The use of hexagon tessellation for virtual network analysis of evacuation distance

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Abstract: Earthquakes and tsunami affecting Central Sulawesi, Indonesia have been recorded since 1927. The last tsunami in 2018 washed the shoreline for not more than five minutes. The objective of this study is to determine evacuation distance by using three different methods of network analysis: the current method (existing road network model), the proposed combined virtual network model, and the real-world evacuation route which is used as the standard parameter. This research includes four steps which are: building the three types of networks, determining the Origin and Destination (O-D) points, running the solver, and finally comparing the distances determined by each method. All of the network builds and analyses use the closest facility solver within the ArcGIS network analysis tools. With different characteristics, this study, carried out in Palu, Indonesia, shows that the evacuation distance method using a combined virtual network model is more closely resembles real-world evacuation distance; only one out of 20 routes which were analysed did not show the maximum performance compared to the real-world network model. On the other hand, the existing road network model shows two routes deviating from the route determined by the combined network model, meaning a weak performance of the method in measuring the evacuation distance.

1.   INTRODUCTION

Studies about the evacuation process during disasters, especially tsunami and flood disasters, have been developed using various methods and models. Evacuation following disaster events is a common approach to reduce level of consequence in emergency management (Cova & Johnson, 2003), this makes the evacuation plan a critical phase to be carefully calculated to minimise the number of victims and loss of property (Li, Li, & Claramunt, 2018). One accessibility analysis that can incorporate network-based evacuation uses the Network Analysis tools which are embedded in ArcGIS software. However, like other accessibility analyses, this network analysis modeling is highly dependent on the availability of existing road network map data in the area to be modeled. Lack of road network data could lead to weak results and provide suboptimal estimations which are very crucial given the limitations of an evacuation process. This research proposes a hexagon tessellation virtual network combined with available existing road

data (hereinafter, combined virtual network model) to measure the evacuation distance from evacuee origin to the temporary evacuation centers (TES) and compares the result with the current existing road model (hereinafter, existing road network model) and the real-world evacuation distance.

Measuring the evacuation distance is important since an urban planner can later measure the available evacuation time which is limited during a tsunami, and a planner can measure the availability of TES within their service area. Studies on TES have been carried out by several researchers such as Budiarjo (2006), Kongsomsaksakul, Yang, and Chen (2005) and Swamy et al. (2017). TES, which are also referred to as Vertical Shelters (Løvholt et al., 2014; Scheer, Varela, & Eftychidis, 2012; UNESCO-IOC, 2009) or Evacuation Shelter Buildings (Budiarjo, 2006) for tsunami, are actually buildings with robust structure that could withstand an earthquake and have higher floors that exceed tsunami upper-inundation levels (Budiarjo, 2006), and should be located within the disaster-prone area so they could be easily accessed (Federal Emergency Management Agency, 2003; UNESCO-IOC, 2009). Different to evacuation centers or evacuation shelters, where people can stay longer and use it until the relief and recovery efforts have finished, the TES is a temporary space for people to immediately evacuate to immediately prior to a disaster occurring. Similar to a flash flood (Mardin & Shen, 2019; Huang, Shen, & Mardin, 2019) the time window for evacuation is very limited for tsunami disasters; evacuation centers or long-term evacuation shelters cannot easily be accessed within five minutes after aninitial evacuation has been announced. Other things that should be noted are that evacuees usually go on foot, and that is why it is very important that TES are spread throughout vulnerable areas for ease of evacuee access in the shortest time.

Several methods have been developed to measure the evacuation route to TES. Depending on the GIS system, the vector or raster, the method shares the same basic idea which is using time and route to access the destination points from the origin points. The raster models usually use least-cost path methods, which has the measurement based on the pixel value between the origin and destination (O-D). The other type of GIS route analysis is network analysis which uses vector-based GIS. Although it is possible for raster-based GIS to equal the vector-based GIS, especially in travel time surface analysis, the vector-based is the current standard for most GIS research and practice (Mulrooney et al., 2017). The advantage of vector-based mapping is the ability to mimic the real-world existing road/network, relatively low data size which leads to faster analyst processing, and more detailed results. Several GIS softwares use network analysis, for example ArcGIS, QGIS, and FLOWMAP. In this research, the model is mainly developed using ArcGIS solver.

The ArcGIS network analysis consists of seven different solvers (ESRI, n.d.), the simplest one is the route solver. The route solver determines the best route for visiting a single location or multiple location points efficiently. The second solver is the closest facility solver. The solver will find the closest facility point from the available facilities. To measure the facility distance, the solver uses Dijkstra's algorithm; the solver under network analysis is mainly based on Dijkstra's algorithm (ESRI, 2012). This second solver, which is the closest facility solver, is used as the main analysis tools in this research. Other than these two solvers which are already mentioned above, there are other more advanced and complicated solvers which are Service areas, O-D cost matrix, Vehicle routing problem,

Location-allocation, and Time-dependent analysis which are not going to be used in this research.

As mentioned previously, although there is an advantage to conducting network analysis using existing road data, this network model also brings disadvantages. The quality of the road network data (map) plays an essential role in this method. Limited data will lead to less accuracy on route predictions and this less accuracy with small time windows could result in catastrophy during the evacuation process. In an area where map data are not detailed enough, such as in developing countries in Asia, for example in Indonesia where the city planning is developed on a map scale of 1:50.000, maps cannot display very small roads and informal access routes between buildings. Other than this limitation, the current analysis method cannot identify open parks and open ground as accessible routes, since these types of urban land cover usually do not have a function as a network path, which is contrary with the real-world where the open parks and open ground are actually walkable.

To coupe the disadvantages of predicting routes, Mardin (2009) proposed hexagon tessellation of the virtual network in his research of people traveling from their home to their nearest train station, while Budiarjo (2006) presented the population unit zone in a hexagon tessellation, further, he also uses triangle tessellation only on beaches (bare land) that could be passed through during evacuation. His research did not include small alleyways in settlements. Both researchers suggested virtual networks as additional routes to complete route models. Virtual networks are non-existent networks or non-existent roads, but are embedded in the model to help with evacuation prediction. The use of tessellation in the model is because of the advantage of tessellations. The tessellation itself is a kind of geometric iteration that forms a tile pattern without leaving a gap in between. The purpose of this tessellation is to divide a large area into smaller and equal size areas. This is to make uniform the unit of analysis or network length and avoid geographic differences within a sub-area (De Jong & Van der Vaart, 2010). Mainly there are two types of tessellation, which are irregular tessellation and regular tessellation. Irregular tessellation appears in GIS such as in the spatial units of a choropleth map (Boots, Okabe, & Sugihara, 1999), the land unit between the road and administration unit. While the regular tessellation is very well known in the GIS environment as grid tessellation. Grid tessellation usually appears in raster data from satellite images or other raster maps. Although it is rarely used for GIS analysis, the other regular tessellations which are more commonly used are triangle and hexagon tessellations (Boots, Okabe, & Sugihara, 1999). Different to the research carried out by Budiarjo and Mardin (Budiarjo, 2006; Mardin, 2009), this research will use virtual hexagon tessellations through all the settlement area, not only on the open bare-land, and evaluate the distance of the selected route. The result will later be compared with the existing road network model and then compared with the real-world route distance.

2.   METHOD

The research method is divided into two different parts, the first part is the study area, while the second part is the analysis procedure. The procedure itself is divided into three parts which are building the network,

defining the origin and destination points (O-D points) and lastly, running the model to find the results**Study area**

Palu is the capital city of Central Sulawesi Province, which is defined as one of the National Activity Centers, which functions to serve the international, national and some provincial scale activities. The region consists of five dimensions of mountains, valleys, rivers, bays and oceans. The city of Palu is between 0°, 36' - 0°, 56' south latitude, and 119°, 45" - 121°, 1" east longitude; it is located almost directly on the equator. The altitude of Palu is between 0-700 meters above sea level. Palu has an area of 395.06 square kilometers and is divided into eight districts (Kecamatan), see the map shown in *Figure 1*.

Figure 1. Administration Map of Palu

According to BPBD Kabupaten Donggala (2011), several earthquakes that followed by tsunami in the Palu bay area have been recorded since 1927, and the latest tsunami occurred recently, in September 2018. The earthquake of 1968 which was followed by a tsunami ('standing water' in the local dialect), is still a good example in the local community in Palu. Based on testimony, at the time of the incident, people were not aware of the physical symptoms of the tsunami. When the seawater suddenly decreased after an earthquake, people crowded on the beach to collect trapped fish, only then did the water head back toward the coast. People had no time to return to the highlands, with no permanent buildings or shelter to access. This tsunami destroyed the community settlement and claimed hundreds of victims, some of the bodies were found lodged in a palm tree on the beach.

In the latest disaster hitting Palu on September 28, 2018, an estimated 2,113 people died, and 13.82 trillion Rupiah was lost in damages. Different from previous events, the critical aspect of the latest case is that the Palu earthquake delivered a tsunami within a very short time interval. CCTV recorded the Palu tsunami showing not more than five minutes following the earthquake (Tentang Palu, 2018), which is extremely dangerous. From this latest case, it can be understood that preparedness for a tsunami is not only the availability of evacuation centers, but also availability of temporary evacuation centers where people can evacuate to as soon as a warning has been initiated due to awareness of a tall wave. Such an option for a TES would only be available in a high building with a decent structure.

The tsunami prone area lies from the west to the east, along the coast of the Palu Bay area, according to the "Map of Tsunami Prone Areas" from the Meteorology and Geophysics Bureau (Municipality of Palu, 2009). The Palu area is divided into four zones which are: (1) very vulnerable, (2) vulnerable, (3) relatively safe, and (4) non-vulnerable areas (see *Figure 2*) . According to the data, 23.57 km^2 is in the tsunami-prone area (very vulnerable and vulnerable areas) which is 6% of the total Palu administrative area. Although the tsunami-vulnerable area only comprises 6% of Palu's total administration area, this region is relatively flat and very suitable for settlement. The data shows 19.55 km^2 is settlement area with a population of 232,695. This means more than half of the Palu population is living in this tsunami prone area (Palu Statistic Bureau, 2016).
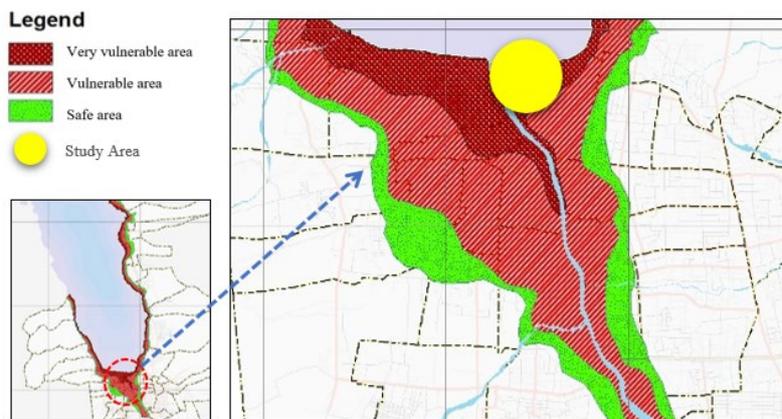
Figure 2. Map of Tsunami Prone Area (Source: BMG 2005 – RTRW)

Figure 2 shows the very vulnerable and vulnerable areas marked in dark red and red, while the relatively safe area is marked with green dots, the other white area is the non-vulnerable area for tsunami events. The study area (marked with a big yellow dot) falls within the very vulnerable area which is in the administration of Besusu Barat Ward (*Kelurahan*) as seen in *Figure 3*.
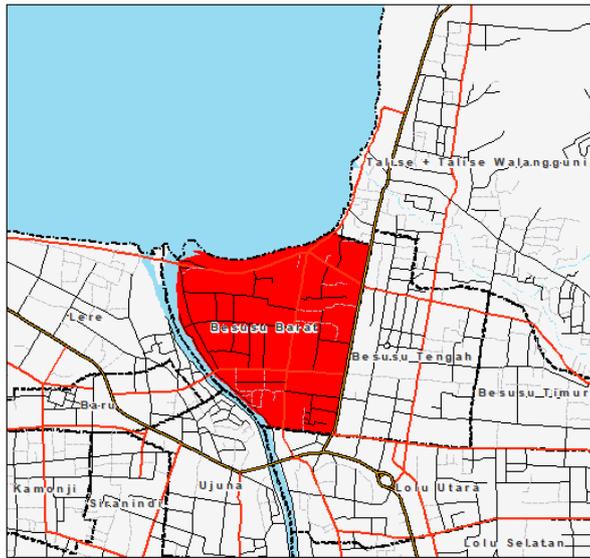
Figure 3. Study Area

The study area is in the most populous settlement in the city, and this area is the oldest settlement. The relatively flat terrain is an alluvial landform and invited settlers to stay and develop. In 2016, the area consisted of 81.43 ha with 17,985 people living in this area, with a population density of 220 people per hectare. This density is considerably high since the total density for Palu is four people per hectare (Palu Statistic Bureau, 2016).

2.2   Simulation Procedure

This research involves four steps prior to reaching its result, which are:(1) Preparation for the network which involves building the networks, (2) Creating and defining the origin and destination, (3) Running the routes analysis, and (4) Comparing three different types of result. The whole process is explained in the following section, while the procedural framework can be seen in *Figure 4*.
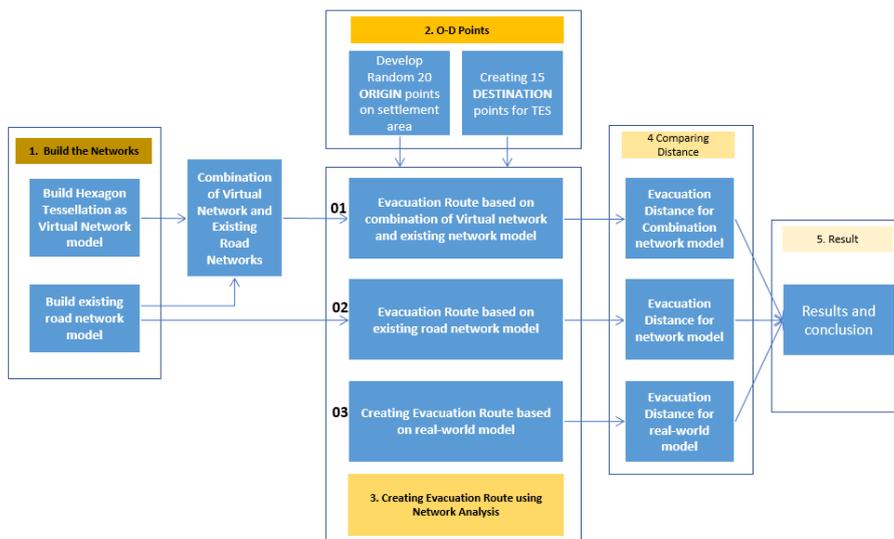
Figure 4. Simulation Procedure Framework

2.2.1   Building the Network Models: Three different network models

This research aims to study different network models which are, firstly, the combination of hexagon tessellation as a virtual network with the existing road network, secondly, combined with the existing road network model and, finally, combined with the real-world model. Based on this aim, this research develops three basic networks as follows:

2.2.1.1   Existing road network

The network system which has been built using this model utilizes existing road conditions that exist in the study area. The existing road network used is based on the local urban masterplan map (RTRW) which is produced by the local government ([Municipality of Palu, 2009](#)). The RTRW Map uses a scale of 1:50.000. This map scale is a standard map scale in Indonesia for urban planning, and consequently some detailed data cannot be contained in it, only primary and local roads are available in the data (see *Figure 5*). Having the data, the topology can be cleaned to produce a vector map which meets the network analysis solver standard in ArcGIS 10.

Figure 5. The existing road in the study area

2.2.1.2   Hexagon tessellation networks as virtual networks

The hexagon tessellation is built using hexagon edge lines which have been developed through all parts of the study area, and the circumscribed radius size of each hexagon is 20 meters, with 10 meter length for each side, adapting the average length of the land parcels in the study area (see *Figure 6*).
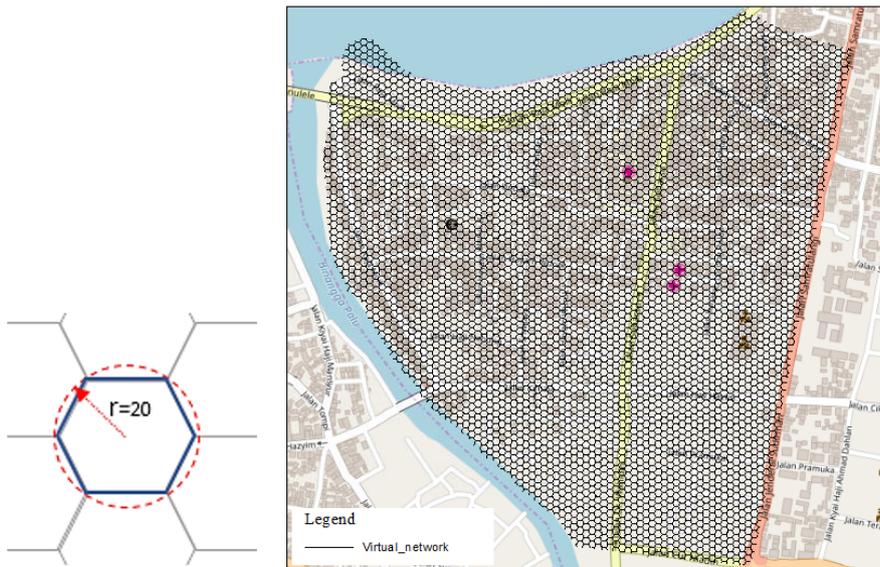
Figure 6. Hexagon tessellation size and the spread of the tessellation within the study area

2.2.1.3   Combination of virtual network and existing road network

Due to the limitations of the map scale used, there are parts of the existing road, especially very small lanes, and open land which could be used as an access to the TES that do not appear (see Section 2.2.1.1). Anticipating the need for evacuation access in these unmapped lanes, this model incorporates a virtual road network and uses the hexagon tessellation pattern (see Section 2.2.1.2). In this research, the combined virtual network is a mixture of the hexagon tessellation and existing road network; the model is built by merging the two data sets as one network model. The result can be seen in *Figure 7*.

Figure 7. Combined network of the virtual and existing road models

2.2.1.4   Real-world network

The real-world network is a network digitized based on the nearest or closest route of each origin point to the destination points (TES) of evacuation. The real-world network is mimicking the logical scenario where people will access only the nearest TES, while the route path itself is an

existing route path in the real-world, whether it is available on the map as a road or not, and the route path also uses open bare land which can be accessed in everyday life. To determine the route, fieldwork was carried out during this research.

The real-world network displays the standard distance for both the combined virtual network model and the existing road network model, meaning the value of route distance to the real-world network is more accurate. The following *Figure 8* is a sample of the traced route on the real-world conditions, shown as a dashed line.
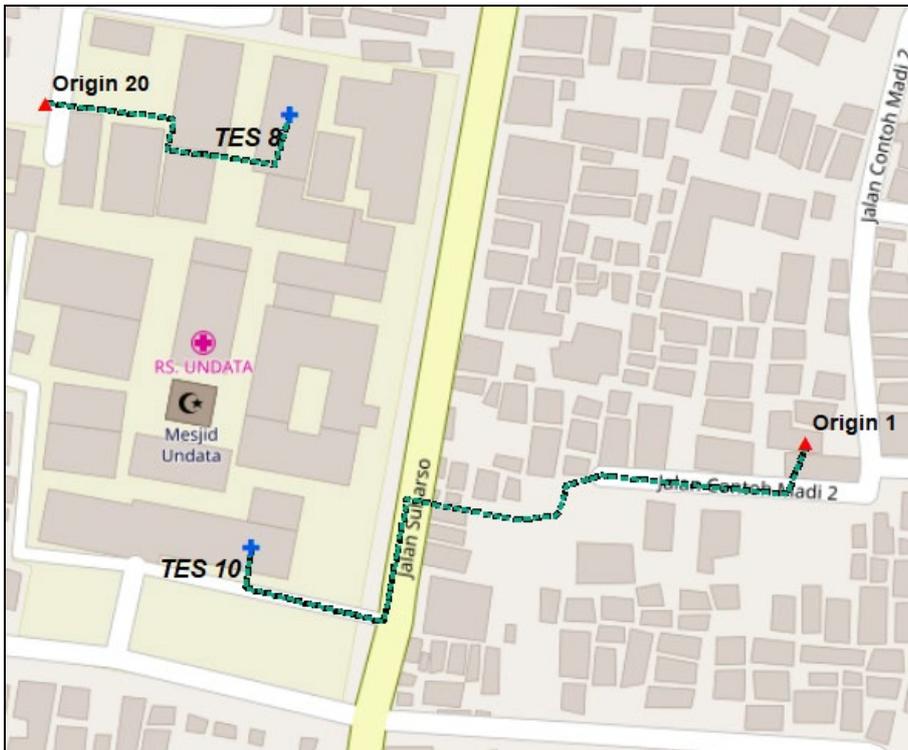
Figure 8. Sample of the traced route based on real-world networks

2.2.2　Defining the origin and destination points

2.2.2.1　Origin points
The origin points are generated randomly. There are 20 origin points which cover the study area, all the origin points are spread throughoutthe settlement area, including around the beach which is one of main tourist locations in the city. The points which are mimicking the daily position of people can be seen in *Figure 9*.

2.2.2.2　TES destination points
In this study, the TES locations were selected based on several buildings that were considered to meet certain structure requirements. One consideration is building height; to face the high waves, the building must have more than one floor. The other requirement is that the building, to be used as a shelter, is a public building. These public buildings, such as places of worship (mosque or church), school/university, trade center/mall, can be accessed by the public at any time. The total number of the buildings which meet the standard as vertical TES in the study area are 15 buildings. *Figure*

9 and *Table 1* show the vertical shelter points as temporary evacuation shelters (TES).
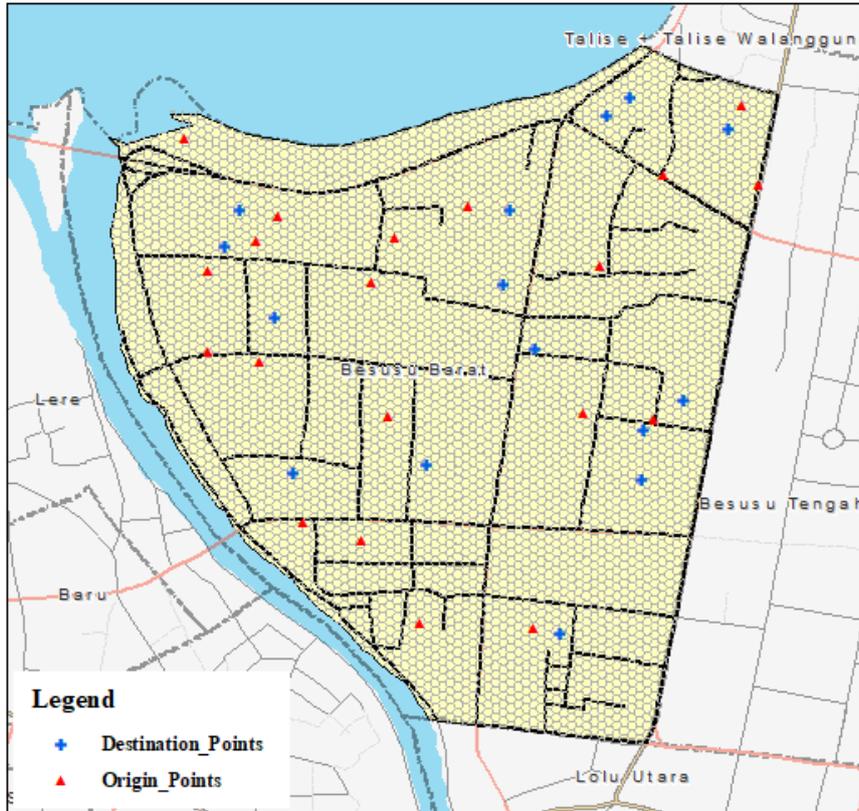
Figure 9. Location of Origin Point and TES Destination Points

Table 1. List of Vertical TES

No.	Name	Destination no.	X-Coord	Y-Coord
1	Court	1	819542	9902050
2	AMIKOM	2	818544	9901820
3	Hospital - Police	3	819158	9901610
4	DPRD	4	819376	9901450
5	Church	5	819210	9901040
6	Police Office	6	819455	9901510
7	SAMSAT Office	7	818573	9901890
8	Hospital	8	819111	9901890
9	Local Mosque	16	818678	9901360
10	Hospital	10	819098	9901740
11	DPRD	11	819371	9901350
12	Mosque	12	818946	9901380
13	Hotel	13	819301	9902080
14	Hotel	14	819349	9902110
15	Local Mosque	15	818643	9901670

2.2.3   Running the route analysis

The model is developed using ArcGIS software with the Network Analysis extension, which is the closest facility solver. The solver is based on Dijkstra's algorithm to calculate the route. This method is used to connect two edges, which are the facility point (in this case the TES) and the

demand source (Origin points), with the less estimated time or distance. The solver generates line routes which contain total distance or time (ESRI, 2012). In this model, the closest facility solver is used for measuring the TES accessibility within 10 minutes of walking. There are variables introduced to run the analysis of the model in this research, the following section describes the variables.

2.2.3.1   Cost of the selecting route in the combined virtual network model

Since there are different route types which are shared in this research, especially the hexagon tessellation virtual network and existing road network, it is important to differentiate between those two types of networks, especially when combined within one model analysis. The existing road network works predicatbly and has a smooth track without obstacles. While the virtual network model, since this network does not exist in the real world, undoubtedly will have a lot of obstacles such as buildings, walls, trees, puddles of water and rocks. Based on this logic, the evacuee will prefer the available and much better paved existing road. This means evacuees are likely to prioritise the existing road network rather than the virtual network. In the combination of the virtual network and existing road network analysis model, the cost of selecting the virtual network is assigned twice the value compared to choosing the existing road network. This will lead the evacuee to only select the virtual network if there is no other existing road available nearby.

2.2.3.2   Result of analysis of the three network models

For the analysis process using the closest facility solver in ArcGIS, all of the three network models resulted in 20 different routes, named Route 1 to Route 20, and share similar route directions. For example Route 1 starts from origin point 1 and evacuation is to TES number 10. This is applied to all three network models. The next 19 route directions display similar behaviours for selecting the directions, except for Route 7 and Route 20. In Route 7 for the existing road model, the evacuee origin points start from point number 7 and the route ends up at TES number 12, while the other two network models (Combination virtual model and Real-world model) start from the same point but end up at TES number 9. This phenomenon also appears on Route 20. For the existing road model, the origin point number 20 ends on TES number 7, while both the combined virtual model and real-world model end at TES number 8. The result can be seen in the following *Figure 10* to *Figure 12*.

In this analysis, not all the TES are accessed by an evacuee, at least five TES in the model are not utilised as destinations. These five TES are TES numbers 3, 6, 9, 11 and 14. This happens because there are alternative TES much closer to the evacuee starting points.

Existing Road Networks Model

Route	Existing Route	Existing Model Distance (meters)
Route 1	Origin Point Number 1 - TES Number 10	213.82
Route 2	Origin Point Number 2 - TES Number 7	146.92
Route 3	Origin Point Number 3 - TES Number 2	62.36
Route 4	Origin Point Number 4 - TES Number 12	94.85
Route 5	Origin Point Number 5 - TES Number 7	73.08
Route 6	Origin Point Number 6 - TES Number 12	334.61
Route 7	Origin Point Number 7 - TES Number 12	321.34
Route 8	Origin Point Number 8 - TES Number 2	32.28
Route 9	Origin Point Number 9 - TES Number 12	203.14
Route 10	Origin Point Number 10 - TES Number 4	99.31
Route 11	Origin Point Number 11 - TES Number 13	160.47
Route 12	Origin Point Number 12 - TES Number 1	51.44
Route 13	Origin Point Number 13 - TES Number 5	135.80
Route 14	Origin Point Number 14 - TES Number 2	298.36
Route 15	Origin Point Number 15 - TES Number 15	153.82
Route 16	Origin Point Number 16 - TES Number 1	98.03
Route 17	Origin Point Number 17 - TES Number 4	23.14
Route 18	Origin Point Number 18 - TES Number 15	99.68
Route 19	Origin Point Number 19 - TES Number 2	368.73
Route 20	Origin Point Number 20 - TES Number 7	440.10
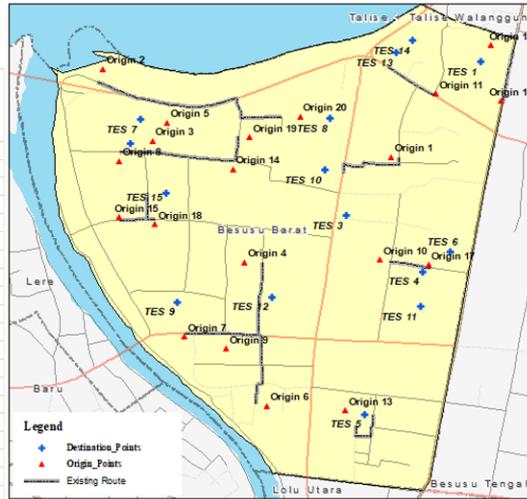
Figure 10. Existing road networks model based on closest facility solver

Combination Networks Model

Route	Combination Route	Combination Model Distance (meters)
Route 1	Origin Point Number 1 - TES Number 10	240.74
Route 2	Origin Point Number 2 - TES Number 7	246.54
Route 3	Origin Point Number 3 - TES Number 2	84.16
Route 4	Origin Point Number 4 - TES Number 12	159.65
Route 5	Origin Point Number 5 - TES Number 7	104.10
Route 6	Origin Point Number 6 - TES Number 12	403.37
Route 7	Origin Point Number 7 - TES Number 9	132.79
Route 8	Origin Point Number 8 - TES Number 2	84.26
Route 9	Origin Point Number 9 - TES Number 12	276.86
Route 10	Origin Point Number 10 - TES Number 4	145.93
Route 11	Origin Point Number 11 - TES Number 13	199.52
Route 12	Origin Point Number 12 - TES Number 1	72.32
Route 13	Origin Point Number 13 - TES Number 5	67.06
Route 14	Origin Point Number 14 - TES Number 2	342.57
Route 15	Origin Point Number 15 - TES Number 15	203.59
Route 16	Origin Point Number 16 - TES Number 1	171.42
Route 17	Origin Point Number 17 - TES Number 4	34.42
Route 18	Origin Point Number 18 - TES Number 15	126.34
Route 19	Origin Point Number 19 - TES Number 2	417.65
Route 20	Origin Point Number 20 - TES Number 8	110.08
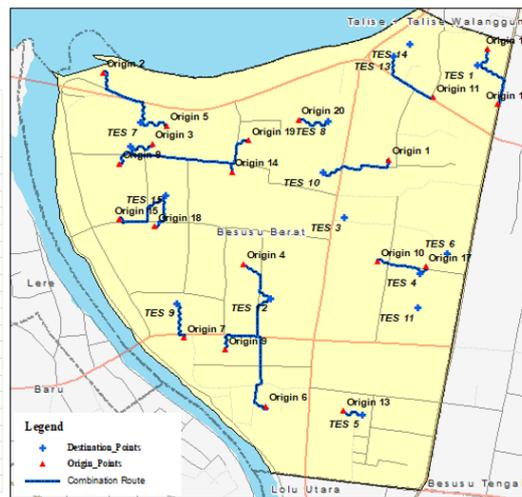
Figure 11. Combined virtual network model based on closest facility solver

Real-World Networks Model

| Route	Real-World Route	Real-World Model Distance (meters)
Route 1	Origin Point Number 1 - TES Number 10	262.65
Route 2	Origin Point Number 2 - TES Number 7	190.18
Route 3	Origin Point Number 3 - TES Number 2	85.91
Route 4	Origin Point Number 4 - TES Number 12	160.19
Route 5	Origin Point Number 5 - TES Number 7	223.94
Route 6	Origin Point Number 6 - TES Number 12	404.04
Route 7	Origin Point Number 7 - TES Number 9	287.10
Route 8	Origin Point Number 8 - TES Number 2	96.89
Route 9	Origin Point Number 9 - TES Number 12	242.32
Route 10	Origin Point Number 10 - TES Number 4	135.76
Route 11	Origin Point Number 11 - TES Number 13	201.56
Route 12	Origin Point Number 12 - TES Number 1	99.40
Route 13	Origin Point Number 13 - TES Number 5	68.55
Route 14	Origin Point Number 14 - TES Number 2	332.51
Route 15	Origin Point Number 15 - TES Number 15	255.66
Route 16	Origin Point Number 16 - TES Number 1	171.01
Route 17	Origin Point Number 17 - TES Number 4	31.24
Route 18	Origin Point Number 18 - TES Number 15	199.07
Route 19	Origin Point Number 19 - TES Number 2	413.51
Route 20	Origin Point Number 20 - TES Number 8	107.89
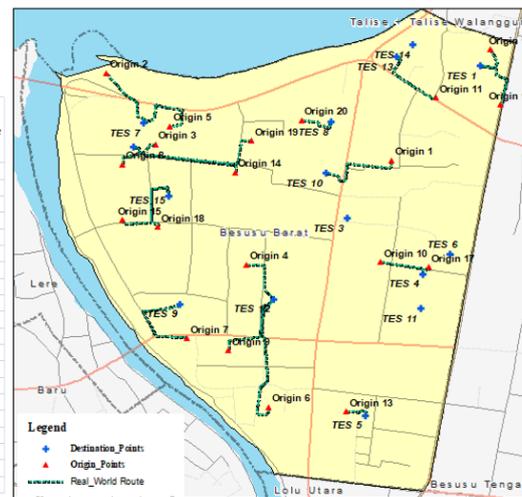
Figure 12. Real-world networks model based on closest facility solver

3. RESULT AND DISCUSSION

Based on all three models' results, this research found several differentiating behaviours of each model, especially with regard to the combined virtual network model and existing road network model. Comparing the two models with real-world condition networks also gave other interesting findings. The following *Table 2* and *Figure 13* show the different distances produced by each model.

Table 2. Distance of Three different networks model

| No	Route	Distance of Real-World Network (meters)	Distance of Combined Virtual Network (meters)	Distance of Existing Road Network (meters)
1	Route 1	262.65	240.74	213.82
2	Route 2	190.18	246.54	146.92
3	Route 3	85.91	84.16	62.36
4	Route 4	160.19	159.65	94.85
5	Route 5	223.94	104.10	73.08
6	Route 6	404.04	403.37	334.61
7	Route 7	287.10	132.79	321.34
8	Route 8	96.89	84.26	32.28
9	Route 9	242.32	276.86	203.14
10	Route 10	135.76	145.93	99.31
11	Route 11	201.56	199.52	160.47
12	Route 12	99.40	72.32	51.44
13	Route 13	68.55	67.06	135.80
14	Route 14	332.51	342.57	298.36
15	Route 15	255.66	203.59	153.82
16	Route 16	171.01	171.42	98.03
17	Route 17	31.24	34.42	23.14
18	Route 18	199.07	126.34	99.68
19	Route 19	413.51	417.65	368.73
20	Route 20	107.89	110.08	440.10
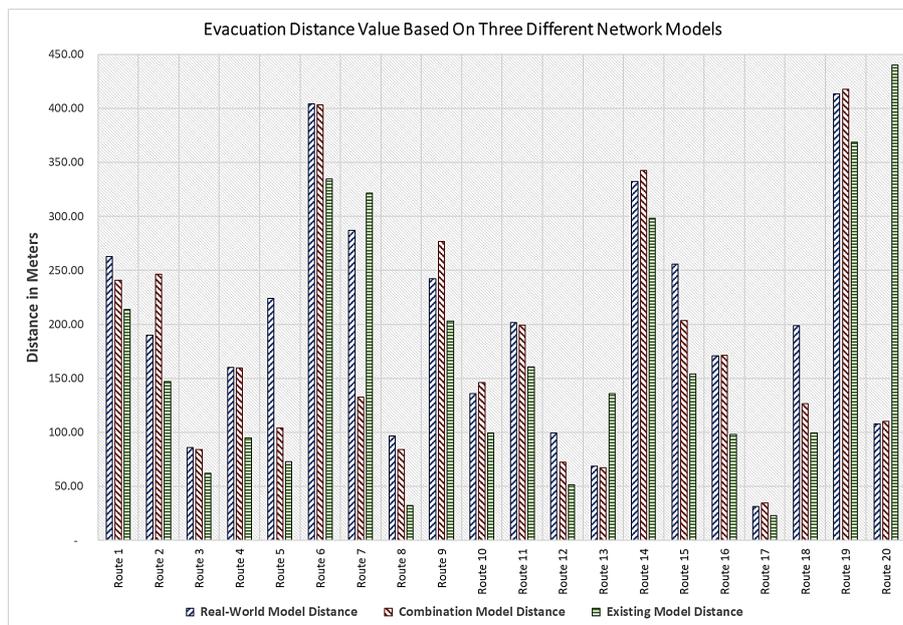
Figure 13. Graphic charts of three different network models

All the models show almost similar behaviour on O-D route choice, with the only difference appearing to be along the existing road network routes of

Route 7 and Route 20. As appears on the map in *Figure 14*, while the nearest TES is chosen by the combined virtual network model, the existing road network cannot access the same nearest TES, but chose the other TES which is closer to the available existing road. As shown in the results, the distance becomes significantly longer.
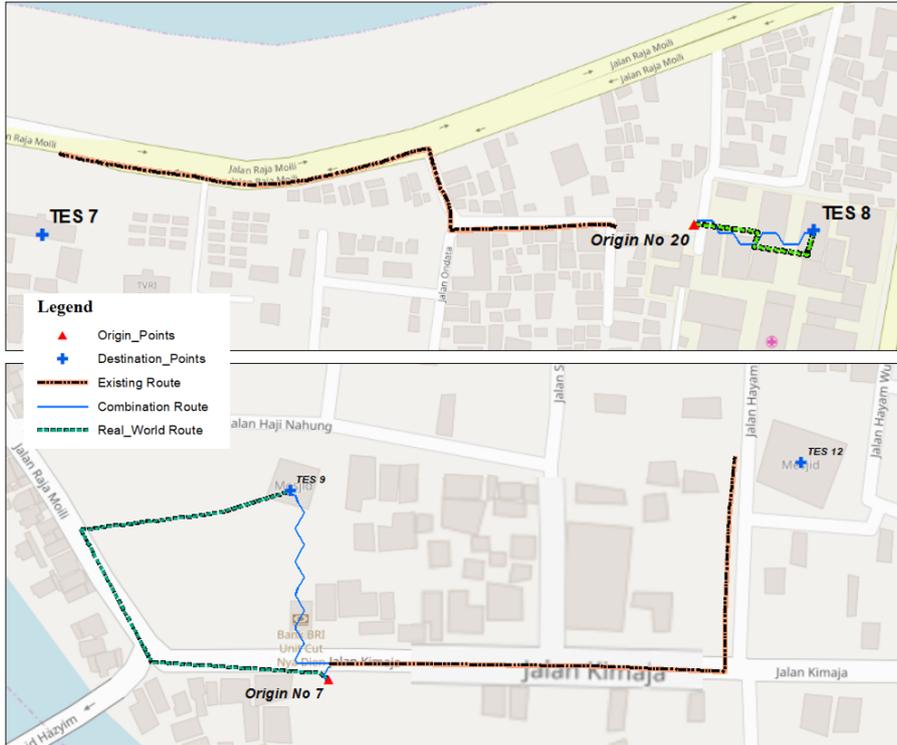


Figure 14. A different choice for Routes 7 and 20
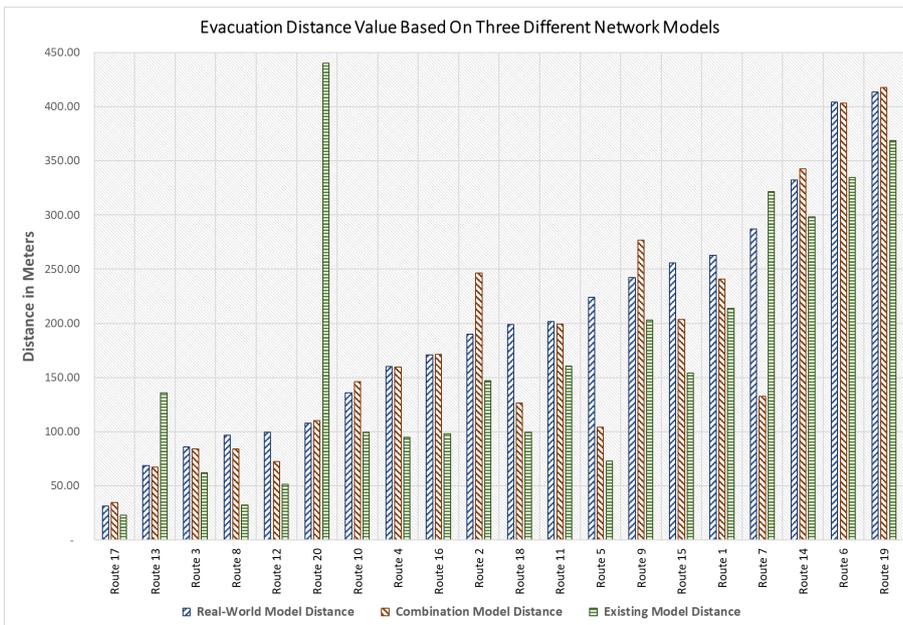
Figure 15. Chart of three different networks model based on distance

For Route 7, the combined virtual network may be deceiving with a shorter route compared to the real-world context. Some notes on use of the combined virtual network which must be considered are in regard to the method of predicting the cost of travel (see Section 2.2.3.1). In this research, the model assigns the cost of traveling in a virtual network as two times higher compared to choosing the existing road. The value 'two times' needs further research, it is possible the cost should be three or four times the cost to obtain a more accurate travel distance result for the combined virtual network model.

Other than Route 7 and Route 20, using the same O-D route, the largest distance differences between the existing road network and real-world network compared with the combined model are for Routes 5, 8, 12 and 13. The recorded distance of Route 5 and 8 were less than half of the real-world distance. For Route 12, the length of the existing road model is 52% of the real-world distance (99.40 meters for the real-world network model, 72.32 meters for the combined network model, and 51.44 meters for the existing road network model). For Route 13, the distance is twice as long compared to the real-world network result. For the combined network model, the result shows a slightly better result for Route 5 compared to the existing model, although still under half of the real-world distance (223.94 meters for the standard real-world distance and 104.10 meters for the combined network model, while 73.08 meters was recorded for the existing road network model). For two other routes, Route 8 and Route 13, the result of the combined network model compared to the real-world network model was close, with a difference less than 20% (see *Table 2*).

Overall findings from all 20 routes show only Route 7 as a weakness of the combined virtual network model, while the other 19 routes showed results much closer to the real-world condition (see *Figure 15*). Based on this finding, this research concludes that the combined virtual network model produces a better result for predicting the evacuation distance to the TES compared with the current method, which only uses the available existing road network.

For further research, several further questions arise related to using the combined network model for evacuation analysis, especially linked to the network analysis tools of ArcGIS. Since the network analysis tools consist of seven solvers (*Route; Closest facility; Service areas; OD cost matrix; Vehicle routing problem; Location-allocation;* and *Time-dependent analysis*) it would be interesting to see the combined virtual network model used with other solvers, especially the two solvers which are very related to the evacuation process, the *Service areas* and *Location-allocation* solvers (ESRI, n.d.). Comparing different types of tesselation is also essential to analyse weaknesses or advantages and the model's potential for use as a virtual network for evacuation planning. Future research should review the performance of these two solvers and compare the results with the standard model and with different types of tesselation, especially the triangle and grid models.

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