Tables 3 and 4 show the average distance cost per person and per incident for nine months (July 2016 to March 2017) respectively for EL and OL. The average distance cost for EL ranges from 0.068 to 11.241 and it ranges from 0.057 to 0.093 for OL. There have been 73 ambulance incidents from July 2016 to March 2017 in the Mackay region so the average distance cost per incident for EL ranges from 71.31 to 11,713.97. For OL the average distance cost per incident is from 59.86 to 97.34.

We also have the percentage cost increase in Table 4 which shows that there will be cost saving of 11934.08% if the *p*-median problem is used to locate the two existing ambulance stations optimally. This shows that the current ambulance locations at node 1 and node 4 have been located non-optimally.

6. CONCLUSION

The study is to assess the ambulance stations in Mackay metropolitan area. The study shows that the existing ambulance stations have not been optimally located. There is a large difference between the two existing locations and the locations obtained from the *p*-median model. We have outlined the importance of distance minimization in the study using the *p*-median model.

The results showed that the current ambulance locations have been located non-optimally. Some of the consequences of non-optimal locations are the reduction in accessibility of facilities for the customers and an increase in the cost of running the facilities. This might also lead to most of the customers (demand) not being served in a reasonable time. The operations of ambulances can clearly be improved if facilities are located more optimally or if more facilities are constructed. Maybe the facilities are located non-optimally at Mackay City (node 1) and North Mackay (node 4) because of local demand, public opinion or political decision.

The projected distance costs when facilities are added to existing facilities optimally are also noted and it decreases as more facilities are added. For further studies it will be worthwhile to compare the results from the *p*-median problem with the *p*-centre and the covering problems and their variants.

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