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The Application of the Shortest Path and Maximum Flow with Bottleneck in Traffic Flow of Kota Kinabalu

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Abstract: Urban mobility problems such as traffic flows that cause traffic congestions have become a global transportation problem. Traffic congestion happens as traffic volume exceeds the capacity of an existing road facility. The occurring traffic congestion is due to freedom of owning private vehicles, poor traffic facilities and unrestricted urban population growth. In this study, the identification of maximum flow, the bottleneck path and the shortest path were carried out. The scope of this study is a network from Bandaraya Mosque to Kampung Air in Kota Kinabalu. All the possible routes from source to sink were selected. Traffic volume data were collected by manual traffic count with video recordings. Distance data were collected from the Google Earth Software. Directed network graphs were formed with all the obtained data. The maximum flow problem was solved by using Ford-Fulkerson Algorithm to find the maximum flow. The identification of bottleneck path was done by using the max-flow and min-cut theorem. Besides, the shortest path was determined by Dijkstra's Algorithm. Next, the maximum flow and the shortest path problem was formulated using linear programming, and then was solved by using excel solver in Microsoft Excel. The results obtained would allow the traffic engineers to decide which roadway facilities should be improved. Drivers can also refer to these results to choose the desired alternative paths for their journeys.

Keywords: traffic congestion, capacity, maximum flow, bottleneck, shortest poath.

1. Introduction

Traffic congestion has become a major urban transportation problem worldwide. This occurs when the number of traffic items has exceeded the capacity of existing road facilities. Besides affecting the economic productivity, traffic congestion also affects the environment and the overall quality of life for many people. Possible reasons of congestions may be due to slow improvement of traffic facilities, unrestricted private car owning and behavior of drivers on road. Traffic congestion can be categorized into two types, namely, recurring congestion and non-recurring congestion. Recurring congestion occurs especially in peak hours of weekdays, and they usually happen in the area of Central Business District (CBD). Non-recurring congestion is an unexpected congestion due to accidents, sudden road closures, and maintenance which will slow the traffic flow. Moreover, non-recurring congestion is a troublesome traffic problem because it is unpredictable. The happening of the non-recurring congestion causes the temporary reduction of roadway capacity [1].

The traffic volume and distances are collected to form the network graph. After the capacitated network is formed, the maximal flow will be computed using the Ford-Fulkerson algorithm, and will be followed by the max-flow and min-cut theorem to find the bottleneck path of the network [2]. Weighted network graph is formed to find the shortest path, while bottleneck path limits the maximum flow of a network. The identification of the shortest path is carried out using the Dijsktra's algorithm. An alternative path with the shortest distance and high maximum flow with bottlenecks can thus be identified.

As reported by the Borneo Post, World Bank had highlighted the increasing congestion and transportation issues in Kota Kinabalu as a major economic hindrance [3]. The decrement of road capacity will result in the decrease of maximal traffic flow and the speed of traffic vehicle will drop dramatically. The scope of this study is a network from Bandaraya Mosque in Kota Kinabalu (source node) to Kampung Air (sink) where all the routes between source and sink node are established. The routes between Bandaraya Mosque and Kampung Air are selected because this area is part of a central business district for Kota Kinabalu where the demand of traffic is higher than the other locations. Hence, this study aspires to find the maximum flow of the desired route as well as its bottleneck, and also to determine the shortest path to reach a selected destination.

2. Literature Review

A study [4], presented an applied minimum-cut maximum-flow using cut set of a weighted graph on the traffic flow network. A capacitated graph is a resulting graph with a real number of capacity which serves as a structural model in transportation. The traffic control strategy of minimal cut and maximum flow is to minimize number of edges in network and maximum capacity of vehicles which can move through these edges. With a minimal cut in traffic network, it allows to minimize the waiting time of traffic participants for a smooth and uncongested traffic flow.

As presented in one study [5], there are some empirical methods to estimate the capacity on Indian urban roads. Two main types of capacity estimation were Direct Empirical Methods and Indirect Empirical (Simulation) Methods. Due to the complexity and high traffic volume on Indian urban roads, it was appropriate to use direct empirical method for capacity estimation. By using direct empirical methods, the observed traffic data like Headway, volume and speed were needed. In direct empirical method, three approaches were suggested which were Headway method, Observed volume method and Fundamental diagram method. From the results of this study [5], the headway method was able to achieve a high accuracy of capacity estimation by comparing all the three approaches.

Based on another study [6], the maximum flow problem in Ethiopian Airlines was investigated. This paper mainly studied the maximum flow problem and solution algorithm which was Ford and Fulkerson algorithm. By using Ford-Fulkerson algorithm, different number of augmenting paths, and flow of augmenting path might be different, but the obtained maximum flow value was the same. It meant that the solution of the maximum problem could have different augmenting path and different number of augmenting path, but the maximum flow value was unique.

The maximum flow in road networks with speed dependent capacities application to Bangkok traffic was studied in another investigation [7]. A traffic maximum flow problem had arcs represented as capacity of road (maximum vehicles per hour) that were functions of the traffic speed (kilometer per hour) and traffic density (vehicles per kilometer). To estimate road capacities for a given speed, empirical data on safe vehicle separations for a given speed were used. A modified version of the Ford-Fulkerson algorithm was developed to solve maximum flow problems with speed-dependent capacities, with multiple source and target nodes. It was found that the maximum safe traffic flow occurs at the speed of 30 km/hr.

A case study [8] was presented for method of path selection in the graph. Dijkstra's algorithm was used in this paper to find additional paths among nodes in the maritime sector. The shortest path was not always the best alternative path because it involved single criterion. Hence, other parameters were calculated such as the average time, number of indirect vertices, and the safety factor. The method in selecting one desirable path from several paths was multi-criteria decision making. Dempster-Shafer theory was a method that could be applicable to a fused data and combination of evidences.

3. Methodology

3.1 Network Graph

Network is formed with paths that are connected with points. Capacitated network graph and weighted network graph are needed in this study to get the shortest path and maximal flow. First, a capacitated network graph was formulated with all the edges. Each of the edges has a non-negative capacity, $c(u,v) \geq 0$ and flows $f(u,v)$ that cannot be more than capacity of the edge. The source node, s and sink node, t of a network are starting point, and ending point respectively. A capacitated network must fulfill the conditions below: First, the capacity constraint, $\forall (u,v) \in E\ f(u,v) \leq c(u,v)$ which flow of the edges must not exceed its own capacity. Then, the next condition is skew symmetry, $\forall u,v \in V, f(u,v) = -f(v,u)$ which net flow from u to v and from v to u must be opposite to each other. Lastly, flow conservation constraints, $\forall u \in V: u \neq s\ and\ u \neq t => \sum_{(s,u)\in E} f(s,u) = \sum_{(v,t)\in E} f(v,t)$ is the net flow to a node is zero except source node and sink node and the flow from the source node must be equal to the flow at the sink node. Weighted network graph is a network graph that is formulated by the edges with the non-negative distances. It is almost the same as the capacitated network graph [9].

3.2 Ford-Fulkerson Algorithm

Maximal flow in a capacitated flow network is the total flow from a source node to a sink node. First, find an augmenting path from the source node to the sink node. After the formation of augmentation path, compute the bottleneck capacity. Lastly, augment each edge and the total flow until the capacity of sink node reaches maximum [10].

3.3 Dijkstra's Algorithm

First, assign to every node a tentative distance value. Then, label starting node with zero, and to infinity for all other nodes. Set starting node as temporary, and mark other nodes as unvisited nodes. For the temporary node, choose the unvisited arcs that are connected to the starting node with the least value. Mark the temporary node as visited as all the neighbors of the temporary node are considered. Temporarily label all the nodes that are connected to the permanent labelled nodes with the distances from starting node. Choose the temporary label of the least value. Repeat the steps until the destination node has a permanent label [11].

3.4 Maximum Flow and Minimum Cut Theorem

The minimum capacity of an (s,t)-cut is equal to the maximum value of a flow.

$$\max\{val(f) \mid f\ is\ a\ flow\} =$$
$$\min\{cap(S,T) \mid (S,T) is\ an\ \{s,t\} - cut\}$$

3.5 Capacity Estimation: Direct Empirical Method

There are different methods to estimate the roadway capacity. Basically, it can be categorized into two types which are direct empirical method and indirect empirical method. The needed data for the method just mentioned are roadway width, traffic volume, headway, speed and density. The direct empirical method makes use of observed data to estimate the capacity directly. For indirect empirical method, it is a method that makes use of simulation software to get the estimated capacity. Therefore, the direct empirical method was selected to apply in this study because it was an easy performing method that leads to high accuracy results. Direct empirical method can be volume approach, fundamental diagram approach and headway approach [12]. Volume approach was selected in this study instead because it would be a direct and easy method to be done regarding the scope of this study.

3.5.1 Capacity Estimation: Direct Empirical Method (Volume Approach)

Volume approach takes peak hour data and uses the Selected Maxima Model to estimate the capacity. The flows in each 5-minute interval for different composition of vehicles were extracted. The capacities were calculated in equivalent Passenger Car Unit (PCU) based on the recommended value by [13]. Among 5-minute intervals in one peak hour, one of the 5-minute intervals with maximum flow was identified. The obtained peak hour rate of 5-minute intervals was multiplied by a factor 12 to get the estimate capacity flow per hour.

4. Data Collection

In this study, traffic volume and distances as two types of data were collected. Traffic volume can be collected by two main methods. It could be either manual traffic count or automatic traffic count. Manual traffic count would take the least cost, but required more manpower. On the other hand, automatic traffic count could achieve a high accuracy result, but would cost higher than the manual count method. Manual traffic count was selected in this study because it was considered as one of the user friendly methods [14].

Traffic volume was collected through manual traffic count method by using a camera. The camera was placed on a tripod stand, at a higher place to get a clearer view. The paths between Bandaraya Mosque and Kampong Air were selected for video shots. Videos were recorded in the evenings at peak hours from 5 pm to 6 pm. The video clips were reviewed to do manual counting in order to get the actual traffic volume. The collected traffic volume was categorized into the different compositions of traffic vehicles which were motorcycle, car, bus or truck and medium goods vehicle or heavy goods vehicle respectively. Besides, distances were needed in this study to form the weighted network graph. The distances data were collected from the Google Map. The distances can be obtained by entering the address of a starting point and a destination using the link on Google Map.

Table 1: Passenger Car Unit (PCU) value for Urban Road

Class of vehicles	Urban Road PCU value
Car, Taxi, Light Goods Vehicle (LGV)	1.00
Motorcycle, Scooter	0.75
Medium Goods Vehicle (MGV) or Heavy Goods Vehicle (HGV)	2.00
Bus, Truck	3.00

In Table 1, the PCU values for different categories of vehicle were displayed by referring to the Urban Traffic System [15]. The estimation of capacity by the volume approach was making use of Passenger Car Unit (PCU) value in Table 1. Table 2 showed the composition of traffic so as to calculate the total capacity of the selected locations in PCU values.

In Table 3, the maximum flows for 5-minute intervals in PCU were obtained from the multiplication of number of vehicle with PCU values. Total capacity in PCU was computed by taking the Max Flow in 5 Minutes in PCU and multiplied it to the factor of 12.

Table 2: Composition of Traffic (Max Flow in 5 minutes interval)

No	Location name	From	To	Car	Motorcycle	MGV & HGV	Bus & Truck
1	Jalan Tun Fuad Stephen 1	s	V_1	171	39	7	6
2	Jalan Pasir	s	V_2	114	18	9	10
3	Jalan Tun Fuad Stephen 2	V_1	V_5	173	32	10	1
4	Jalan Tuaran 1	V_2	V_3	162	28	11	5
5	Jalan Kompleks sukan and Jalan Bunga Nasar	V_3	V_4	114	5	2	3
6	Jalan Kompleks sukan and Jalan Bunga Nasar	V_4	V_3	56	11	3	0
7	Jalan Istiadat	V_4	V_1	58	15	2	3
8	Jalan Istiadat	V_1	V_4	50	8	3	3
9	Jalan Tuaran 2	V_3	V_6	130	19	3	2
10	Jalan K.K Bypass	V_5	V_7	90	18	2	3
11	Jalan Tuaran 3	V_6	V_9	169	13	19	5
12	Jalan Tunku Abdul Rahman 1	V_7	V_8	57	20	2	3
13	Jalan Tunku Abdul Rahman 2	V_8	V_9	62	12	3	6
14	Jalan Kemajuan	V_9	V_{10}	153	32	8	6
15	Jalan Laiman Diki	V_7	t	91	21	4	2
16	Jalan Coastal	V_{10}	t	81	9	4	0

Table 2 depicted the number of vehicles in one of the 5-minute maximum flow intervals which were counted and categorized into different compositions as in one of studies.

Table 3: Capacity estimation of selected locations (5 min time slice) using Selected Maxima Model

Location No	Max Flow in 5 Minutes in PCU	Total Capacity in PCU
1	226.25	2715
2	175.5	2106
3	220	2640
4	242.75	2913
5	130.75	1569
6	70.25	843
7	82.25	987
8	74	888
9	156.25	1875
10	118.5	1422
11	231.75	2781
12	87	1044
13	95	1140
14	211	2532
15	120.75	1449
16	95.75	1149

Table 4: Distance of the branches from Bandaraya Mosque to Kampung Air

Location name	From	To	Distance (km)
Jalan Tun Fuad Stephen 1	s	V_1	1.5
Jalan Pasir	s	V_2	0.63
Jalan Tun Fuad Stephen 2	V_1	V_5	2.3
Jalan Tuaran 1	V_2	V_3	2.4
Jalan Kompleks sukan and Jalan Bunga Nasar	V_3	V_4	1.22
Jalan Kompleks sukan and Jalan Bunga Nasar	V_4	V_3	1.22
Jalan Istiadat	V_4	V_1	0.8
Jalan Istiadat	V_1	V_4	0.8
Jalan Tuaran 2	V_3	V_6	2.4
Jalan K.K Bypass	V_5	V_7	1.6
Jalan Tuaran 3	V_6	V_9	0.72
Jalan Tunku Abdul Rahman 1	V_7	V_8	0.65
Jalan Tunku Abdul Rahman 2	V_8	V_9	0.2
Jalan Kemajuan	V_9	V_{10}	0.49
Jalan Laiman Diki	V_7	t	0.34
Jalan Coastal	V_{10}	t	0.84

Table 4 showed the distances for the selected routes that were obtained from the Google Earth Software. The data in Table 4 were used to form a weighted and capacitated directed network graph as shown in Figure 1 and Figure 2 respectively.

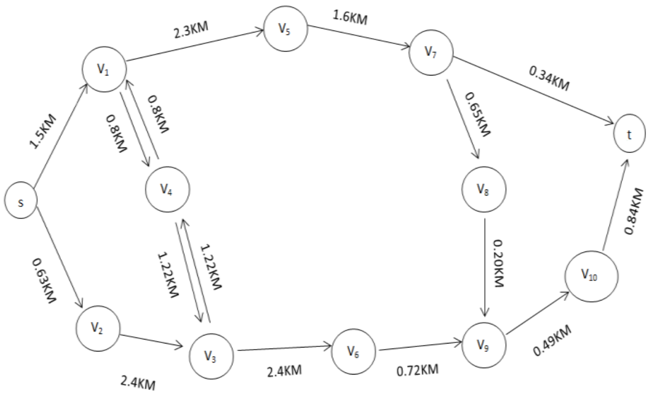


Figure 1: Weighted directed network graph from Bandaraya Mosque to Kampung Air

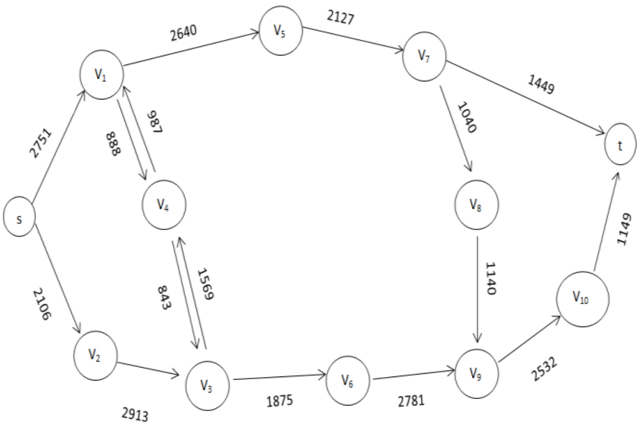


Figure 2: Capacitated directed network graph from Bandaraya Mosque to Kampung Air

5. Results

5.1 Results of Shortest Path Problem Using Dijkstra's Algorithm

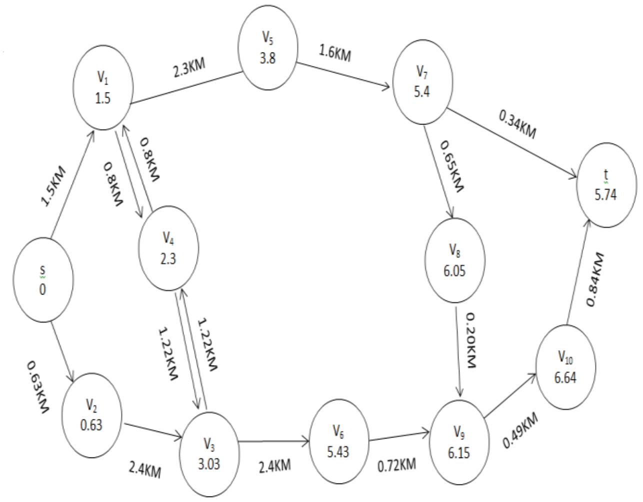
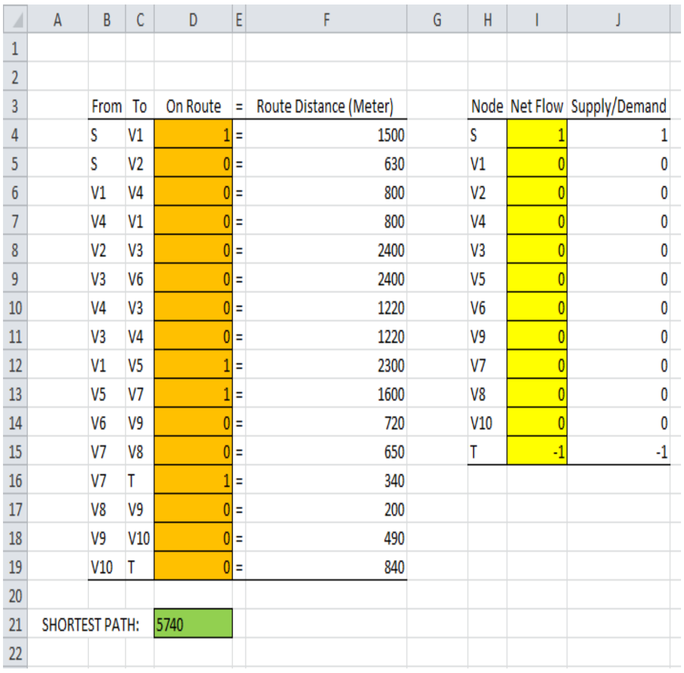


Figure 3: Result of Dijkstra's Algorithm

From Figure 3, the shortest path in this weighted network wss $s \rightarrow V_1 \rightarrow V_5 \rightarrow V_7 \rightarrow t$. It was about 5.74 km from the Bandaraya Mosque to Kampung Air.

5.2 Results of Shortest Path Problem Using Excel Solver (Simplex Linear Programming)



From	To	On Route	=	Route Distance (Meter)	Node	Net Flow	Supply/Demand
S	V1	1	=	1500	S	1	1
S	V2	0	=	630	V1	0	0
V1	V4	0	=	800	V2	0	0
V4	V1	0	=	800	V4	0	0
V2	V3	0	=	2400	V3	0	0
V3	V6	0	=	2400	V5	0	0
V4	V3	0	=	1220	V6	0	0
V3	V4	0	=	1220	V9	0	0
V1	V5	1	=	2300	V7	0	0
V5	V7	1	=	1600	V8	0	0
V6	V9	0	=	720	V10	0	0
V7	V8	0	=	650	T	-1	-1
V7	T	1	=	340			
V8	V9	0	=	200			
V9	V10	0	=	490			
V10	T	0	=	840			

SHORTEST PATH: 5740

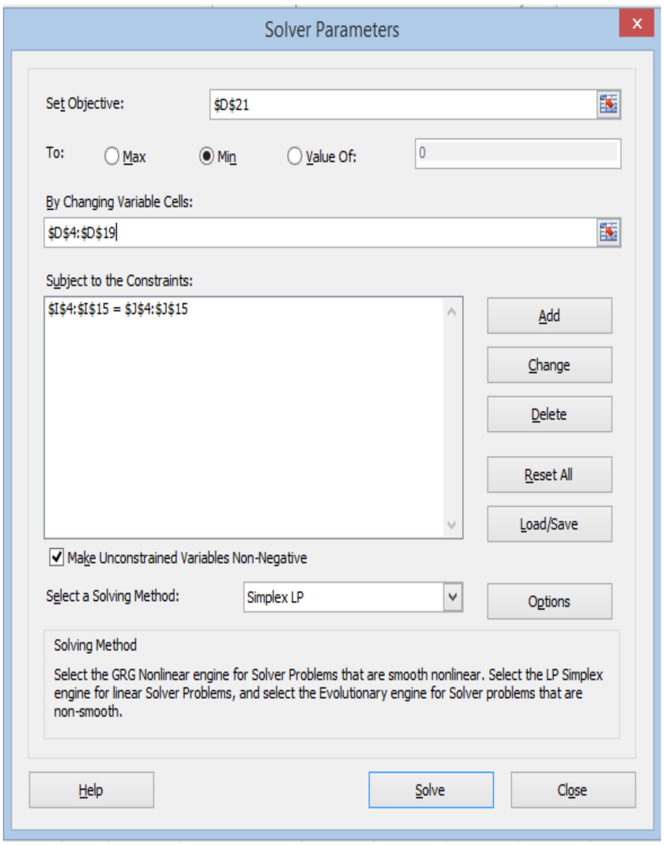
Figure 4: Shortest path problem solved by using simplex linear programming in Microsoft excel

In Figure 4, column F represented the distance of the edge. The objective function was the cell D21 which contained the formula of '=SUMPRODUCT (D4:D19,F4:F19)' as shown in Table 5. The cell from I4 to I15 represented the net flow were the constraints cells. The 'On Route' from cell D4 to cell D19 were the variable cells. The number '1' showed in the column of 'on route' denoted for the route selected, and number '0' denoted for route unselected. Hence, the selected routes for shortest path were from node "s" to V1, V1 to V5, V5 to V7' and 'V7 to t'. In the supply or demand column, that source node, "s" was set as number '1' and the sink node, t was set as number '-1' because both of the nodes were the starting and the ending nodes [16].

Table 5: Formula of the cells in Figure 4

Key Cell Formulas		
Cell	**Formula**	**Copied to**
D21	=SUMPRODUCT(D4:D19,F4:F19)	-
I4	=SUMIF($B$4:$B$19,$H$4,$D$4:$D$19)-SUMIF($C$4:$C$19,$H$4,$D$4:$D$19)	I5:I15

Figure 5 showed the solver parameters for the shortest path problem in Microsoft Excel. First, the cell D21 was set as the Objective. Since the goal was to find the shortest path, therefore the minimum button was chosen in order to minimize the shortest path problem. The changing variable cells were the cells from D4 to D19. Next, the constraints of the Net Flow (cells I4 to I5) must be equal to Supply/Demand (cell J4 to J15). Before clicking on the solve button, Simplex Linear Programming was selected as the solving method. The output of the shortest path by using the excel solver would be the same as the output of the Dijkstra's algorithm in Figure 3.



Set Objective: $D$21

To: ○ Max ● Min ○ Value Of: 0

By Changing Variable Cells:
$D$4:$D$19

Subject to the Constraints:
$I$4:$I$15 = $J$4:$J$15

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: Simplex LP

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Figure 5: Solver parameter for shortest path problem in Excel

5.3 Results of Maximum Flow Problem Using Ford-Fulkerson Algorithm

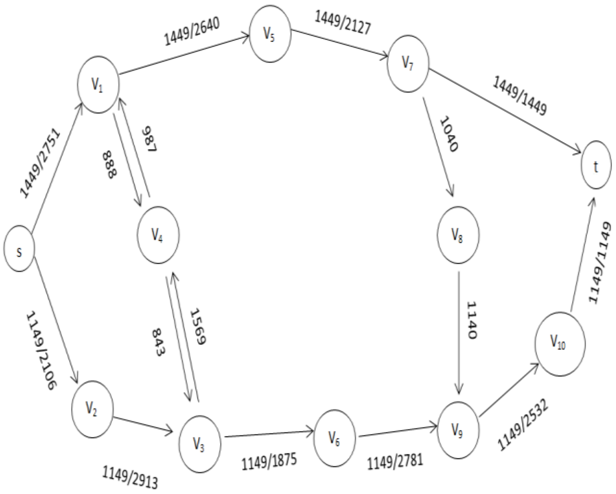
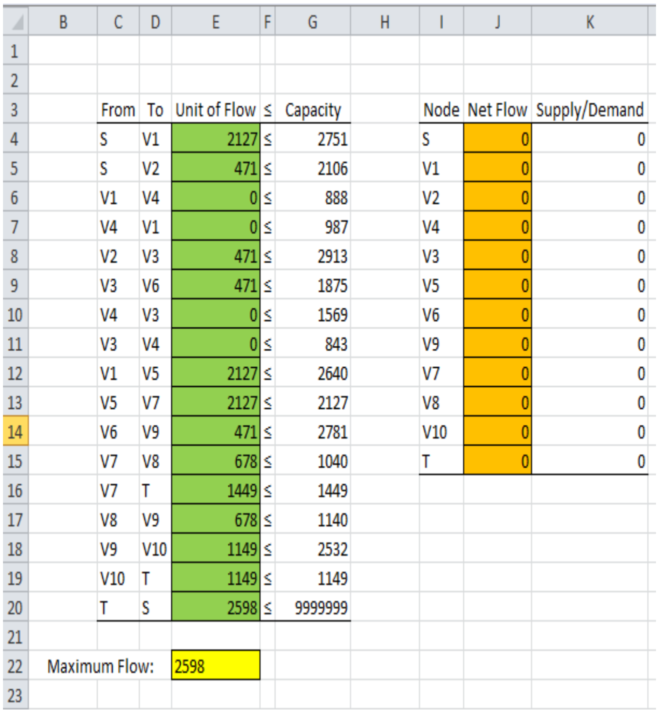


Figure 6: Results of Ford-Fulkerson Algorithm

Figure 6 showed the first route from $s \rightarrow V1 \rightarrow V5 \rightarrow V7 \rightarrow t$ which carried a maximum flow of 1449 vehicles per hour. The second route was from $s \rightarrow V2 \rightarrow V3 \rightarrow V6 \rightarrow V9 \rightarrow t$. The total maximum flow value using the Ford-Fulkerson algorithm was 2598 vehicles per hour.

5.4 Results of Maximum Flow Problem Using Excel Solver



	B	C	D	E	F	G	H	I	J	K
1										
2										
3		From	To	Unit of Flow	≤	Capacity		Node	Net Flow	Supply/Demand
4		S	V1	2127	≤	2751		S	0	0
5		S	V2	471	≤	2106		V1	0	0
6		V1	V4	0	≤	888		V2	0	0
7		V4	V1	0	≤	987		V4	0	0
8		V2	V3	471	≤	2913		V3	0	0
9		V3	V6	471	≤	1875		V5	0	0
10		V4	V3	0	≤	1569		V6	0	0
11		V3	V4	0	≤	843		V9	0	0
12		V1	V5	2127	≤	2640		V7	0	0
13		V5	V7	2127	≤	2127		V8	0	0
14		V6	V9	471	≤	2781		V10	0	0
15		V7	V8	678	≤	1040		T	0	0
16		V7	T	1449	≤	1449				
17		V8	V9	678	≤	1140				
18		V9	V10	1149	≤	2532				
19		V10	T	1149	≤	1149				
20		T	S	2598	≤	9999999				
21										
22	Maximum Flow:			2598						
23										

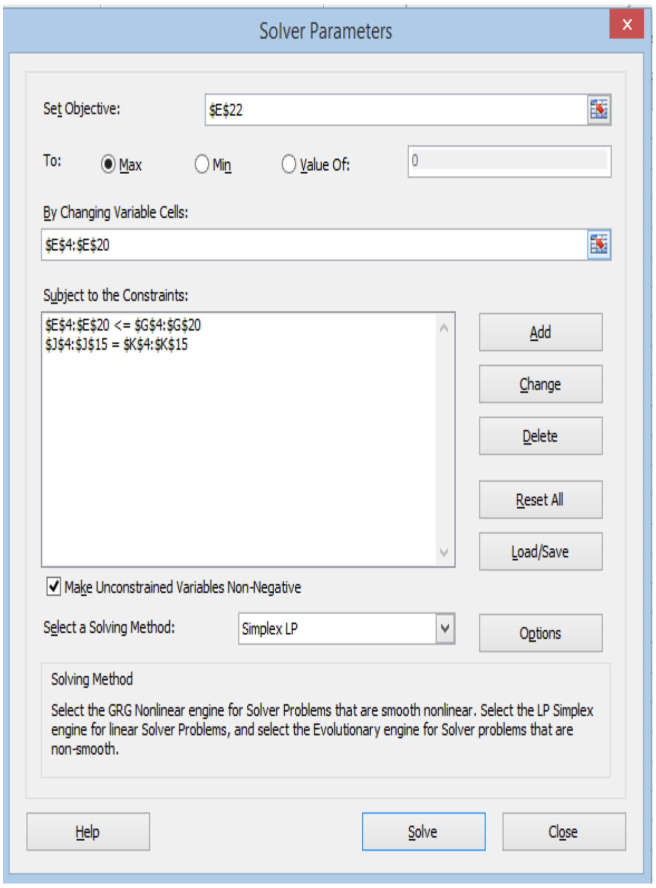
Figure 7: Maximum flow problem solved by using simplex linear programming in Microsoft Excel

In Figure 7, column G represented the capacity for each edge. The objective function was the cell E22 which contained the formula of '=E20'. Cell E20 was the flow from node "t" to node "s". The cell J4 to cell J15 represented the net flow which was the constraints cells, as shown in Table 6. The units of flow, from cell E4 to cell E20, were the variable cells. The unutilized paths were from node V_1 to V_4, node V_4 to V_1, node V_4 to V_3 and node V_3 to V_4 respectively.

Table 6: Formula of the cell in Figure 7

Key Cell Formulas		
Cell	**Formula**	**Copied to**
E22	=E20	-
J4	=SUMIF($C$4:$C$20,$I$4,$E$4:$E$20)-SUMIF($D$4:$D$20,$I$4,$E$4:$E$20)	J5:J15

Figure 8 below shows the solver parameters for the maximum flow problem in Microsoft Excel. First, the cell E22 was set as the Objective. The minimum button was chosen in order to minimize the shortest path problem. The changing variable cells were the cells from D4 to D19. Next, constraints were the Unit of Flow (cell E4 to E20) less than or equal to Capacity (cells G4 to G20) and Net Flow (cells J4 to J15) must equal to the Supply/Demand (cells K4 to K15). Simplex Linear Programming was selected as the solving method. The augmenting path of the maximum flow path by excel solver might not be the same as the augmenting path of the Ford-Fulkerson algorithm as shown in Figure 6. However, the maximum flow value for Ford-Fulkerson algorithm and excel outputs were expected to be the same.


Solver Parameters

Set Objective: $E$22

To: ● Max ○ Min ○ Value Of: 0

By Changing Variable Cells: $E$4:$E$20

Subject to the Constraints:

$E$4:$E$20 <= $G$4:$G$20
$J$4:$J$15 = $K$4:$K$15

☑ Make Unconstrained Variables Non-Negative

Select a Solving Method: Simplex LP

Solving Method

Select the GRG Nonlinear engine for Solver Problems that are smooth nonlinear. Select the LP Simplex engine for linear Solver Problems, and select the Evolutionary engine for Solver problems that are non-smooth.

Figure 8: Solver parameters for maximal flow problem

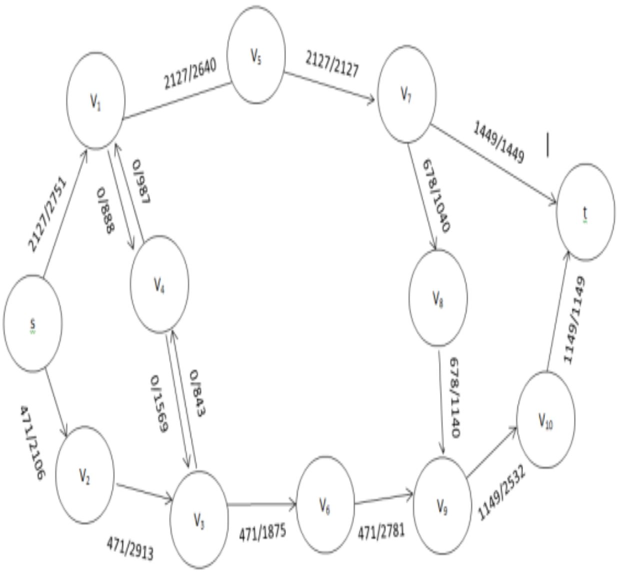


Figure 9: Results of the maximum flow problem using Excel Solver

In Figure 9, the first route from $s \rightarrow V1 \rightarrow V5 \rightarrow V7 \rightarrow t$ carried a maximum flow of 1449 vehicles per hour. The second route from $s \rightarrow V2 \rightarrow V3 \rightarrow V6 \rightarrow V9 \rightarrow t$ carried a maximum flow of 678 vehicles per hour, while the third route from $s \rightarrow V2 \rightarrow V3 \rightarrow V6 \rightarrow V9 \rightarrow V10 \rightarrow t$ carried a maximal flow of 471 vehicles per hour. The total maximum flow value was 2598 vehicles per hour.

5.5 Bottleneck Path using Maximum Flow and Minimum Cut Theorem

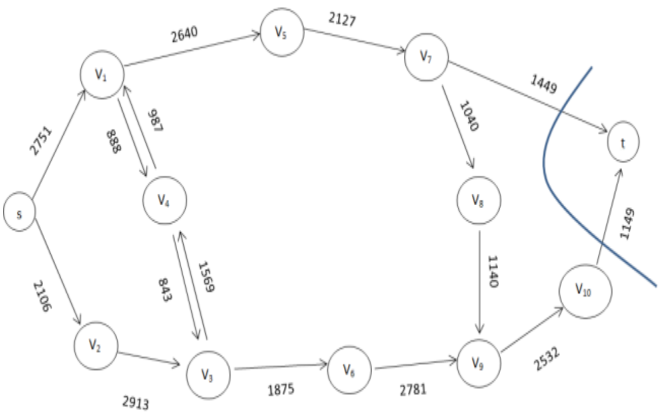


Figure 10: Minimum Cut

The cut capacity was the same as the sum of the capacities of its arcs. Bottleneck capacity was the minimum residual capacity of any edge in the augmenting path. The cut with the smallest capacity gave the maximum flow in the capacitated network. From Figure 10, the blue line denoted the minimum cut with the smallest capacity which was the same as the maximum flow that was computed by the Ford-fulkerson method. The bottleneck routes of the network in Figure 10 were denoted by V_7 and V_{10}, namely Jalan Laiman Diki, and Jalan Coastal respectively.

6. Conclusion

The shortest path in this weighted network was $\rightarrow V_1 \rightarrow V_5 \rightarrow V_7 \rightarrow t$, viz. Bandaraya Mosque=> Jln. Tun Fuad 1=> Jln. Tun Fuad 2=> Jln. KK Bypass=> Jln. Laiman Diki=> Kampung Air, and it took about 5.74 km from Bandaraya Mosque to reach Kampung Air in Kota Kinabalu. The maximum flow was 2598 vehicles per hour, while the bottleneck paths were found to be Jalan Laiman Diki and Jalan Coastal. Thus, with these outputs, traffic planar can make decisions on the bottlenecks, and traffic drivers can avoid this respective traffic congestion routes, and reach their respective selected destinations in a shorter time.

Acknowledgement

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