International Journal of *Geo-Information*

MDPI

Article

Locating Automated External Defibrillators in a Complicated Urban Environment Considering a Pedestrian-Accessible Network that Focuses on Out-of-Hospital Cardiac Arrests

Pil Kwon [1], Min-Jun Kim [2], Youngmin Lee [1], Kiyun Yu [3] and Yong Huh [4,*]

1 Department of Civil and Environmental Engineering, Seoul National University, 1, Gwanak-gu, Gwanak-ro, Seoul 08826, Korea; pil0706@snu.ac.kr (P.K.); daldanka@snu.ac.kr (Y.L.)
2 Department of Industrial and Management Engineering, Pohang University of Science and Technology, 77 Cheonam, Nam-gu, Pohang, Gyeongbuk 37673, Korea; kojo0913@gmail.com
3 Department of Civil and Environmental Engineering, Institute of Construction and Environmental Engineering, Seoul National University, 1, Gwanak-ro, Gwanak-gu, Seoul 08826, Korea; kiyun@snu.ac.kr
4 Spatial Information Research Institute, Korea Cadastral Survey Corp., 141, Ulsadang-daero, Yeongdeungpo-gu, Seoul 07332, Korea
* Correspondence: huhyong78@lx.or.kr; Tel.: +82-2-880-6286

Academic Editors: Michael Leitner and Wolfgang Kainz
Received: 1 October 2016; Accepted: 29 January 2017; Published: 6 February 2017

Abstract: Automated external defibrillators (AEDs) are portable devices that defibrillate and diagnose sudden-cardiac-arrest patients. Therefore, AEDs are widely installed in public places such as airports, schools, sport complexes, etc., and the installation of AEDs is required by law in these places. However, despite their usefulness, AEDs are mostly installed indoors with limited coverage outdoors. Hence, this study conducts research in the placement of AEDs in outdoor locations. This study considers a complicated urban environment using a pedestrian network dataset and network barriers. We draw on the Teitz and Bart's (1968) heuristic method that was built in the location-allocation solver in ArcMap. The results of this study found that a total of 455 AEDs, including 227 pre-installed AEDs, could be placed in the study area, thus providing an additional 228 devices. Compared with 10 different installation methods that were set as experimental groups, our test results found that additional installations were able to cover 10% to 30% more actual out-of-hospital cardiac-arrest cases. The main contribution of this study is the proposal of a new method in locating AEDs in optimal areas while considering complicated urban environments. We predict that the cardiac-arrest-related mortality rate would be reduced through implementing the findings of this study.

Keywords: AED; Cardiac Arrest; GIS; Location-allocation; OHCA

1. Introduction

The number of patients with cardiovascular diseases and who have suffered from acute cardiac arrest increases every year due to the rapid population-aging phenomenon. Meanwhile, various research works have pointed out that a patient who receives cardiopulmonary resuscitation (CPR) has a higher survival or live discharge rate than those who do not receive CPR [1–6]. Therefore, the survival rate of patients with acute cardiac arrest is closely related to first-aid [7], which is important in increasing the survival rates. Despite this fact, the bystander CPR rate in South Korea is low because people worry about harming others by performing inadequate CPR [8,9]. In this case, the patients have no other choice but to wait for emergency medical service (EMS) to come. Yet, studies have shown that the delayed arrival time of the EMS at the incident site due to traffic [10] can be fatal. Because of the various reasons mentioned above, the survival rate of out-of-hospital-cardiac-arrest (OHCA) patients remains at approximately 3% [9].

Automated external defibrillators (AEDs) save cardiac-arrest victims by delivering electric shocks to a victim's heart to try to restore its normal rhythm [11]. Research has shown that non-medical lay rescuers (even children) were able to properly utilize the device without any guidance [12]. Jorgenson et al. (2013) also showed that untrained people can successfully use an AED in emergency situations without any safety issues [13]. One of the reasons for the low CPR rate is the concern of skeletal chest injury [14], and the low percentage of the survival rate is due to the delay of EMS. Adopting AEDs can be used to overcome the aforementioned issues that the limitations in providing CPR and EMS suffer. Therefore, the South Korean government is actively expanding the supply of AEDs [15].

According to revised the EMS Act 38-2 passed in 2008 in South Korea, most of the AEDs must be located in places such as sport complexes, airports, and bus terminals. An increasing number of AEDs are being installed in compliance to this Act. However, this rule limits the accessibility of AEDs because people who are not within these specific facilities have lesser access to the devices. Approximately 70% of OHCAs occur in residential areas [16,17], whereas 20% occur outdoors [1,3], resulting in non-coordination between the AED and OHCA locations. Installing AEDs at each household and in every notable spot in an open space is the best method of increasing the survival rate of OHCA patients. However, this is not realistic. Therefore, the focus of this study is to propose locations of AEDs in open spaces so that they can cover a wider area where OHCA cases are likely to happen.

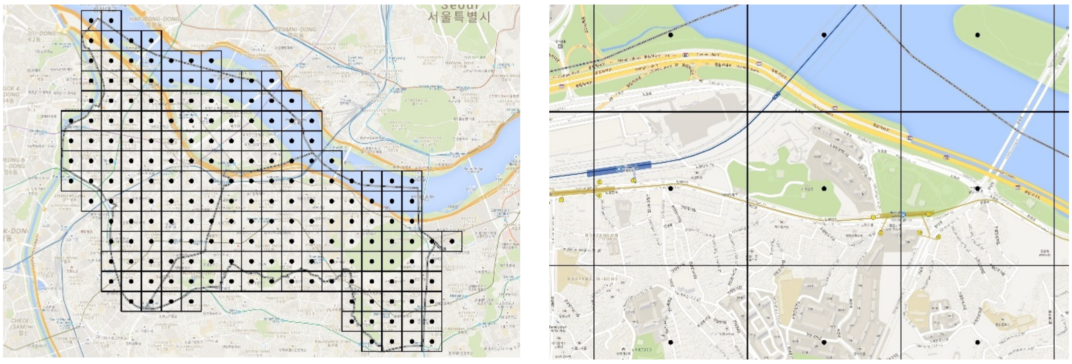
Meanwhile, Mitamura (2008) found that people cannot easily access AEDs even if AEDs are widely located because they are not aware of where these devices are located [18]. Sakai et al. (2011) also insisted that AEDs are difficult to find; thus, knowing where the AEDs are installed is important for the public [19]. Even if these devices have been installed and distributed, their usages still remain low [18]. Some researchers insisted that studies on AED locations should continue [13,15] because AEDs are of no value if people cannot locate them [20]. However, only a few research works that study AED locations from the perspective of geography are available [21]. Considering all these previous studies, a study on locating AEDs is applied here by considering complicated urban environments from the GIS perspective.

One of the common approaches of locating a facility is to select a p number of facilities from an n number of potential facility sites or candidate nodes (these two terms are used interchangeably through this paper). Therefore, selecting not only the optimal location of facilities but also the location of candidate nodes is important. Despite the importance of the locations, in previous studies such as the airport fire-station location problem by Tzeng and Chen (1999) [22], fire-station location problem by Liu et al. (2006) [23], and locating wireless broadband networks by Lee and Murray (2010) [24], the selected candidate nodes are usually the centroid points of grids (Figure 1a), which is an inappropriate method for the following reasons:

- As shown in Figure 1b, considering the geographical characteristics of a study area is impossible unless the grid size is sufficiently small to distinguish the features from the pedestrian perspective.
- Distorted results can be obtained if the candidate nodes are simply the centroid of grids or administration boundaries because the grid size changes (i.e., modifiable areal unit problem).
- Pedestrian barriers such as crosswalks and buildings, which are important components in complicated urban environments, as well as underpasses and overpasses or similar network structures, have 3D information that cannot be represented using the centroid of grids or administration boundaries.

Theoretically, creating many small-size grids will allow detection of the geographical features; however, this will also create too many grids (i.e., the number of potential facility sites are increased). The total number of combinations (i.e., selecting a p number of facilities from an n number of potential facility sites) becomes exponentially larger. Because the purpose of the present study is to improve the accessibility of AEDs by installing additional AEDs based upon considerations of population distribution and other real-world factors, the additional devices are deemed to be better located in corners of blocks or junctions of road networks where they can be easily seen, rather than in the grid centroid.

Thus, additionally installed AEDs are expected to be more publicly visible and accessible by locating them using a complicated urban network dataset built by Kim et al. (2015) [25] and developed in Seoul, South Korea. Utilizing this dataset, the AEDs can be located from the perspective of a bystander, in addition to being able to consider the geographical characteristics. The coverage rate using real OHCA cases in year 2014 was employed to determine the effectiveness and validity of the AED location in this work.



(**a**) (**b**)

Figure 1. Examples of potential facility points: (**a**) entire area; (**b**) larger scale.

2. Study Area, Data, and Method

2.1. Study Area

Yeongdeungpo-gu and Dongjak-gu ("gu" is a municipal level equivalent of "districts" in the West) in Seoul were chosen as the study areas (Figure 2). At the left of Yeungdeunpo-gu is the Yeoeuido Business District (YBD), which is the largest financial district in Seoul. Hence, the population distribution is unequal. In contrast, Dongjak-gu is simply a typical gu in Seoul, which is considered a residential area. Therefore, the population is quite equally distributed except where the national cemetery is located.

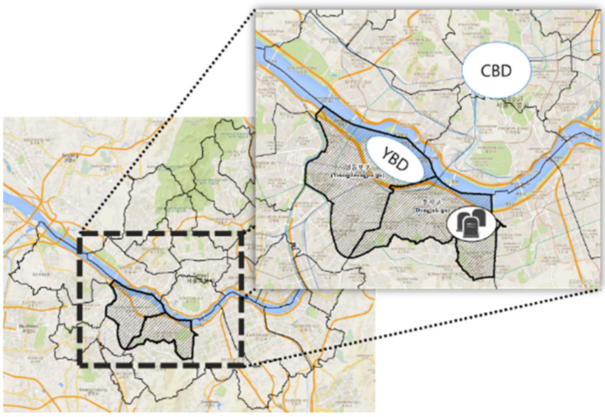
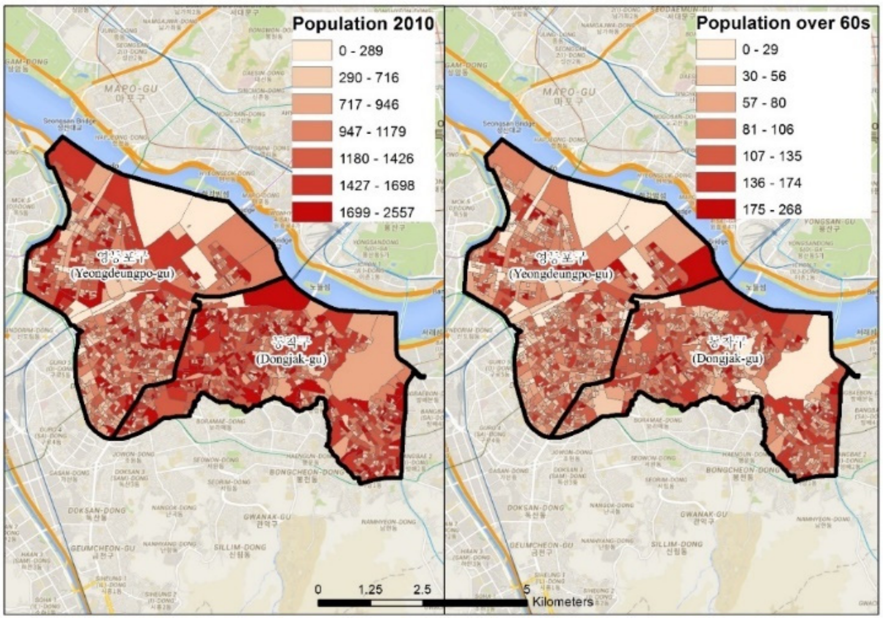


Figure 2. Study area in a hatched symbol.

According to Statistics Korea, which is equivalent to the United States Census Bureau, the total populations of Yeongdeungpo-gu and Dongjak-gu in 2010 were 703,845 and 740,785, respectively. Meanwhile, the population of the elderly (i.e., those who are older than 60 years and vulnerable to a sudden cardiac arrest) in Yeongdeungpo-gu and Dongjak-gu were 54,280 and 56,521, respectively (Figure 3) [25].



(**a**) (**b**)

Figure 3. Study area census data. (**a**) entire population in the study area. (**b**) elderly population in the study area.

2.2. Data Process and Methods

This section presents the dataset setup to simulate the complicated real world conditions and the considerations required for the installation of additional AEDs. Figure 4 shows the study workflow.

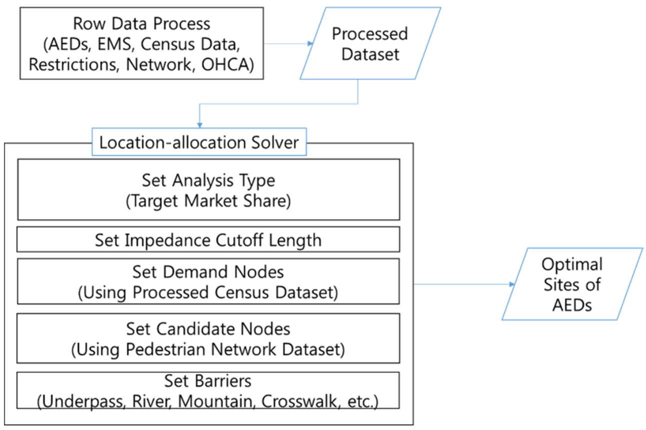


Figure 4. Workflow. AEDs, automated external defibrillators; EMS, emergency medical service; OHCA, out-of-hospital-cardiac-arrest.

The workflow can generally be explained as follows:

- The Network Analyst in the ArcMap platform is applied to locate the AEDs.
- The analysis type in the location-allocation solver in the Network Analyst of ArcMap is adjusted by the "target market share" method to consider the relationship between the pre-installed and additionally installed AEDs.

- The effective AED coverage (cutoff length) is calculated by considering the normal walking speed of pedestrians.
- The candidate and demand nodes are extracted based on the pedestrian network and census datasets (i.e., floating population). The details of the candidate and demand nodes are described in the next section.
- The psychological barriers under emergency situations (e.g., tunnel, crosswalk, and overpass) are determined on the road network to reflect a real-world situation.

2.2.1. Data Description and Process

In this section, the data used in this study are introduced for further understanding and explanation on how the data have been modified for further analysis.

The raw data need to be processed (filtered, re-aggregated, and geocoded) for further analysis and application because most of them were delivered in table formats and in different projections. The data used in this study were as follows: pre-installed AED location, fire-department location, hospital location, floating population, network dataset, barriers, and OHCA records.

The pre-installed AED locations, fire-department locations, hospital locations, and network data were downloaded from various government websites. The census data were originally created by a phone carrier in South Korea, and they could be extracted from the Seoul City GIS data warehouse. The network data developed by Kim et al. (2015) were also acquired from the government website. The network barriers were extracted from the network dataset using its attribute. Meanwhile, the OHCA data were obtained from the Ministry of Public Safety and Security under a non-disclosure agreement.

Figure 5 shows the data-processing flow in this study.

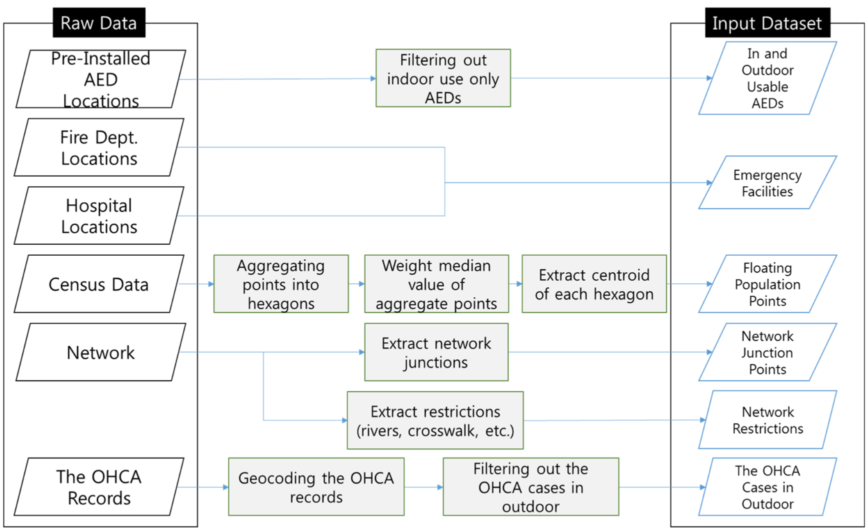


Figure 5. Data processing.

When OHCA occurs, AEDs offer a significant potential to save the patients [26]. However, AEDs are rarely utilized. Leung et al. (2013) explained that the non-utilization is due to the fact that people cannot locate them during emergencies, or in some cases, no AEDs are installed nearby [27]. Therefore, knowing where the AEDs and emergency facilities (fire department and hospitals) are located is crucial in installing additional AEDs in optimal locations, especially outdoors.

Among the 432 pre-installed AEDs in the study area, we filtered out the AEDs that are only available indoor based on their attribute. As a result, 227 AEDs were determined as usable AEDs for outdoor OHCA cases. The study area contained 11 fire departments and nine hospitals. Because the two facilities have AEDs and professionals that can help OHCA patients, we counted them as extra facilities that can be utilized in emergencies. These data are shown in Figure 6.

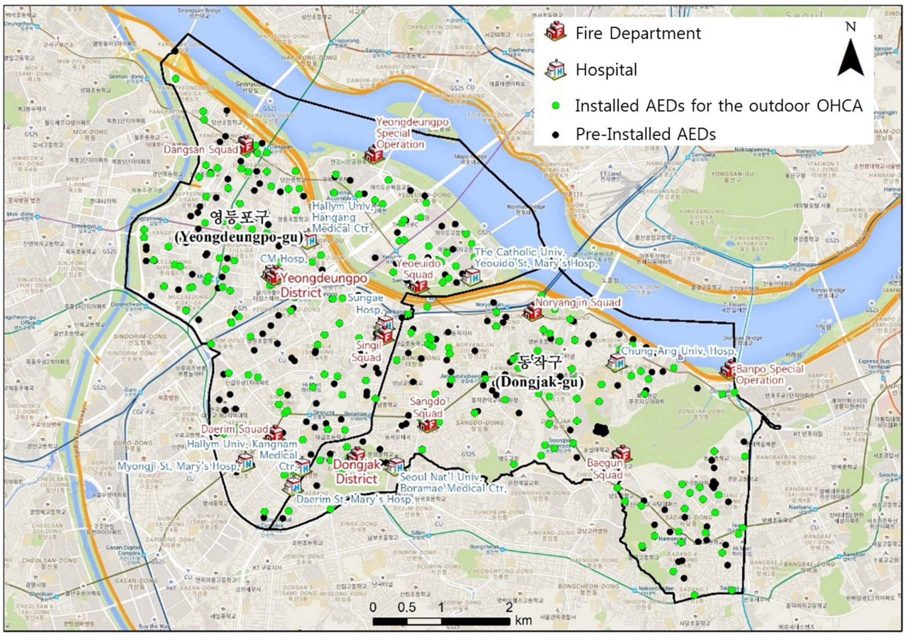


Figure 6. Facilities in the study area.

The floating population point data were utilized instead of the residential demographics or other types of census data. The floating population data were based on the call traffic of a mobile network carrier, which were contained in more than 10 billion calls per month, and were considered as points [28]. Each point was a center of a fishnet grid containing floating population attributes (e.g., ages and sex). These data were created based on the call traffic. Hence, places such as rivers and mountains where people cannot physically access did not have any information. Figure 7 shows a sample area of the floating population.

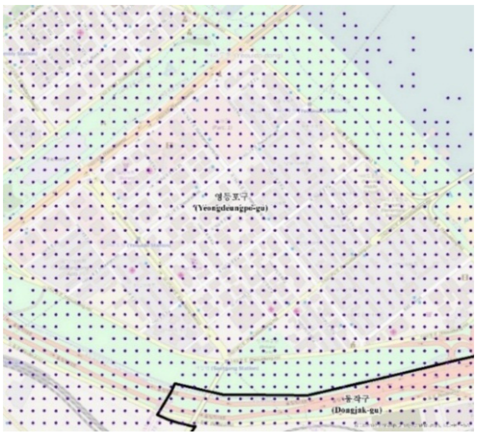


Figure 7. Floating population.

Meanwhile, the pedestrian network dataset developed by Kim et al. (2015) was utilized for a more precise analysis. The precision, which was compared with a real-world pedestrian network, calculated from the F-measure was 0.991, which reflects almost all real-world walkways [29].

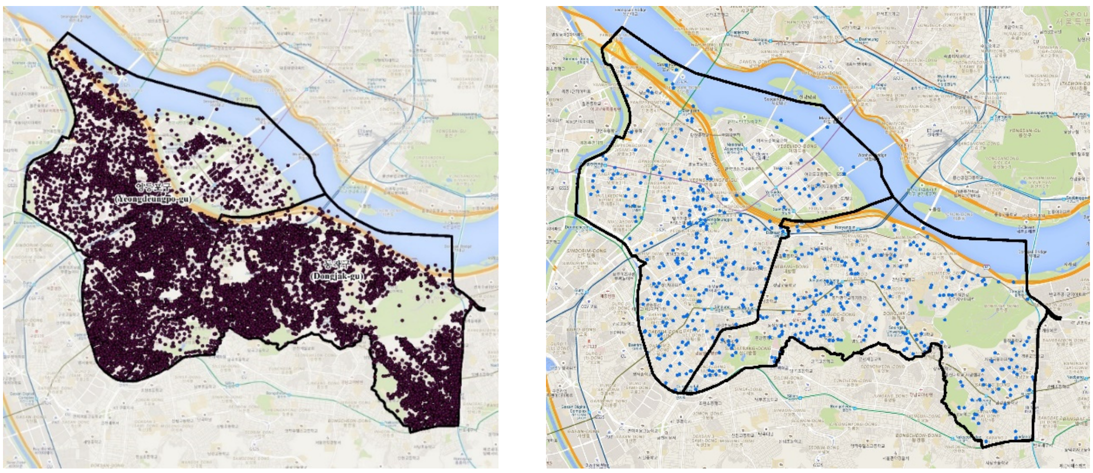
The network contained all roads that pedestrians can access, including underpasses, bridges, alleys, pedestrian overpasses, and crosswalks. These additional data can enhance the result precision because some of the links can be considered as network impedances that delay pedestrian movement. Network impedances such as crosswalks, underpasses, and overpasses are defined as links that prevent transit of vehicles or pedestrians [30]. In normal situations, a certain time lag is added to these network impedances. However, under emergency situations, these network impedances can be regarded as psychological barriers that block pedestrian movement. Therefore, in the present study, we defined these network impedances as psychological network barriers.

A visual comparison between the (regular) vehicle network dataset provided by the Korea Transport Database (KTDB) [31] and the pedestrian network dataset shows the road network details in Figure 8.

(**a**) (**b**)

Figure 8. Network comparison. (**a**) Vehicle network dataset provided by the KTDB. (**b**) Pedestrian network dataset.

The most sensitive data (i.e., the OHCA records shown in Figure 9b) were extracted from the emergency call logs (Figure 9a) provided by the Ministry of Public Safety and Security. The records contained addresses, incident types, coordinates of incidents, times, arrival and departure times from the hospital, incident locations, fire departments, patient detailed information, and treatments performed during the transportation, among others. The total number of incident cases (i.e., cases where ambulances were dispatched and those with symptom information) in the study area in 2014 was 26,305, as shown in Figure 9a. The number of OHCA records was 634, as shown in Figure 9b.



(**a**) (**b**)

Figure 9. Incident records with appropriate information in the study area: (**a**) entire emergency call records and (**b**) OHCA records only.

2.2.2. Finding Optimal Locations for Additional AEDs

The search for optimal locations to install additional AEDs was performed on the ArcGIS platform. The location-allocation solver in the Network Analyst extension of ArcMap 10.2.2 and the Python script-based ArcGIS ModelBuilder were utilized.

Meanwhile, the purpose of the fundamental objective function of the model used in this study is to minimize the sum of the weighted distances between demand node i and candidate node j, as expressed in Equation (1) [32].

$$\text{minimize } Z = \sum_{i \in I} \sum_{j \in J} a_i d_{ij} x_{ij} \tag{1}$$

Subject to

$$x_{ij} \leq x_{jj} \; \forall i, j \tag{2}$$

$$\sum_{j \in J} x_{ij} = 1 \; \forall i \tag{3}$$

$$\sum_{j \in J} x_{ij} = p \; \forall j \tag{4}$$

$$x_{ij} = \begin{cases} 1, & \forall i, j \\ 0, & \end{cases} \tag{5}$$

where I denotes a set of demand nodes and J denotes a set of candidate nodes. a_i denotes a weighted population to be served at demand node i. d_{ij} denotes the distance from node i to node j. p denotes the number of facilities to be located. $x_{ij} = 1$ indicates that demand node i is assigned to a facility located at node j, and $x_{ij} = 0$, otherwise. Equation (2) ensures that a facility needs to be located with a separate demand node. Equation (3) ensures that an open facility must be located on a demand node. Equation (4) ensures that only a p number of facilities need to be located.

The algorithm used in the Network Analyst of esri's ArcMap is the Teitz and Bart (1968) vertex substitution heuristic [33], and the algorithm is known to be one of the most popular heuristic algorithms for this problem [34]. Meanwhile, the potential AED locations should consider the pre-existing facilities (e.g., pre-installed AEDs, hospitals, and fire departments) because the pre-existing facilities cannot be removed due to EMS Act 38-2. Furthermore, the additional and pre-installed AEDs are supposed to complement each other to increase the coverage. However, the pre-installed AED coverage is smaller than the additional AED coverage in the real world because they are not perfectly located outdoors (e.g., most of them are located in front of elevator, lobbies, and similar places). We assumed that the pre-installed AEDs can cover half of the additional AED requirement.

From this perspective, the target market share is chosen in this study to find the minimum p number of additional AEDs and their optimal locations when the k number of pre-existing facilities is added, together with the demand nodes, within the impedance distance of the facilities [35].

The following parameters should be determined after the analysis type (target market share) is set:

- impedance cutoff (how far can a facility be effective)
- demand nodes (where needs must be served and contain a certain quantity of service needs)
- candidate nodes (possible locations for new facilities)
- network barriers

Impedance cutoff is defined as the most effective distance to a facility. In other words, the cutoff is the maximum distance that people (demand nodes) are willing to travel to access the facility [36]. The impedance cutoff distance for this analysis was set to 345 m. The distance was measured as follows using Equation (6):

$$\frac{f(speed) \times f'(time)}{\text{the number of round trip}}, \tag{6}$$

where $f(speed)$ is the constant running or walking speed of a person under an emergency situation and $f'(time)$ is the golden time of resuscitating the OHCA patients (i.e., maximum time before brain damages occur). Accordingly, a bystander will go to where the AEDs are installed if he/she finds an OHCA patient and return to where the patient is. In other words, the bystander will have to make a round trip. Therefore, the maximum distance must be divided by two.

According to Im et al. (2006), the average walking speed of young people in South Korea is 1.175 m/s [36]. Therefore, 1.175 m/s was multiplied by two on the assumption that people will likely run during an emergency. The speed was based on the assumption that people can continuously run without losing speed. Therefore, $f(speed)$ can be calculated using Equation (7).

$$f(speed) = 1.175 \text{ m/s } \times 2 = 2.35 \text{ m/s} \tag{7}$$

Meanwhile, Jude et al. (1961) suggested that cardiac resuscitation is needed within 3 to 5 min immediately before permanent brain damage occurs [37]. Hence, the $f'(time)$ value is provided by Equation (8), and the final impedance cutoff length is calculated using Equation (9).

$$f'(time) = 5 \text{ min} \tag{8}$$

$$\frac{2.35 \text{ m/s } \times 5 \text{ min}}{2} \tag{9}$$

Demand location denotes the points where the request facilities are needed. In the real world, the demand locations for the AED should be within real-time moving people. However, collecting the data and modeling them are difficult. Hence, the accumulated floating population data were applied instead. Patients who are over 60 years old are at a high risk of experiencing acute cardiac arrest [3,38]. Therefore, the high-risk cardiac-arrest floating population points were defined as demand nodes. The population percentage in the study area with high risk of cardiac arrest was between 3.35% and 45.28%, depending on its geographical location. The ratio was then assigned as the weight of the demand nodes.

A facility location problem usually contains multiple candidate nodes. In other words, the location–allocation solvers (i.e., optimization programs) choose the most optimal locations of a facility irrespective of its feature by searching for the relationship between the demand and candidate nodes. Therefore, the candidate nodes in this study should also be determined for further analysis. We considered the candidate nodes as an individual network junction because the AEDs should be located in an open space along the road networks so that anyone can see and access the devices. The total number of surveyed junctions was 23,546.

Network restrictions were then added to the simulation. The restrictions were divided into two different types: polygon and line. Polygonal barriers are motorways and rivers, whereas line barriers represent tunnels, crosswalks, and underpasses. As mentioned earlier, these restrictions are psychological network barriers that delay pedestrian movements. We managed to add more reality into this analysis by adding these abundant data.

Meanwhile, 12 different approaches were employed to verify whether the coverage of the study result was actually effective. Because locating AEDs on pedestrian networks has not been adequately conducted in previous studies, we randomly distributed the AEDs to compare the coverage under four different scenarios. These are random AEDs in the entire study area (Figure 10a), random AEDs in road segments (because this study focuses on outdoor OHCA cases), as shown in Figure 10b, random AEDs at the center of a grid (used by most location–allocation studies), as shown in Figure 10c, and random AEDs on network junctions (using the same candidate nodes as those in the present study), as shown in Figure 10d.

(**a**) (**b**) (**c**) (**d**)

Figure 10. Random AED examples: (**a**) random AED allocation on road segments; (**b**) random AED allocation in study area; (**c**) random AED allocation on grid based; and (**d**) random AED allocation on network junctions.

One trial of the random AED distribution can skew the result. Therefore, random AED installations on the road and in the entire study area (Test Nos. 3, 3′, 4, and 4′) were conducted 100 times. On the other hand, we iterated the process 1000 times in the grid- and network junction-based AED allocation tests (Test Nos. 5, 5′, 6, and 6′) so that the results can obtain close probabilities that can also be achieved using an algorithmic method.

We divided the scenarios into two categories: all OHCA cases and outdoor OHCA cases within the same time period (Table 1). Because this study focuses on installing AEDs outdoors, the two different approaches provide a good insight into the characteristics of the OHCA cases.

Table 1. Evaluation methods (control and experimental groups).

No.	OHCA Cases	Evaluation Methods	Testing Groups
1		Coverage of the OHCA cases from the existing and additionally installed AEDs	Control group 1
2		Coverage of the OHCA cases from the “filtered” existing AEDs only	Experimental group 1-1
3		Coverage of the OHCA cases from the existing and randomly located AEDs distributed in the entire study area	Experimental group 1-2
4	For all	Coverage of the OHCA cases from the existing and randomly installed AEDs distributed on the road segments	Experimental group 1-3
5		Coverage of the OHCA cases from the existing and randomly located AEDs on the grid base	Experimental group 1-4
6		Coverage of the OHCA cases from the pre-existing and randomly located AEDs on the network junctions	Experimental group 1-6
7		Coverage of the OHCA cases from the pre-installed AEDs (assuming that all pre-installed AEDs are usable)	Experimental group 1-5
1′		Coverage of the outdoor OHCA cases from the existing and additionally installed AEDs	Control group 2
2′		Coverage of the outdoor OHCA cases from the “filtered” existing AEDs only	Experimental group 2-1
3′		Coverage of the outdoor OHCA cases from the existing and randomly located AEDs distributed in the entire study area	Experimental group 2-2
4′	Outdoor	Coverage of the OHCA cases from the existing and randomly located AEDs distributed on the road segments	Experimental group 2-3
5′		Coverage of the OHCA cases from the existing and randomly located AEDs on the grid base	Experimental group 2-4
6′		Coverage of the OHCA cases from the pre-existing and randomly located AEDs on the network junctions	Experimental group 2-6
7′		Coverage of the OHCA cases from the pre-installed AEDs (assuming that all pre-installed AEDs are usable)	Experimental group 2-5

3. Results and Analysis

Figure 11 shows the optimal locations of the AEDs based on the testing process in accordance with our processed dataset and method.

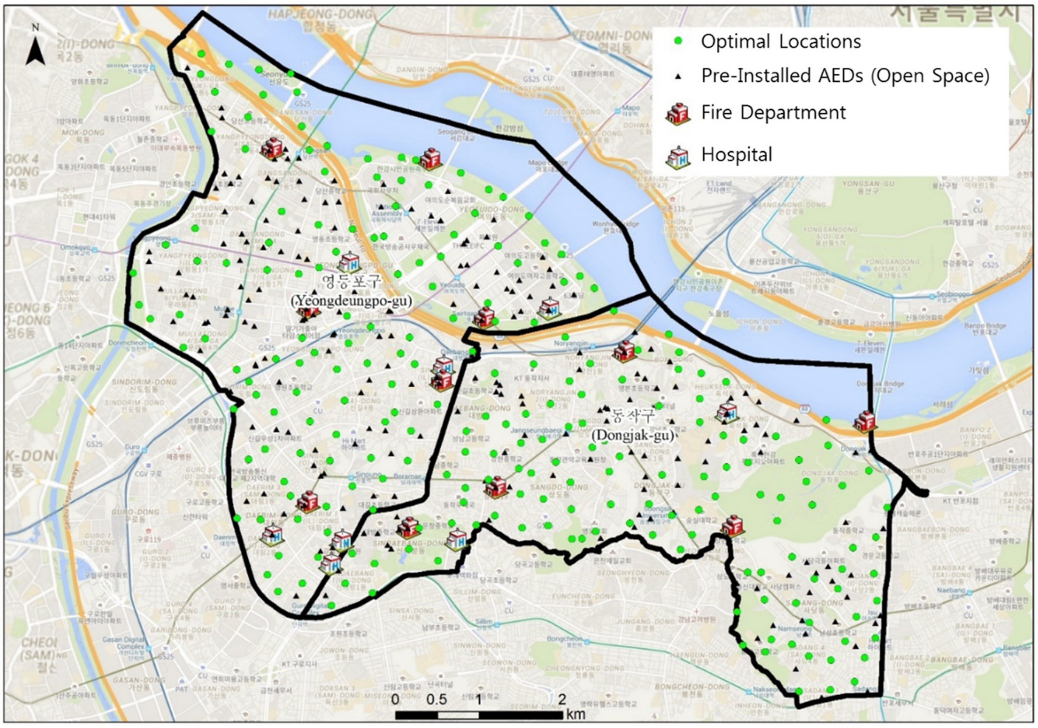


Figure 11. Optimal AED locations.

The entire numbers of cardiac-arrest cases in Yeongdeungpo-gu and Dongjak-gu in 2014 were 348 and 286, respectively (634 cases in total).

Tables 2 and 3 list the coverage ratio of the OHCA cases.

Table 2. Evaluation methods and results of all the OHCA cases.

No.	OHCA Cases	Evaluation Methods	Testing Group	Ratio	Percentage (%)
1		Coverage of the OHCA cases from the pre-existing and additionally installed AEDs	Control group 1	516/634	81.39
2		Coverage of the OHCA cases from the "filtered" pre-existing AEDs only	Experimental group 1-1	221/634	34.86
3		Coverage of the OHCA cases from the pre-existing and randomly located AEDs	Experimental group 1-2	451.83/634	71.27
4	For all	Coverage of the OHCA cases from the pre-existing and randomly located AEDs on the road segments only	Experimental group 1-3	380.89/634	60.08
5		Coverage of the OHCA cases from the existing and randomly located AEDs on the grid base	Experimental group 1-4	364.07/634	57.42
6		Coverage of the OHCA cases from the pre-existing and randomly located AEDs on the network junctions	Experimental group 1-6	393.39/634	62.05
7		Coverage of the OHCA cases from the pre-installed AEDs (assuming that all pre-installed AEDs are usable)	Experimental group 1-5	347/634	54.73

Table 2 lists the coverage ratio results of all the OHCA cases. The first evaluation was performed to determine the coverage of the OHCA cases from both pre-existing and additionally installed AEDs.

Among the 634 OHCA cases in the study area, 516 cases were inside the coverage of the AEDs. The first evaluation represented the objective of this study and was set as a control group.

The second evaluation was conducted to determine the coverage ratio of the pre-installed AEDs only. A total of 221 OHCA cases out of 634 (approximately 35%) were inside the coverage of existing AEDs. The coverage ratio was much lower than that in the first experiment due to the lack of adequate number of installed AEDs.

In the third and fourth evaluations, we programmed the installed number of AEDs in the control group to be the same as that in the study area. According to this study, 71% of the OHCA cases could be covered by both the existing and randomly located AEDs, whereas 60% of the OHCA cases occurred on the road segments. The coverage percentage of the AEDs was lower by 10% in the fourth evaluation because the road network was not sufficiently dense; thus, AEDs were not likely to be located where OHCA cases occurred.

The potential facility locations were set at the grid center because many previous studies set their candidate nodes at the center of the grids or administration boundaries. We assigned the same number of AEDs among the centroid of the grids for 1000 times so that we can achieve the same probability of coverage using the algorithmic method. As a result, approximately 57% of the entire OHCA patients were inside the coverage. This result proved that locating the AEDs in the grid base is not practical. The coverage ratio in terms of the number of iterations gradually converged to 57.40% (364 people), as shown in Figure 12a.

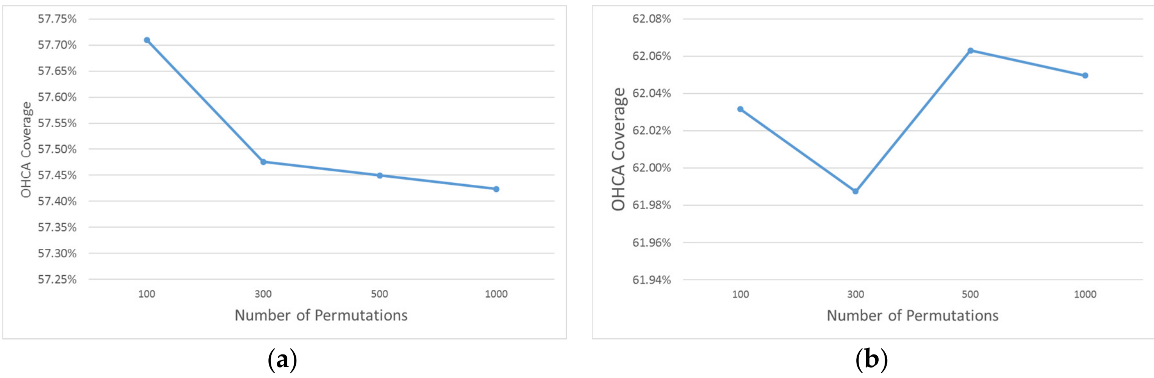


Figure 12. Coverage ratio in terms of the number of permutations for all OHCA cases. (**a**) Grid-based coverage. (**b**) Network junction-based coverage.

In the sixth evaluation, we randomly installed AEDs at the pedestrian network junctions. According to this evaluation, 62% of the OHCA cases were covered, whereas 81.39% of the OHCA cases were covered by this study result. Because we selected the same number of facilities from the same number of candidate nodes and we permuted sufficient time to achieve reliability, this evaluation was considered to be the most important evaluation among all the methods. Approximately 20% more of the OHCA cases were covered using our study method. Therefore, we confirm that the present study is far superior to the other tests described in this paper. The coverage ratio in terms of the number of iterations is shown in Figure 12b.

Finally, we conducted investigations based on the assumption that "all pre-installed AEDs (432 AEDs without filtering) will be reinstalled at entrances of buildings". Their coverage ratio was therefore calculated. Only over 50% of the total OHCA cases were inside the AED coverage. The coverage percentage was not remarkably different from that of the grid-based AEDs because the spatial pattern of the pre-installed AEDs exhibited clustering (the average nearest neighbor (NN) index was 0.7038).

The previous tests considered all the OHCA cases. In our study, we also considered the outdoor OHCA cases. The total number of outdoor OHCA cases was 126 out of 634 (Figure 13).

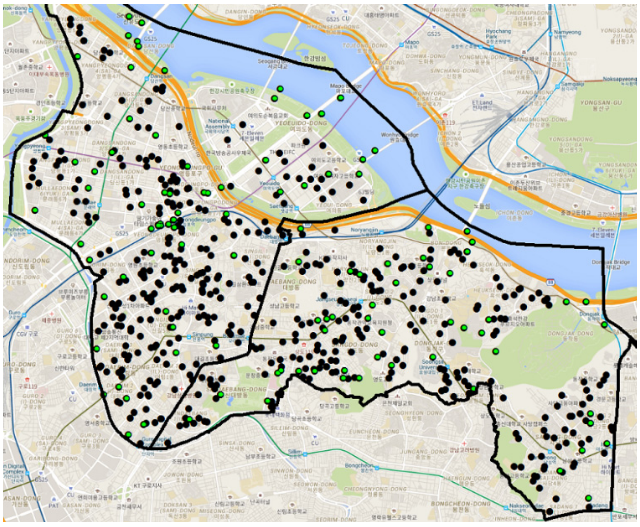


Figure 13. OHCA cases (total OHCA cases in black dots; outdoor OHCA cases in yellow dots).

Table 3. Evaluation methods and results of the outdoor OHCA cases.

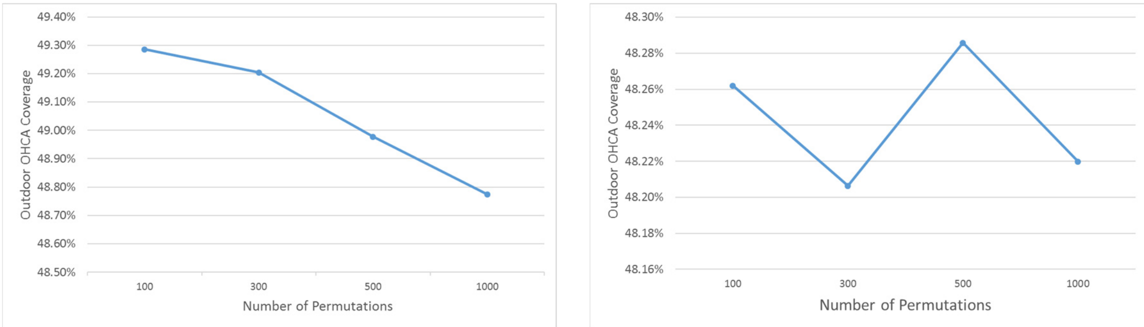
No.	OHCA Cases	Evaluation Methods	Testing Group	Ratio	Percentage (%)
1′	Outdoor	Coverage of the OHCA cases from the pre-existing and additionally installed AEDs	Control group 2	92/126	73.02
2′		Coverage of the OHCA cases from the "filtered" pre-existing AEDs only	Experimental group 2-1	36/126	28.57
3′		Coverage of the OHCA cases from the pre-existing and randomly located AEDs	Experimental group 2-2	80.9/126	64.21
4′		Coverage of the OHCA cases from the pre-existing and randomly located AEDs on the road segments only	Experimental group 2-3	66.59/126	52.06
5′		Coverage of the OHCA cases from the existing and randomly located AEDs on the grid base	Experimental group 2-4	61.46/126	48.78
6′		Coverage of the OHCA cases from the pre-existing and randomly located AEDs on the network junctions	Experimental group 2-6	60.76/126	48.22
7′		Coverage of the OHCA cases from the pre-installed AEDs (assuming that all pre-installed AEDs are usable)	Experimental group 2-5	51/126	40.48

The first evaluation was set as a control group (Control group 2 in Table 3), except that the indoor OHCA cases were filtered out. Among the 126 outdoor OHCA cases, 92 cases were inside the coverage of the AEDs.

We calculated only the outdoor OHCA coverage ratio of the existing AEDs in the second evaluation. The coverage ratio decreased by approximately 6% (from 34.86% to 28.57%). The reduction was caused by the fewer number of OHCA cases (634 to 126) and the ineffective coverage of the existing AEDs (i.e., currently located AEDs were not available for outdoor OHCA cases).

The third and fourth evaluations were performed. The same number of random AEDs were allocated in the entire study area and on the roads for 100 times each. The average coverage ratio of the OHCA cases from the AEDs set in the entire study area (third evaluation) was approximately 64%, whereas that on the road segment (fourth evaluation) was approximately 52%. This pattern was shown in the previous test listed in Table 2. The result can be attributed to the road network in the study area not being sufficiently dense.

The grid-based AED location (fifth evaluation) result showed that more than half of the outdoor OHCA cases were not saved using this method even after 1000 repetitions. The coverage ratio in terms of the number of iterations gradually converged to 48.77%, as shown in Figure 14a.



(**a**) (**b**)

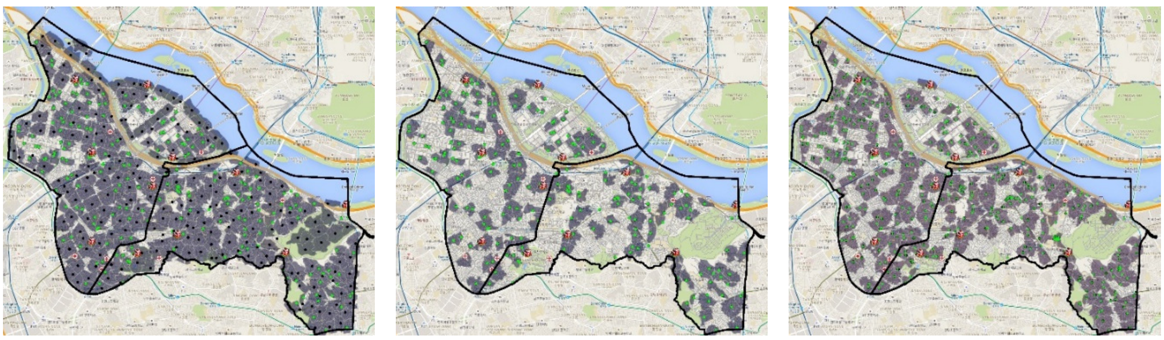
Figure 14. Coverage ratio in terms of the number of permutations for outdoor OHCA cases. (**a**) Grid-based coverage. (**b**) Network junction-based coverage.

Additionally, random distribution of AEDs on the network junction was conducted in the sixth evaluation. Approximately 48.22% of the outdoor OHCA cases were inside the coverage, which did not provide us any significant results compared with the other tests. The coverage ratio in terms of the number of iterations is shown in Figure 14b.

The seventh evaluation did not show a remarkable coverage ratio. We note that the lowest coverage ratio could not even cover half of the outdoor OHCA cases even if the pre-installed AEDs are available to the public.

The overall percentage of the coverage ratio of the second test (considering outdoor OHCA cases only) was lower than that of the first test (coverage ratio for all OHCA cases) because almost 80% of the OHCA cases were filtered out (from 634 cases to 126 cases). However, the control group coverage was still 10% to 30% higher than when the AEDs were randomly located in the study area. The evaluation test results provided us with an unequal distribution of the AEDs that could result in lesser coverage of the OHCA cases. The coverage of the outdoor OHCA cases can even be less when the AEDs were unequally distributed.

The coverage maps of the pre-installed and additionally installed AEDs (Figure 15a), filtered pre-installed AEDs (i.e., AEDs that can be publicly used among the entire pre-installed AEDs) (Figure 15b), and the entire pre-installed AEDs without filtering (Figure 15c) are shown in Figure 15.



(**a**) (**b**) (**c**)

Figure 15. Coverage area comparison. (**a**) Additionally installed and pre-installed AEDs (455 AEDs). (**b**) "Filtered" pre-installed AEDs (227 AEDs). (**c**) Total pre-installed AEDs (432 AEDs).

4. Conclusions

A total of 228 new locations were determined as optimal AED locations. Accordingly, 455 AEDs were installed in the study area with 227 pre-installed AEDs. The average Euclidean distance and the NN were calculated to find out whether the AEDs were clustered (not equally distributed) or dispersed (well distributed).

The average distance between the total AEDs was measured as 281.26 m. According to the average NN calculation, the NN ratio was 1.12. The Z-score of the NN was 3.53, and the p-value was 0.0004. Moreover, the mean distance of the location and the expected mean distance were 281.26 and 250.60 m, respectively. In other words, the trend of the AED locations was well distributed. When the total AEDs were dispersed, the average distance between the pre-existing AEDs was calculated to be 194.60. The NN ratio was 0.79. The Z-score of the NN was -5.89, and the p-value was zero. The NN ratio index was less than one, which can be interpreted as a clustering pattern. The average NN analysis confirmed that the average distance between the AEDs became shorter. We can also conclude that the installed AEDs were dispersed.

In the current situation, most of the AEDs are installed indoor. Hence, basic accessibility to AEDs is very limited. Accordingly, the local government of South Korea has increased its expenditures in advertisements to demonstrate how these AEDs should be used. This inequality can cause social problems if only a few selected people can access the AEDs. Therefore, the primary problems are how to increase accessibility to AEDs in public areas and how to increase their usability in high-risk areas with sudden cardiac-arrest occurrence, rather than advertising them. We used various parameters to solve these issues and set up an optimal location for AEDs.

AEDs are portable. Therefore, bystanders should be able to easily find them and help patients suffering from OHCA. Moreover, AEDs should be located in pedestrian-friendly locations. In the present study, the pedestrian network dataset was applied to locate the AEDs from the perspective of pedestrians. In other words, the potential facility sites (candidate nodes) of the AEDs were set in each intersection of the road networks, whereas other studies set their potential facilities in buildings where most AEDs are not publicly accessible or at the center of a grid that ignores the geographical characteristics of the study area. Every road, street, and alley can be considered to be an optimal AED location by setting the pedestrian network nodes as potential facility sites, which is more practical.

Previous studies applied various spatial statistics or analyses to define the demand nodes of the facilities. However, a floating population was used in this study. In this manner, the demand node can carry more realistic factors when these floating population data are used, rather than using the aggregated demographic data in the census track or block group size.

Moreover, the coverage of each AED was based on the average walking speed of a person. Thus, each AED can have a certain range of effectiveness. A total of 455 AEDs were located in the study area, including the 227 pre-existing AEDs, which considered the psychological network barriers that block pedestrians during emergency situations (e.g., crosswalks, underpasses, and overpass bridges).

The actual OHCA cases in 2014 were used to evaluate the optimal AED locations. The coverage ratios of the OHCA cases from the AEDs and the randomly distributed AEDs were compared. Eight different evaluation methods were proposed for more precision. The grid-based AED location (experimental groups 1-4 and 2-4 listed in Tables 2 and 3) did not show any improvement in coverage, which covered 57% and 48% in all OHCA and outdoor OHCA cases, respectively. The average coverage ratio of all the OHCA cases in the grid-based AED location showed the lowest coverage ratio. The results showed that the AED locations extracted by this study covered 81% of the real OHCA cases and 73% of the outdoor OHCA cases. The coverage ratio in this study was higher in all scenarios. Therefore, we can assume that if the AEDs were installed based on this study, 45% of the OHCA cases could have possibly received first aid from the AEDs within 5 min based on the year 2014 OHCA records.

This study suffers from some limitations. First, among all emergency calls, OHCA-related cases represent only 634 (approximately 2.5%) in the study area in 2014. The low percentage of the sample size could lead to misunderstandings of the data reliability. Furthermore, most of the OHCA cases occurred in houses. The 20% outdoor OHCA cases were sufficient to evaluate the study result; however, this can also present a perception that the data for evaluation were not abundant. Therefore, accumulated OHCA cases of more than one year should be utilized to obtain a much larger sample size to evaluate the validity of the AED locations. Finally, the pre-installed AEDs data used in this study were obtained from registered public AED system in the government of Korea. In other words, other unregistered AEDs in the study area were not considered as pre-installed AEDs because we were not able to acquire their exact locations. Therefore, the coverage ratio of this study can be changed if the unregistered AEDs are registered and included in the future.

In some cases, organizing and analyzing a massive volume of data can more easily solve real-world issues than using complicated algorithms. The survival rate of patients suffering from sudden cardiac-arrest cases and the live discharge rate of those in the OHCA cases are expected to increase when the proposed method and dataset are utilized.

Acknowledgments: This research was supported by the Ministry of Land, Infrastructure, and Transport in Korea under the Urban Planning and Architecture (UPA) research support program and was supervised by the Korea Agency for Infrastructure Technology Advancement (KAIA) (13 Urban Planning & Architecture 02).

Author Contributions: Pil Kwon, Youngmin Lee, Kiyun Yu, and Yong Huh provided the core idea for this study. Yong Huh provided the precious dataset. Min-Jun Kim reviewed the manuscript. Pil Kwon implemented the methodology and performed the experimental validation. Pil Kwon also wrote the main manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Ahn, K.O.; Do Shin, S.; Suh, G.J.; Cha, W.C.; Song, K.J.; Kim, S.J.; Lee, E.J.; Ong, M.E.H. Epidemiology and outcomes from non-traumatic out-of-hospital cardiac arrest in Korea: A nationwide observational study. *Resuscitation* **2010**, *81*, 974–981. [CrossRef] [PubMed]
2. Becker, L.B.; Ostrander, M.P.; Barrett, J.; Kondos, G.T. Outcome of cpr in a large metropolitan area—Where are the survivors? *Ann. Emerg. Med.* **1991**, *20*, 355–361. [CrossRef]
3. Herlitz, J.; Engdahl, J.; Svensson, L.; Ängquist, K.-A.; Young, M.; Holmberg, S. Factors associated with an increased chance of survival among patients suffering from an out-of-hospital cardiac arrest in a national perspective in Sweden. *Am. Heart J.* **2005**, *149*, 61–66. [CrossRef] [PubMed]
4. Ritter, G.; Wolfe, R.A.; Goldstein, S.; Landis, J.R.; Vasu, C.M.; Acheson, A.; Leighton, R.; Medendrop, S.V. The effect of bystander CPR on survival of out-of-hospital cardiac arrest victims. *Am. Heart J.* **1985**, *110*, 932–937. [CrossRef]
5. Stiell, I.G.; Wells, G.A.; DeMaio, V.J.; Spaite, D.W.; Field, B.J.; Munkley, D.P.; Lyver, M.B.; Luinstra, L.G.; Ward, R.; Group, O.S. Modifiable factors associated with improved cardiac arrest survival in a multicenter basic life support/defibrillation system: OPALS study phase I results. *Ann. Emerg. Med.* **1999**, *33*, 44–50. [CrossRef]
6. Swor, R.A.; Jackson, R.E.; Cynar, M.; Sadler, E.; Basse, E.; Boji, B.; Rivera-Rivera, E.J.; Maher, A.; Grubb, W.; Jacobson, R. Bystander CPR, ventricular fibrillation, and survival in witnessed, unmonitored out-of-hospital cardiac arrest. *Ann. Emerg. Med.* **1995**, *25*, 780–784. [CrossRef]
7. Valenzuela, T.D.; Roe, D.J.; Cretin, S.; Spaite, D.W.; Larsen, M.P. Estimating effectiveness of cardiac arrest interventions a logistic regression survival model. *Circulation* **1997**, *96*, 3308–3313. [CrossRef] [PubMed]
8. Kim, H.S.; Uhm, D.C.; Hong, S.W. Factors influencing cardiopulmonary resuscitation performance on a stranger. *J. Korean Acad. Soc. Nursi. Educ.* **2010**, *16*, 339–346. [CrossRef]
9. Ro, Y.S.; Do Shin, S.; Song, K.J.; Lee, E.J.; Kim, J.Y.; Ahn, K.O.; Chung, S.P.; Kim, Y.T.; Hong, S.O.; Choi, J.-A. A trend in epidemiology and outcomes of out-of-hospital cardiac arrest by urbanization level: A nationwide observational study from 2006 to 2010 in South Korea. *Resuscitation* **2013**, *84*, 547–557. [CrossRef] [PubMed]
10. Lyon, R.; Cobbe, S.; Bradley, J.; Grubb, N. Surviving out of hospital cardiac arrest at home: A postcode lottery? *Emerg. Med. J.* **2004**, *21*, 619–624. [CrossRef] [PubMed]
11. U.S. Department of Health & Human Services. What is an automated external defibrillator? Available online: https://www.nhlbi.nih.gov/health/health-topics/topics/aed (accessed on 26 November 2016).
12. Gundry, J.W.; Comess, K.A.; DeRook, F.A.; Jorgenson, D.; Bardy, G.H. Comparison of naive sixth-grade children with trained professionals in the use of an automated external defibrillator. *Circulation* **1999**, *100*, 1703–1707. [CrossRef] [PubMed]

13. Jorgenson, D.B.; Skarr, T.; Russell, J.K.; Snyder, D.E.; Uhrbrock, K. Aed use in businesses, public facilities and homes by minimally trained first responders. *Resuscitation* **2003**, *59*, 225–233. [CrossRef]
14. Hoke, R.S.; Chamberlain, D. Skeletal chest injuries secondary to cardiopulmonary resuscitation. *Resuscitation* **2004**, *63*, 327–338. [CrossRef] [PubMed]
15. Jin, S.-M. The public perception and importance of public education and information about automated external defibrillator (AED). Master's Thesis, Kyungpook National University, Daegu, Korea, 2013.
16. Folke, F.; Gislason, G.H.; Lippert, F.K.; Nielsen, S.L.; Weeke, P.; Hansen, M.L.; Fosbøl, E.L.; Andersen, S.S.; Rasmussen, S.; Schramm, T.K. Differences between out-of-hospital cardiac arrest in residential and public locations and implications for public-access defibrillation. *Circulation* **2010**, *122*, 623–630. [CrossRef] [PubMed]
17. Ong, M.E.H.; Tan, E.H.; Yan, X.; Anushia, P.; Lim, S.H.; Leong, B.S.-H.; Ong, V.Y.K.; Tiah, L.; Yap, S.; Overton, J. An observational study describing the geographic-time distribution of cardiac arrests in Singapore: What is the utility of geographic information systems for planning public access defibrillation? (PADS Phase I). *Resuscitation* **2008**, *76*, 388–396. [CrossRef] [PubMed]
18. Mitamura, H. Public access defibrillation: Advances from Japan. *Nat. Clin. Pract. Cardiovasc. Med.* **2008**, *5*, 690–692. [CrossRef] [PubMed]
19. Sakai, T.; Iwami, T.; Kitamura, T.; Nishiyama, C.; Kawamura, T.; Kajino, K.; Tanaka, H.; Marukawa, S.; Tasaki, O.; Shiozaki, T. Effectiveness of the new 'mobile AED map'to find and retrieve an AED: A randomised controlled trial. *Resuscitation* **2011**, *82*, 69–73. [CrossRef] [PubMed]
20. Merchant, R.M.; Asch, D.A. Can you find an automated external defibrillator if a life depends on it? *Circ. Cardiovasc. Qual. Outcomes* **2012**, *5*, 241–243. [CrossRef] [PubMed]
21. Imai, K.; Fujii, A.; Nabeshima, K. AED location in public spaces: A case study in ueno park using voronoi diagrams with obstacles. *J. Asian Archit. Build. Eng.* **2008**, *7*, 271–278. [CrossRef]
22. Tzeng, G.H.; Chen, Y.W. The optimal location of airport fire stations: A fuzzy multi-objective programming and revised genetic algorithm approach. *Transp. Plan. Tech.* **1999**, *23*, 37–55. [CrossRef]
23. Liu, N.; Huang, B.; Chandramouli, M. Optimal siting of fire stations using GIS and ANT algorithm. *J. Comput. Civ. Eng.* **2006**, *20*, 361–369. [CrossRef]
24. Lee, G.; Murray, A.T. Maximal covering with network survivability requirements in wireless mesh networks. *Comput. Environ. Urban Syst.* **2010**, *34*, 49–57. [CrossRef]
25. Korea Statistics. Data Request. Available online: http://sgis.kostat.go.kr/contents/shortcut/shortcut_05.jsp (accessed on 29 June 2016).
26. Chrisinger, B.W.; Grossestreuer, A.V.; Laguna, M.C.; Griffis, H.M.; Branas, C.C.; Wiebe, D.J.; Merchant, R.M. Characteristics of automated external defibrillator coverage in Philadelphia, PA, based on land use and estimated risk. *Resuscitation* **2016**, *109*, 9–15. [CrossRef] [PubMed]
27. Leung, A.C.; Asch, D.A.; Lozada, K.N.; Saynisch, O.B.; Asch, J.M.; Becker, N.; Griffis, H.M.; Shofer, F.; Hershey, J.C.; Hill, S. Where are lifesaving automated external defibrillators located and how hard is it to find them in a large urban city? *Resuscitation* **2013**, *84*, 910–914. [CrossRef] [PubMed]
28. SK Telecom. SK Telecom Geovision Data. Available online: http://datablog.geovision.co.kr/index.php/data/ (accessed on 15 November 2016).
29. Kim, J.; Huh, Y.; Kim, J.O.; Lee, J.B. Proposal for the generation of network data for pedestrians in South Korea using large-scale maps. *KSCE J. Civ. Eng.* **2015**, *19*, 1483–1491. [CrossRef]
30. Oh, K.; Jeong, S. Assessing the spatial distribution of urban parks using GIS. *Landsc. Urban Plan.* **2007**, *82*, 25–32. [CrossRef]
31. Korea Transport Database. Data Download. Available online: https://www.ktdb.go.kr/www/index.do (accessed on 12 July 2016).
32. Alshwesh, I.; Comber, A.; Brunsdon, C. *A Comparison of GIS-Based Location Allocation Heuristics: Minimise Impedance vs Grouping Genetic Algorithm p-median*; GIS Research UK: Liverpool, UK, 2013.
33. Esri. Algorithms Used by the ArcGIS Network Analyst Extension. Available online: http://resources.arcgis.com/en/help/main/10.2/index.html#/Algorithms_used_by_the_ArcGIS_Network_Analyst_extension/004700000053000000/ (accessed on 18 November 2016).
34. Alp, O.; Erkut, E.; Drezner, Z. An efficient genetic algorithm for the p-median problem. *Ann. Oper. Res.* **2003**, *122*, 21–42. [CrossRef]
35. Esri. Location-Allocation Analysis. Available online: http://desktop.arcgis.com/en/arcmap/latest/extensions/network-analyst/location-allocation.htm (accessed on 13 July 2016).

36. Im, W.-S.; Choe, H.-S.; Jeong, M.-G.; Ryu, T.-B.; Choe, H.-U. A comparison of gait characteristics between korean and western young people. *J. Ergon. Soc. Korea* **2006**, *25*, 33–42.
37. Jude, J.R.; Kouwenhoven, W.B.; Knickerbocker, G.G. Cardiac arrest: Report of application of external cardiac massage on 118 patients. *Jama* **1961**, *178*, 1063–1070. [CrossRef] [PubMed]
38. Eckstein, M.; Stratton, S.J.; Chan, L.S. Cardiac arrest resuscitation evaluation in Los Angeles: Care-la. *Ann. Emerg. Med.* **2005**, *45*, 504–509. [CrossRef] [PubMed]