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FOCUSING ON CENTRALITY MEASURE IN EMERGENCY MEDICAL SERVICES

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Abstract

Emergency Medical Services (EMS) attracted many researchers because the demand of EMS was increasing over time. One of the major concerns of EMS is the response time and ambulance despatching is one of the vital factors which affects the response time. This paper focuses on the problem of ambulance despatching when many emergency calls emerge in a short time, which exists under the condition of catastrophic natural or manmade disasters. We modify a new method for ambulance despatching by centrality measure, this method constructs a nearest-neighbor coupled emergency call network and then prioritize those calls by the score of fitness, where the score of fitness considers two factors: centralized measure a call by the emergency call network and the closest policy which means despatching to the closest call site. This method is testified by a series of simulation experiments on the real topology road network of Hong Kong Island which contains 8 hospitals. These analyses demonstrate the real situation and proof the potential of centrality measure in reducing response time of EMS.

Keywords: Emergency Medical Services, Ambulance Despatching Decision, Centrality Measures, Network Analysis.

1 INTRODUCTION

Emergency Medical Services (EMS) is a type of service providing pre-hospital treatments to those in need of emergency medical care. An important performance measurement of EMS is the response time which means the time of ambulance taken to reach the patient after an emergency call is received. So the ambulance despatching decision is a critical factor which reflects the efficiency and effectiveness of EMS. O'Keeffe and Nicholl (O'Keeffe, Nicholl et al. 2011) point out that the effect of a 1 min reduction in response time for patients with the sudden cardiac arrest is estimated to increase the survival rate by 24%, at the same time, the demand of EMS was increasing over time(Lee 2014), these situations lead to the need of useful techniques of despatching ambulance to reduce response time.

Three types of ambulance decisions for the EMS significantly influence the response time: ambulance location, ambulance relocation and ambulance dispatching (Lee 2010). The decision of ambulance location involves establishing optimal location in terms of coverage and has been the most widely studied (ReVelle and Hogan 1989; Brotcorne, Laporte et al. 2003; Jia, Ordóñez et al. 2007). Relocation decision involves relocating the ambulance to different locations with the purpose of improving coverage (Gendreau, Laporte et al. 2006; Alanis, Ingolfsson et al. 2013). The decision of ambulance despatching assigns appropriate ambulances to the calls, Lee classifies it into two categories based on the busyness of the system of EMS: call-initiated decision and ambulance-initiated decision(Lee 2012 (b)). The call-initiated decisions are more relevant in routine scenarios when the system is not busy and idle ambulances can be found when a new call arrives, thus lead to making decision for selecting an idle ambulance to the call.

However, the ambulance-initiated decisions are applied to the situation that EMS system is very busy and no ambulance is free when many emergency calls arrive in a very short time. This situation involves catastrophic natural disasters (earthquake, hurricane, flooding, etc.) or manmade attacks (September 11th, 2001) which have been evidenced recent years. For example, the natural disasters affected 390 million people in China in 2013 (http://news.xinhuanet.com). Besides, 373 natural disasters in 2010 killed over 296 800 people, affected nearly 208 million and took nearly $110 billion according to the Centre for Research on the Epidemiology of Disasters (http://cred.be/). In response to those kinds of large-scale emergency, carful and well-prepared pre-planning, as well as efficient and professional EMS are necessary and can save many lives. Besides, in the paper of (Simpson and Hancock 2009), Simpson and Hancock suggest that the emergency response research on such catastrophic natural and manmade disasters is an important growth area for the coming 50 years. So this research focuses on the situation of ambulance-initiated decisions in the effort of improving the response time of EMS for catastrophic natural or manmade disasters.

The particular characteristic of ambulance despatching problem in EMS is considering the hospital as a center of service and the patients are transferred to the centre. However, it is not always necessary to transfer every patient to the centre. For example, in the United States the percentage of emergency calls which require transferring to hospital is 25% (Blackstone, Buck et al. 2007). Therefore, the ambulance can continue to serve several emergency calls before transferring to hospital. Under this situation, Lee proposes a novel centralized policy for despatching ambulance based on the combination of centrality measures and closest policy (Lee 2012 ; Lee 2012 (b)). The closest policy despatches the available ambulance to the closest call, which is enable to achieve a minimum response time for the current call, but may increase the response time for the coming calls because the closest policy just ensure the short-term performance. The centrality policy prioritizes the calls by centrality measure and ensures the long-term and short-term performance of response time, so this policy is better than the widely used closest policy. However, there are some shortcomings in these two papers of Lee's. Firstly, he constructs a globally coupled network of the emergency calls by connecting every pairs of calls, which means every call has n-1 edges where n denotes the total number of emergency calls. This globally coupled network will become extremely complicated when the number of calls is large at a moment, which may influence of the computational efficiency of the algorithm and further influence the effectiveness of the centrality policy. Honestly, there are just seven emergency calls at one moment in the illustrative example of paper (Lee 2012); on the other hand, it is not necessary to connect two calls where the geographical distance is quite large. For example, a call locates in the southeast of a city, but the other call locates in the northwest. So to form a globally coupled call network is not appropriate and even necessary in real life. Secondly, in the simulation experiments of these two papers, the service area is a simple square grid which may not reflect the true situation of real EMS.

In order to deal with these shortcomings as mentioned above, in this paper we conduct the simulation experiment in a real situation where the service area is the topology road network of Hong Kong Island which contains eight big and famous hospitals (see Figure 1). We construct the emergency call network as a nearest-neighbor coupled network by giving a threshold value for the geographical distance of call pairs. The purpose of this paper is to testify the usefulness of centrality policy in the real time situation by comparing the performance of centrality policy and the closest policy.

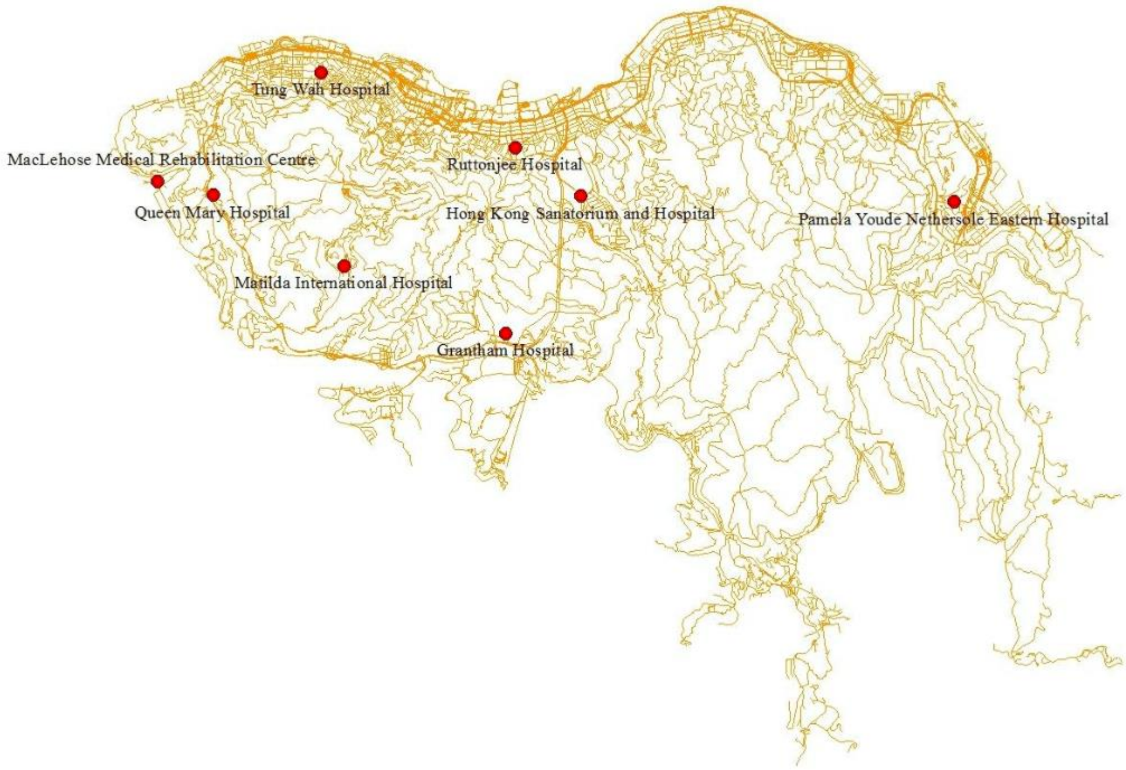

Figure 1. The road topological structure of Hong Kong Island

The paper is organized as follow: section 2 introduces the theoretical background and the centrality policy. Section 3 indicates the simulation experiments we conducted and the analysis about the performance of the centrality policy. Finally, section 4 makes conclusions on this work.

2 THEORETICAL BACKGROUND AND POLICY DEVELOPMENT

This section we present the related theory of centrality measures, policy of ambulance despatching and then we will introduce the centrality policy.

2.1 Centrality Measures

In a network, more central nodes contribute more to the efficiency of the network. Centrality measures, which refer to a series of indices used to localize the most significant node and quantify how important they are relative to other nodes in a networked system, have been discussed for over 50 year in the field of “network science”(Ruhnau 2000). Particularly, centrality measures is widely used in social network to identify the important actors where the social network can formally be represented by a graph $G = (N, L)$ or a weighted graph $G^W = (N, L, W)$. In these kind of graphs, N,L denote the set of nodes (or vertices, or points) and links (or edges, or lines) respectively, W contains the set of weights which are real number of links. Formally, W is a weight matrix whose element $\boldsymbol{w_{ij}}$ is the weight of the link connecting node $\boldsymbol{i}$ and node $\boldsymbol{j}$. A large number of centrality types have been proposed so far within the scope of social network analysis (Friedl and Heidemann 2010), such as, degree centrality, closeness centrality, betweenness centrality, eigenvector centrality and PageRank. However, centrality measures are also applied in many other fields, including optimization problems (Freeman, Borgatti et al. 1991; Gómez, Figueira et al. 2013), complex engineered systems(Sosa, Mihm et al. 2011), complex products development(Batallas and Yassine 2006; Sosa, Eppinger et al. 2007), urban management (Crucitti, Latora et al. 2006) and viral marketing(Kiss and Bichler 2008; Wang and Chiu 2008; Leem and Chun 2014).

In the paper we restrict our considerations on weighted network and two types of centrality measures — degree centrality and closeness centrality. A centre (or important) node is the one that connects to a large number of other nodes, so the centrality can be measured as the number of links connecting to the node (Batallas and Yassine 2006). However, in a weighted network the degree centrality of a node is the sum of weights of all links that connect to the node (Newman 2004). According to this description, the degree centrality of node $\boldsymbol{i}$ can be defined as $C_{d(i)} = \sum_{j \in N} w_{ij}$. Degree centrality just shows the direct relationship where how many nodes are connected to the target nodes, but it does not consider the indirect related nodes. The notion of closeness centrality which reflects the indirect relationship involves a central-close node can connect other nodes through short distance path. So closeness centrality(Crucitti, Latora et al. 2006) is defined as the possibility of a given node to communicate with many other nodes using a minimum number of intermediaries and can be calculated by $C_{c(i)} = (n-1)/\sum_{j \in n} d_{ij}$, where dij denotes the geodesic between node $\boldsymbol{i}$ and $\boldsymbol{j}$. closeness centrality plays a significant role in understanding the structure of a network(Batallas and Yassine 2006).

2.2 Emergency Vehicle Dispatching

Policy of ambulance despatching is included in the problem of emergency vehicle dispatching, and emergency vehicle dispatching is a derivative of the classic travelling repairman problem(Agnihothri 1988) or minimum latency problem(Blum, Chalasani et al. 1994). In order to minimize the total response time of customers rather than the total traveling time, the purpose of travelling repairman problem is to find a path for a given set of customer locations, the travelling repairman problem is a NP-Hard problem (Hochbaum 1996). Two useful methodologies are used in the research of emergency vehicle dispatching: mathematical programming and simulation. The mathematical programming considers emergency vehicle dispatching as operations research and formulates a series of equations or/and inequalities, and then optimize them to get the optimal solution. There are many literatures using mathematical programming to study emergency vehicle dispatching problem, such as,(Shen, Dessouky et al. 2005; Schmid 2012; Bjelić, Vidović et al. 2013). On the other hand, the simulation approach proposes some dispatching rulers/policies (eg. first come first served) for emergency vehicle dispatching, then simulates those policies and verifies them. The simulation model can be embedded into emergency medical services system (Goldberg and Listowsky 1994; Potvin, Shen et al. 1995; Sullivan 2008). In the paper of (Aboueljinane, Sahin et al. 2013), the authors give a detail review on simulation of emergency medical services.

In the seminal work of (Bertsimas and Van Ryzin 1991) , they presented five despatching policies: first come first served policy, stochastic queue median policy, partitioning policy, traveling salesman policy, space filling curve policy and nearest neighbour policy (which is to sever the closet customer, so we called as closest policy), they point out the nearest policy is notably optimal than other policies by a set of numerical experiments. So the closest policy can be considered as an effective policy for dispatching ambulance, even under emergency situations(Lee 2012 (b)). In this paper we consider the closest policy as the baseline policy and conduct a series of simulation experiments.

2.3 Centrality policy

Although the closest policy is computationally simple, it just considers how to minimize the immediate response time without taking into the long-term performance. By considering the short-term performance as well as long-term performance of despatching ambulance, Lee (Lee 2012) propose a novel despatching policy—centrality policy.

Motivated by identifying the structural properties of ubiquitous real networks, many researchers pay attention to the study of network science. Node centrality is an indicator to measure the importance of a node in the network. Here the node centrality is adopted to guide despatching ambulance in a static situation. When many calls emerge, a call network can be formed where the nodes denote the emergency calls, and edges represent the shortest path between two calls. In the paper of (Lee 2012 ; Lee 2012 (b)), Lee construct a globally coupled call network where every pair of calls have an edge, as mentioned before, this globally coupled network will become extremely complicated when the number of calls is large at a moment, which may influence of the computational efficiency of the algorithm and further influence the effectiveness of the centrality policy; on the other hand, it is not necessary to connect two calls where the geographical distance of them is quite large. So in this study, we adopt a threshold value for the shortest path, the calls are connected when the shortest path among them is smaller than the threshold value. This is a big difference between our work and Lee's.

Based on our approach, a call network is constructed. Obviously, it is not a globally coupled network but only shows the geographical distribution of current calls. Node centrality, which is interpreted as the efficiency of the call in reaching other calls, can be calculated by the topology of this call network. When an ambulance is despatched to the most central call, after it finishes the service of the most central call, this ambulance has the chance to serve other calls around the most central call because it is not always necessary to transfer every patient to the hospital. However, despatching ambulance only by the node centrality, the ambulances will travel excessively because of always placing themselves in the central nodes without serving the neighbour calls. Therefore, the centrality policy should be combined with the closest policy which enhances the capability of local exploitation(Lee 2012 (b)). As mentioned before, the closest policy is a policy to pursue the short-term performance by minimizing the current response time, so this policy is embedded into centrality policy to achieve both short-term and long-term performance of despatching ambulance. According to the description, the algorithm of the centrality policy is presented as follows (here the situation of emergency medical service is that many emergency calls arriving in a short time in the setting of catastrophic natural or manmade disasters).

Step 1: Constructing a weighted nearest-neighbor coupled call network by using a threshold value $\boldsymbol{d^*}$ for the shortest path, the weight $\boldsymbol{w_{ij}}$ for link $\boldsymbol{L_{ij}}$ is the shortest path between node $\boldsymbol{i}$ and node $\boldsymbol{j}$;

Step 2: Calculating node centrality $\boldsymbol{C_{(i)}}$ based on the topological structure of this call network, here we just calculate the degree centrality $\boldsymbol{C_{d(i)}}$ and closeness centrality $\boldsymbol{C_{c(i)}}$ (the definition of these two centrality measures are mentioned is section 2.1);

Step 3: Calculating the response time $\boldsymbol{t_{ij}}$, where $\boldsymbol{t_{ij}}$ represents the response time of ambulance $\boldsymbol{i}$ travel to node $\boldsymbol{j}$;

Step 4: Calculating the fitness of $\boldsymbol{K_{ij}}$ for ambulance $\boldsymbol{i}$, where $\boldsymbol{K_{ij}}$ is defined as follow;

$$K_{ij} = \frac{C_{(j)}^{\omega}}{t_{ij}} \qquad (1)$$

Step 5: Despatching the ambulance ***i*** to the call ***j**** that maximize the fitness of $\boldsymbol{K_{ij}}$;

$$\mathrm{j}^* = \arg\max_{j \in n} K_{ij} \qquad (2)$$

Step 6: Transferring the patient located in the call ***j**** to the nearest hospital by a probability ***P***.

The process of step 2 to step 6 will be repeated once there is a free ambulance, the whole process will end when all emergency calls are served.

3 EXPERIMENTS AND ANALYSIS

In this section, we measure the performance of the centrality policy for despatching ambulance in various scenarios based on the changing of number of ambulance, parameter ω and ***P***. The simulation experiments are conducted on the real road topological structure of Hong Kong Island, this is another difference between our work and the Lee's paper. The advantage of our experiments is closer to the real ambulance despatching situation, which has significant implication in emergency medical service. On the other hand, there are two centrality policies where the node centrality is calculated by degree of centrality and closeness centrality respectively. We adopt comparative analysis approach to evaluate the centrality policy by the performance enhancement over the closest policy. The reason of using closest policy as a baseline policy is this policy is widely used in many situations and is an optimal despatching policy across different scenarios. In one word, the effect of the two centrality policies is compared to closest policy.

3.1 Experiment Design

The service area of emergency medical service is Hong Kong Island which is an island in the southern part of the Hong Kong Special Administrative Region, the whole area of this island is approximately 87.4 km^2. There are eight big and famous hospitals in Hong Kong Island, here we assume that the patients will be sent to those hospitals for intensive medical service if necessary, however it is not necessary to send every patient to hospital as mentioned in section 1.Besides, we assume that there are 800 emergency calls being received in a short time in the setting of the same situation as catastrophic natural or manmade disasters. The location of 800 emergency calls and eight hospitals are shown in figure 2. We calculate the distance of the shortest path for each pair of calls based on the road topological structure of Hong Kong Island, if the distance of the shortest path is smaller than the threshold value (we set this value as 5km in our study), this pair of calls will be connected and the weight of each link is the reciprocal of the distance. According to this rule, we can construct a weighted call network which can reflect the density of the calls.

Figure 2. The experiment interface. The green points denote the location of hospitals and the red points denote the emergency calls. T: closest policy, C_d: degree centrality policy, C_c: closeness centrality policy.

The ruler of medical service is described as follow: An ambulance is despatched to a call based on those policies with a velocity (***v***=0.5km/min), and then the ambulance transfers the patient to the nearest hospital around the location of this call with a probability ***P***. If the patient needs to be transferred to hospital, the time for the ambulance driving to hospital is calculated by the distance and the velocity. Otherwise, the ambulance takes 10min to serve this patient at the current location of the call, and then it will be despatched to other calls. According to this medical service rule and three despatching policies, we calculate the total service time for each despatching policy and compare the performance.

On the other hand, four factors are considered in our study for generating different testing scenarios: the number of ambulances, the probability of ***P***, the parameter ω(ω denotes the weight of node centrality) and the threshold value of $\boldsymbol{d}^*$($\boldsymbol{d}^*$ is sued to construct the nearest-neighbor coupled call network). The size of ambulance number is set as four classes: 5, 10, 20, 50. The range of probability of ***P*** is changed from 0 to 1with an increment of 0.1. The parameter ω varies in {0.05, 0.2, 0.6, 0.8, 1.0, 1.5, 2.5, 6}. The threshold value of $\boldsymbol{d}^*$is set as four classes: 3, 5, 8, 10(KM). For each scenario we conduct 50 simulation experiments.

3.2 Performance Evaluation for Centrality Policy over Closest Policy

As mentioned before, there are two centrality policy: closeness centrality policy and degree centrality, 50 experiments for each scenario based on different probability ***P*** and parameter ω for different size of ambulance. We record the response time for each scenario and count the number of experiments for which the response time for centrality policy is shorter than the closest policy. Figure 3 shows this result for closeness centrality over closest centrality policy. When the size of ambulance number is 5 or 10, the number of improved experiments for each scenario reveals that the closeness centrality policy can reduce the response time over the closest policy, especially for the situation when the parameter $\omega$is bigger. For example, when the parameter equals 2.5 or 6 the number of improved experiments exceed 40 over the 50 experiment. However, when the size of ambulance number is 20 or 50, the result shows that the closeness centrality policy is not always the optimal one. Tow probable reasons may be applied. Firstly, there are so many ambulance that every ambulance can easily get to the closest emergency call, so the number of ambulance influences the selection despatching policy. Secondly, the probability ***P*** for transferring to hospital also influence the policy's performance, the response time for closeness centrality is shorter when ***P*** is small. The improvement for closeness centrality is significant when ***P*** approaches to zero.

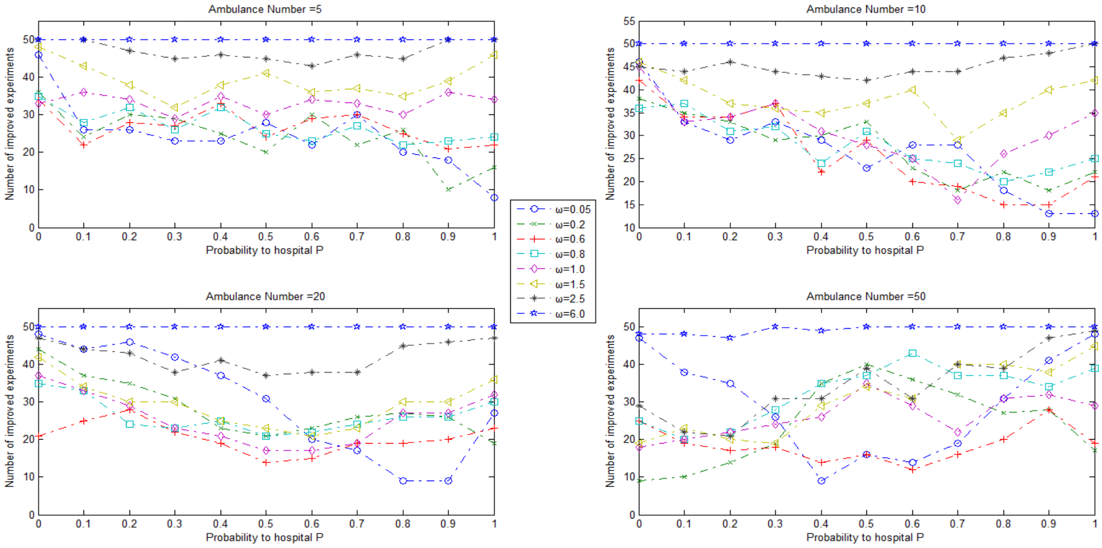

Figure 3. *Performance evaluation for closeness centrality policy over closest policy. The vertical axis represents the number of experiments for which the response time of closeness policy is shorter than closest policy among the fifty experiments for each scenario.*

Figure 4 shows the performance evaluation for degree centrality policy over closest policy. We can also get the same conclusion that the number of ambulance influences the selection of despatching policy and small value for P improves the performance of degree centrality policy.

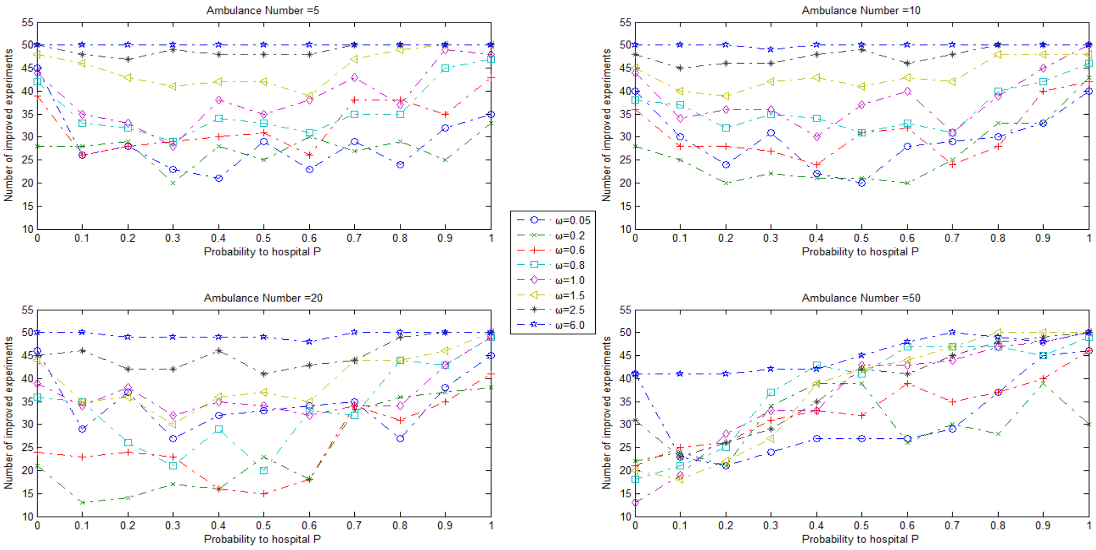

Figure 4. *Performance evaluation for degree centrality policy over closest policy. The vertical axis represents the number of experiments for which the response time of degree policy is shorter than closest policy among the fifty experiments for each scenario.*

We also analyse the influence of the parameter for the performance of centrality policy. Figure 5 presents the influence of parameter ω to those two centrality policies. The vertical axis denotes the average number of improved experiments for probability varying from 0 to 1. The tendency is that the performance of centrality policy is improved when parameter ω is changing to large value. However, the exact relationship for parameter ω to centrality policy is nonlinear behaviour, so a set of detail experiments need to be conducted to obtain the optimal value for ω.

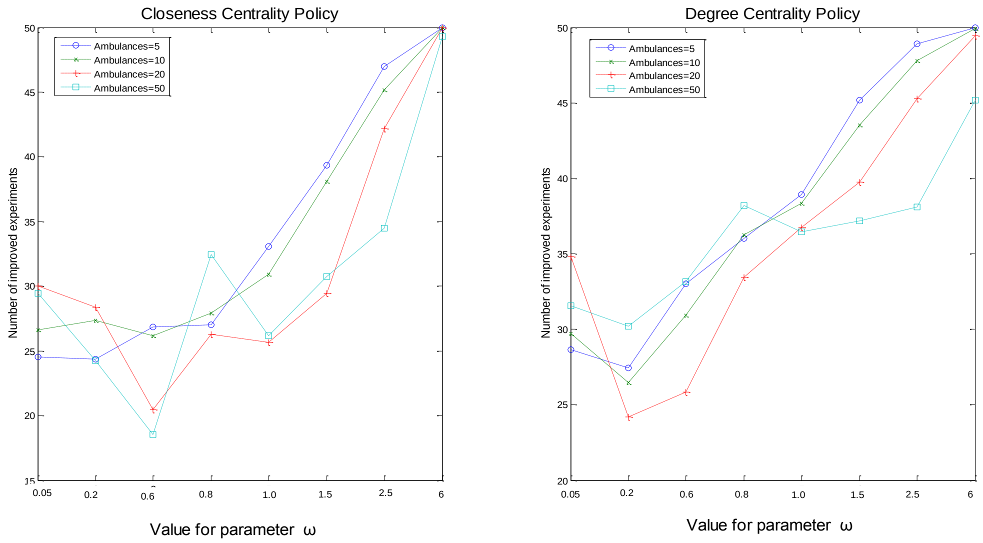

Figure 5. *The influence of parameter ω to centrality policy.*

Figure 6 shows the influence of probability $\boldsymbol{P}$ to the performance of centrality policy by ignoring the parameter ω. The vertical axis represents the average response time over the 50 experiments. For these two centrality policies and four types of ambulance size, the probability $\boldsymbol{P}$ reduces the response time when the value of $\boldsymbol{P}$ is small because smaller probability of $\boldsymbol{P}$ enhances the probability of serving the nearby calls when despatching ambulance to the central emergency calls. Besides, the performance enhancement is not significant when the size of ambulance number is big. One probable reason is that the medical service system is not busy, so every ambulance can get to their closest emergency calls when many ambulances are at work.

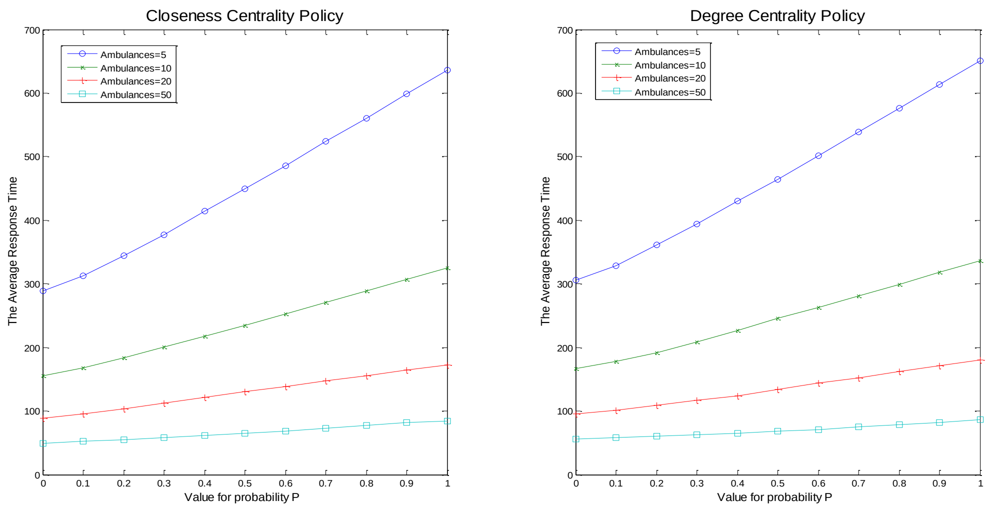

Figure 6. *The influence of probability $\boldsymbol{P}$ to centrality policy.*

3.3 Performance Evaluation between Centrality Policies

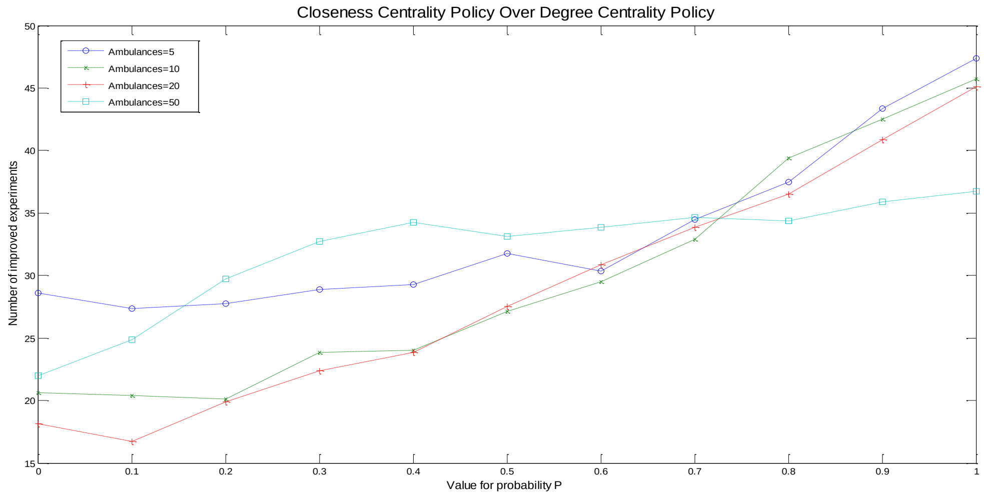

Figure 7. Performance evaluation for closeness centrality policy over degree centrality policy.

This subsection we evaluate the performance of different centrality policies for despatching ambulance. As mentioned before, two centrality policies are proposed based on closeness centrality(Albert and Barabasi 2002) and degree centrality(Newman 2003). Figure 7 shows the performance of closeness centrality policy over the degree centrality by ignoring the influence of parameter ω, the vertical axis represents the average number of experiments for which the response time of closeness centrality policy is smaller than degree centrality policy. We can see from this figure that the probability of ***P*** influences the performance of centrality policy, the response time for despatching ambulance by degree centrality policy is shorter than closeness centrality policy in most case when ***P*** is small for all four types of ambulance size; however, this situation is reversed when ***P*** is closer to 1. For example, when ***P***=0.1, the suitable despatching policy is degree centrality for ambulance size equalling 20, and when ***P***=1, the suitable policy is closeness centrality. Therefore, from these observations, the probability influence the selection of centrality policy, the optimal despatching policy can be searched by simulation study during operating situation.

Here we also exam the performance of different centrality policies on different nearest-neighbor coupled call networks constructed by different threshold value of $\boldsymbol{d}^*$. Figure 8 shows the performance of different centrality policies on different threshold value of $\boldsymbol{d}^*$. Firstly, for both closeness centrality and degree centrality, the total response time is decreased when the threshold value changed from 3 to 5 or 5 to 8; however, when the threshold value changed from 8 to 10, the decrease of the total response time is not significant, sometimes the total time has the trace of increase, for example, when ambulance size equal 20, the total response time of the closeness centrality is increased when the threshold value varied from 8 to 10. So this simulation experiment also reveals that it is not necessary to construct a globally coupled call network. Secondly, the total response time of closeness centrality policy is smaller than degree centrality policy when ambulance size equal 5, and under other situation, he total response time of closeness centrality policy is bigger than degree centrality policy.

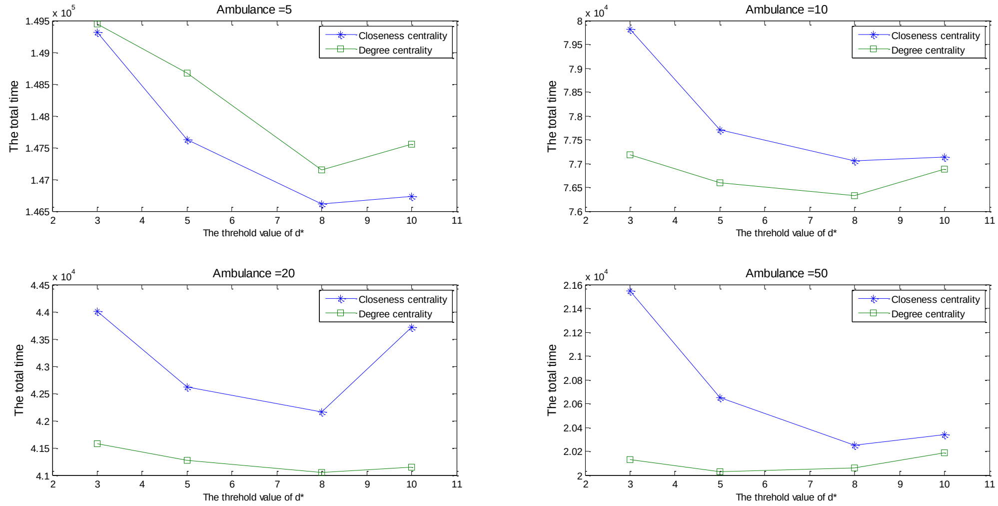

Figure 8. *Performance of different centrality policies on different threshold value of* d^*.

4 CONCLUSION AND DISCUSSION

The centrality policy for despatching ambulance is proposed by Lee(Lee 2012 ; Lee 2012 (b)) based on the centrality measures from the study of social network analysis. A full-connected call network is constructed in his algorithm. Besides, he conduct the simulation experiment in a small grid service area (5×5 square grid in the paper of (Lee 2012 (b))). We argue that it is not necessary to construct a full-connected call network because it influences the computational efficiency of the algorithm. Moreover, we conduct the simulation experiment on the real road topological structure of Hong Kong Island to testify the performance of centrality policy. The results for these experiments reveal that the size of ambulance number, the probability $\boldsymbol{P}$ and the parameter of ω influence the performance of centrality policy. The probability P represents the probability of transferring patient to hospital and ω represents the weight of node centrality. The centrality policy can significantly reduce the response time when selecting the right value for these parameters.

However, in this study we consider the call network as a static network, in reality the emergency calls occur randomly at discrete time, so the call network is dynamic during a period time. But the network is static at a discrete time instants, we can update the network at a time interval (for example, every 1 hour updating the network), and during the time interval, the network is static, the proposed centrality policies can be used. What's more, this study focuses on the EMS under catastrophic natural or manmade disasters, under these situation, many emergency calls erupt in a very short time, after that short time, almost no call occurs. From this two perspectives, considering the network as a static is reasonable.

Besides, this study can be embedded into decision support system for emergency medical service which applies information technology in emergency/disaster management (Snediker, Murray et al. 2008; Shen, Carswell et al. 2012), especially for the situation of catastrophic natural or manmade disasters.

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