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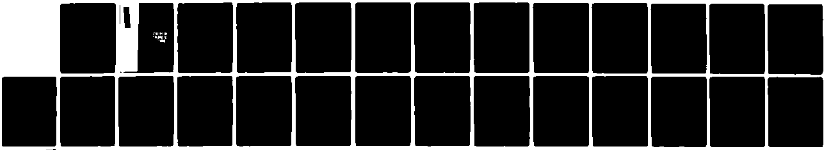

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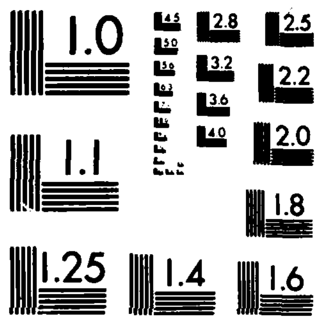

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Research Report CCS 455

A NETWORK MODEL FOR PLANNING INTERNAL MOVEMENTS IN THE HAJJ

by

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Abstract

This paper develops a dynamic capacitated network model for planning the movements of pilgrims in the Hajj, one of the world's largest mass movements, according to religious ritual. The model develops a scheduling plan in order to minimize traffic congestion and the overcrowding of the holy sites. The model is effective in producing background for general policy decisions for the Hajj transportation.

Key Words: Dynamic capacitated network model, goal programming, Hajj, pilgrims, policy analysis.

A NETWORK MODEL FOR PLANNING INTERNAL MOVEMENTS IN THE HAJJ

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1.0 Introduction

The purpose of this paper is to identify issues in the Hajj internal transportation network and model the situation in order to draw general policy decisions in management of this unique situation. The most important constraints in this case are the religious ones, actually they define the transportation and the movement of the people from one place to another. Any model must reflect these constraints in order to be implementable. These religious constraints are represented as time and space constraints. A temporal capacited network is developed to represent the situation, with the objective to minimize congestion of traffic on roads and overcrowding of the holy places. This objective is chosen to enable the visitors to perform their duties as easily as possible.

In section 2 we describe the Hajj situation briefly, and in section 3 we identify issues to be considered in the modeling process. In section 4 we develop the model, and in section 5 we present a numerical example and the conclusion of this paper.

2.0 Description of the Hajj

The Hajj is an annual meeting for about two million Muslims to achieve one of the five pillars of Islam. The Hajj involves several visitations to several holy sites and it occurs every 354 days, since it is dated by the Islamic Lunar year. The Hajj process in this paper will be divided into three phases. Phase one mainly consists of air and sea transportation of foreign population to Jeddah, and also inland transportation of foreign and native population. The duration of this phase is up to the eighth of the last month of the Lunar year, by that time all the pilgrims have gathered in one of the following towns: Jeddah, Makkah, Muna or Medina.

Phase two starts from the morning of the eighth of the last month in the Lunar year up to the end of the Hajj and the arrival of the pilgrims at the ports to leave for home. This phase includes part of the in-land transportation from Jeddah and Medina to Makkah and all the movement between the holy sites up to the completion of the Hajj. Its duration is roughly up to the nineteenth or the twentieth of the month. Phase three consists partly of the transportation between Makkah and the ports. It also includes the departure of all prilgrims for home. In this paper we deal with phase two and that what we call internal transportation network of the intramovement of the pilgrims and this phase constitutes the whole Hajj process.

2.1 Phase Two of the Hajj

This phase starts by the morning of the eighth of the last month of the Lunar calendar year. By this time all pilgrims are either at Makkah, Muna, Jeddah, or Medina. Before arriving at Makkah every pilgrim has to wear the garment of iharm (restriction)--forbidden to hunt, argue, cut their hair, clip their nails, or engage in any sexual activities. At reaching Makkah 45 miles east of Jeddah (see diagram in Figure 1), each pilgrim has to make a greeting tawaf, the prescribed seven counterclockwise circumambulations of the Kaaba. Then they perform the Sa'y--making seven trips between the hills of Safa and Marwah enclosed in a long gallery. Also on the eighth day of Dihu'L-Hijjah (the twelfth and final month of the Muslims' Lunar calendar), pilgrims move to Muna four miles east of Makkah (see Figure 1) for the essential final days of the Hajj. The next day everybody has to be at Arafat another eight miles east of Muna, so as to perform the Standing, the central ritual of the Hajj. The duration of the Standing is from noon until sunset.

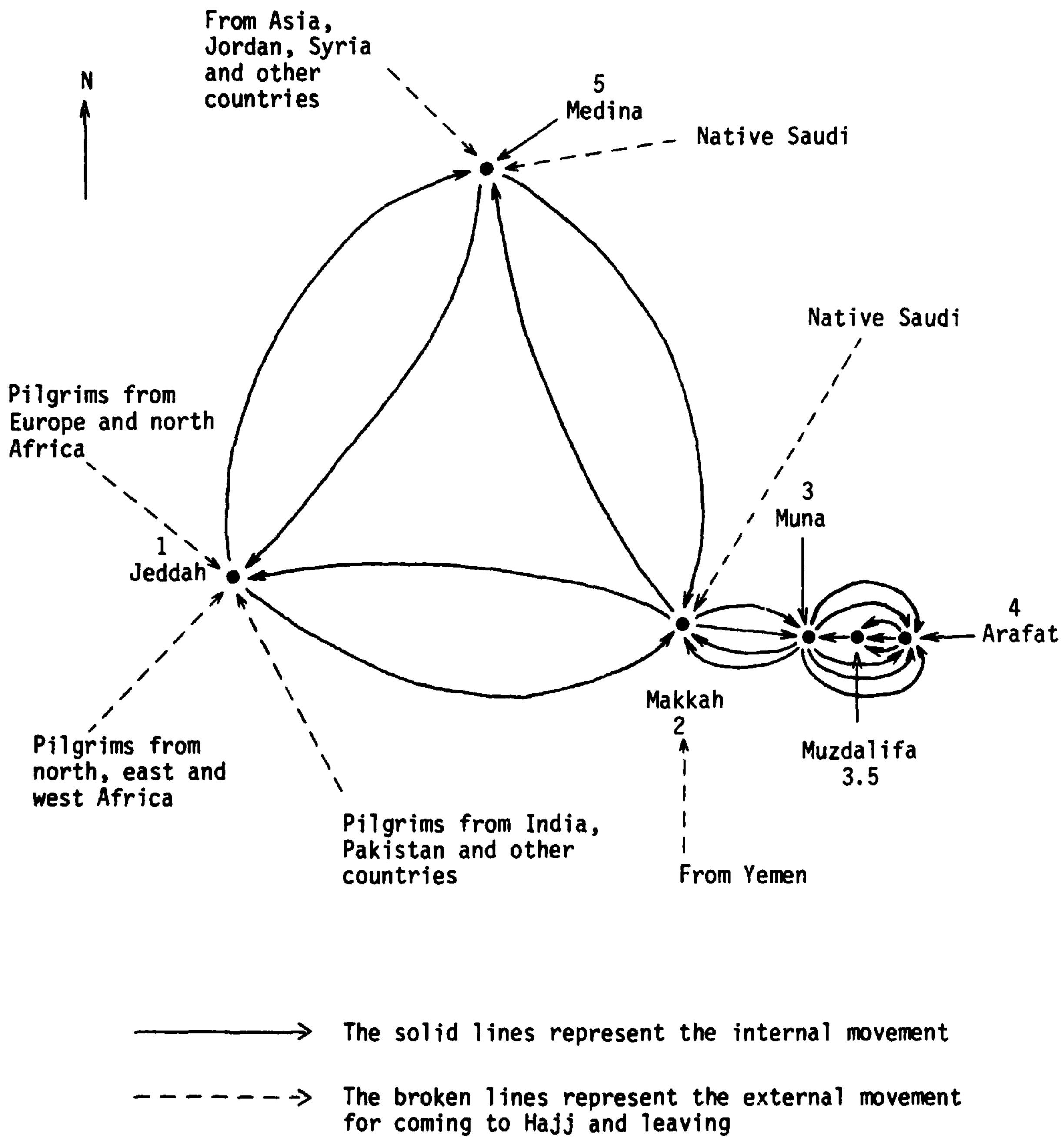
It does not matter when a pilgrim arrives early or late during the 70-day pilgrimage season (which begins annually with the start of the tenth month of the Muslim Lunar Calendar). Most pilgrims spend the eve of the ninth day in Muna and the rest will be in Makkah preparing to leave early in the morning for Arafat to perform the Standing. Everyone has to be in Arafat from noon until sunset on the ninth.

On the eve of the tenth, the pilgrims leave Arafat and stop at Muzdalifa, a place between Muna and Arafat. At Muzdalifa they collect pebbles to throw at the three "Satan's stonning points" in Muna during the following days. These points symbolize the force of evil. Some pilgrims go to Makkah at the same night others stay at Muna. Those who leave for Makkah start doing one of the pillars of the Hajj Tawaf El ifada, the post-Arafat tawaf done in the same manner as the greeting tawaf. After finishing this tawaf pilgrims can put off iharm (restriction) and return to Muna to finish the Stonning of the devil. Most people stay in Makkah or come to Makkah in the morning of the tenth to join the 'Id prayer. Then pilgrims sacrifice and return to Muna to finish the Stonning of the devil. After finishing the Stonning, the Hajj is complete.

All pilgrims after the Hajj perform a farewell tawaf and some of them leave for Medina to visit the prophet grave. Visiting Medina can be done before the Hajj starts and those who did it before the Hajj leave to Jeddah or by inland routes for home. Figure 1 shows all the holy sites and the routes of the pilgrims' movements.

Figure 1

A Diagram for the Islamic Holy Sites and the Flow of Pilgrims



3.0 Issues to be Considered in the Model

The most important element here is the timing and place of each of the holy practices. This determines the flow of people from one place to another. We notice from section two that there is some flexibility in the timing of most of the pillars of the Hajj. The model must take full advantage of that in order to make the Hajj as smooth as possible.

When the pilgrims travel to Makkah they are in large numbers and there is overcrowding of the roads which lead to Makkah. On arrival at Makkah they perform the greeting tawaf and they need some scheduling to ease overcrowding at the Kaaba.

The central ritual of the Hajj is the Standing at Arafat and this is a large place and can take all the pilgrims, but on the way to and from Arafat happens the big crunch. Then the people shuttle between Makkah and Muna until they finish their Hajj.

In scheduling events in the Hajj, the following must be noted. First the greeting tawaf can be done any time before the morning of the ninth of the Hajj month; and the post-Arafat tawaf can be performed at any time from the eve of the tenth to the evening of the twelfth of the Hajj month, but most people like to do it earlier to finish their Hajj. Secondly, the Stonning of the Satan's can be done in two or three days, i.e., from the tenth up to the twelfth of the Hajj month. Third, the Sacrifice of the sheep can be done any time from the morning of the tenth until the evening of the twelfth, but most people do it on the tenth. Fourth, everybody catches the 'Id prayer at the Sacred Mosque on the morning of the tenth. Fifth, the farewell tawaf can be done any time before leaving Makkah. Sixth, the visitation to Medina can be done before or after the Hajj and there is no time constraints on it.

A model should take advantage of the flexibility in the timing of the Hajj rituals, but also give a room to the pilgrims' preferences in choosing the time to do the rituals in order for the model to have any chance of being implemented.

4.0 Statement of the Model

4.1. The Constraints Set

The following is the constraints set of the Hajj internal movement as shown in Figure 2. Figure 2 represents movements of pilgrims by half-day from the eighth of the Hajj month till the nineteenth. Each half a day is considered as a period, so the model consists of twenty-four periods. We think half a day is a reasonable period for general policy decisions, but for close monitoring of the pilgrims' movements the model can be represented in terms of shorter periods, i.e., in terms of one hour period. This will expand the model, but since the model is of network type, it can be solved easily.

Figure 2 gives a complete representation of the Hajj internal movements. There are two sets of arcs in Figure 2, one set represents movement of pilgrims within periods, the other set represents pilgrims who are staying in the same town for the next period.

The upper bounds on the arcs in the model should be considered very closely and the following considerations would be very useful:

(1) the time of the period evening or morning,

(2) the lodging capacity of each town,

(3) the food and public facilities of each location,

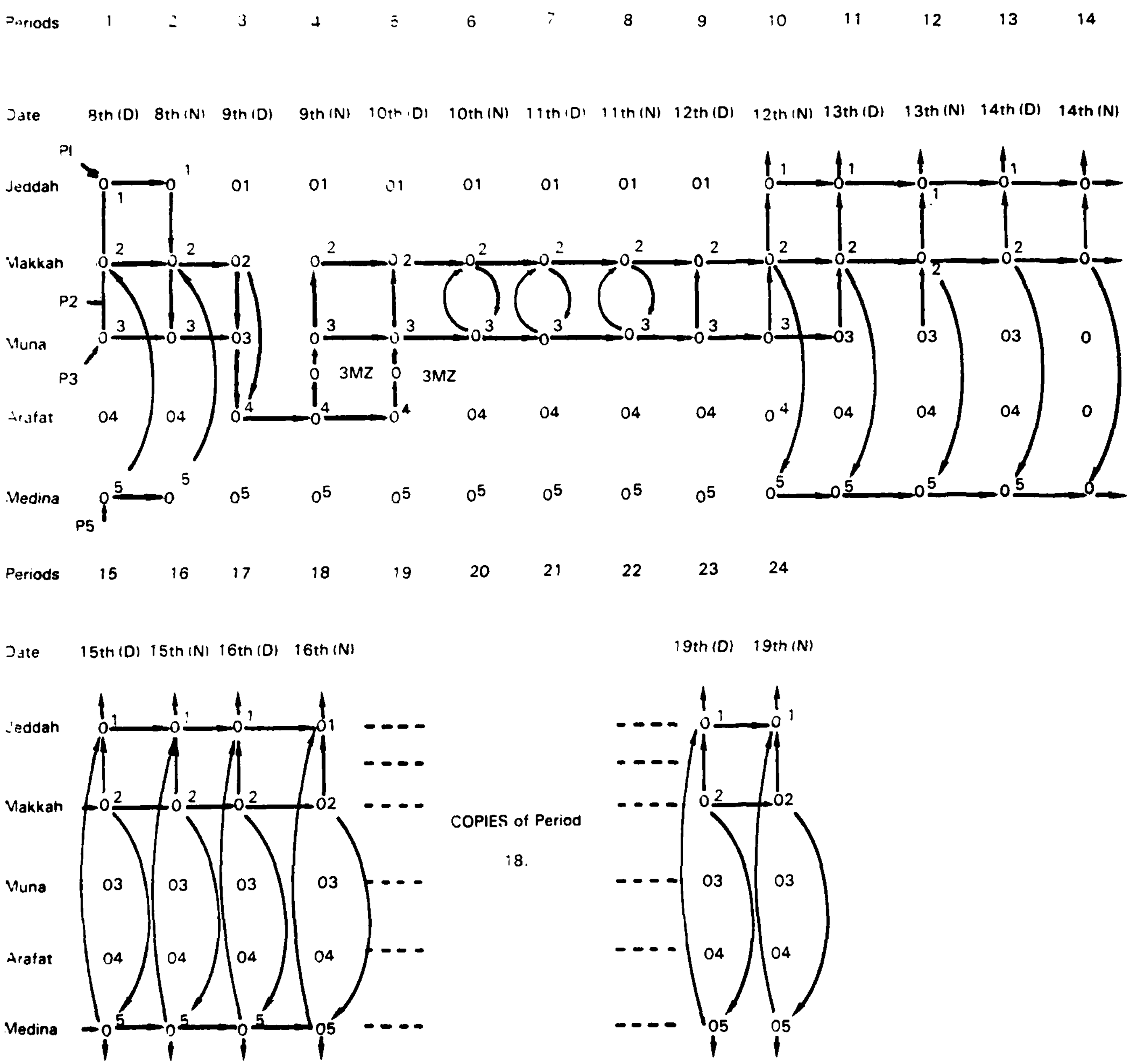
(4) the health facilities,

(5) the availability of buses, cars, between any two towns on each route, and

(6) the timing of each ritual.

FIGURE 2

NETWORK REPRESENTATION For THE HAJJ Internal MOVEMENT Each Half A day is A period



1 ≡ represent Jeddah. 2 ≡ represent Makkah. 3 ≡ represent Muna. 4 ≡ represent Arafat.

5 ≡ represent Medina. 3MZ ≡ represent Mozdalifa

D = Day. N ≡ Night

Let

$x_{ij}(t)$ = number of pilgrims going from location i to location j in period t;

$y_i(t,t+1)$ = number of pilgrims staying at location i during period t;

[In this case, we do not consider cross traveling between periods from one site to another, since travel time of one-half day is more than sufficient to get between any two sites and also the flexibility of rituals timing allow that, but the model can handle that.]

K_{ij} = the maximum number of pilgrims who can travel easily at day times from location i to location j, i.e., this is the capacity of route (i,j)

L_{ij} = the maximum number of pilgrims who can travel easily at night time on route (i,j)

L_i = lodging capacity of town i,

K_i = food capacity of town i,

b_i = the minimum of the public facilities' capacities at town i.

Let 1 be Jeddah, 2 be Makkah, 3 be Muna, 3.5 be Muzdalifa , 4 be Arafat, and 5 be Medina.

P_i = number of pilgrims at town i at the beginning of the first period.

The following are the equations defined by the network in Figure 2. The numbers to the left of the equations represent the period and the node, i.e., 1.5 represent the equation for period one at node 5, or the equation for period one at Medina and so on.

	$x_{12}(1)$	$x_{23}(1)$	$x_{52}(1)$	$y_1(1,2)$	$y_2(1,2)$	$y_3(1,2)$	$y_5(1,2)$	$x_{12}(2)$	$x_{23}(2)$	$x_{52}(2)$	$y_1(2,3)$	$y_2(2,3)$	$y_3(2,3)$	$y_5(2,3)$	
1.1	1			1											$= P_1$
1.2	-1	1	-1		1										$= P_2$
1.3		-1				1									$= P_3$
1.4															$= P_4$
1.5			1				1								$= P_5$
2.1				-1				1			1				= 0
2.2					-1			-1	1	-1		1			= 0
2.3						-1			-1				1		= 0
2.4															= 0
2.5							-1			-1				1	= 0

Part of period 3 is on the next page.

	$x_{12}(1)$	$x_{23}(1)$	$x_{52}(1)$	$y_1(1,2)$	$y_2(1,2)$	$y_3(1,2)$	$y_5(1,2)$	$x_{12}(2)$	$x_{23}(2)$	$x_{52}(2)$	$y_1(2,3)$	$y_2(2,3)$	$y_3(2,3)$	$y_5(2,3)$	
3.1											-1				→
3.2												-1			→
3.3													-1		→
3.4															→
3.5														-1	→

The arrow means the equations are completed on the next page.

Equations for period 3, 4 and part of period 5. Notice period 3 has some variables on the previous period

	$x_{23}(3)$	$x_{24}(3)$	$x_{34}(3)$	$y_2(3,4)$	$y_3(3,4)$	$y_4(3,4)$	$x_{32}(4)$	$x_{4\ 3.5}(4)$	$x_{3.5\ 3}(4)$	$y_2(4,5)$	$y_3(4,5)$	$y_{3.5}(4,5)$	$y_4(4,5)$	
3.1														= 0
3.2	1	1		1										= 0
3.3	-1		1		1									= 0
3.3.5														= 0
3.4		-1	-1			1								= 0
3.5														= 0
4.1														= 0
4.2				-1			-1			1				= 0
4.3					-1		1		-1		1			= 0
4.3.5								-1	1			1		= 0
4.4						-1		1					1	= 0
4.5														

Part of the equations of period 5 and completion of these equations is on the next page.

	$x_{23}(3)$	$x_{24}(3)$	$x_{34}(3)$	$y_2(3,4)$	$y_3(3,4)$	$y_4(3,4)$	$x_{32}(4)$	$x_{4\ 3.5}(4)$	$x_{3.5\ 3}(4)$	$y_2(4,5)$	$y_3(4,5)$	$y_{3.5}(4,5)$	$y_4(4,5)$	
5.1														
5.2										-1				+
5.3											-1			+
5.3.5												-1		+
5.4													-1	+
5.5														+

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Constraints for period 5, 6 and part of period 7:

	$x_{32}(5)$	$x_{4\ 3.5}(5)$	$x_{3.5\ 3}(5)$	$x_{32}(5)$	$y_2(5,6)$	$y_3(5,6)$	$x_{23}(6)$	$x_{32}(6)$	$y_2(6,7)$	$y_3(6,7)$	
5.1											= 0
5.2	-1			-1	1						= 0
5.3	1		-1	1		1					= 0
5.3.5		-1	1								= 0
5.4		1									= 0
5.5											= 0
6.1											= 0
6.2					-1		1	-1	1		= 0
6.3						-1	-1	1			= 0
6.4											= 0
6.5											= 0

Part of the constraints for period 7 and its completion is on the next page.

	$x_{32}(5)$	$x_{4\ 3.5}(5)$	$x_{3.5\ 3}(5)$	$x_{32}(5)$	$y_2(5,6)$	$y_3(5,6)$	$x_{23}(6)$	$x_{32}(6)$	$y_2(6,7)$	$y_3(6,7)$	
7.1											→
7.2									-1		→
7.3										-1	→
7.4											→
7.5											→

Constraints set for period 9, 10 and part of period 11:

	$x_{32}(9)$	$y_2(9,10)$	$y_3(9,10)$	$x_{21}(10)$	$x_{32}(10)$	$x_{25}(10)$	$y_1(10,11)$	$y_2(10,11)$	$y_3(10,11)$	$y_5(10,11)$	
9.1											= 0
9.2	-1	1									= 0
9.3	1		1								= 0
9.4											= 0
9.5											= 0
10.1				-1			1				= 0
10.2		-1		1	-1	1		1			= 0
10.3			-1		1				1		= 0
10.4											= 0
10.5						-1				1	= 0

Part of the constraint set for period 11 and its completion is on the next page.

11.1							-1				→
11.2								-1			→
11.3									-1		→
11.4											→
11.5										-1	→

Constraints set for period 7, 8 and part of period 9:

	$x_{23}(7)$	$x_{32}(7)$	$y_2(7,8)$	$y_3(7,8)$	$x_{23}(8)$	$x_{32}(8)$	$y_2(8,9)$	$y_3(8,9)$	
7.1									= 0
7.2	1	-1	1						= 0
7.3	-1	1		1					= 0
7.4									= 0
7.5									= 0
8.1									= 0
8.2			-1		1	-1	1		= 0
8.3				-1	-1	1		1	= 0
8.4									= 0
8.5									= 0

Part of the constraints set for period 7 and its completion is on the next page.

	$x_{23}(7)$	$x_{32}(7)$	$y_2(7,8)$	$y_3(7,8)$	$x_{23}(8)$	$x_{32}(8)$	$y_2(8,9)$	$y_3(8,9)$	
9.1									→
9.2							-1		→
9.3								-1	→
9.4									→
9.5									→

Equations for period 11, 12 and part of those for period 13:

	$x_{21}(11)$	$x_{25}(11)$	$x_{32}(11)$	$y_1(11,12)$	$y_2(11,12)$	$y_3(11,12)$	$y_5(11,12)$	$x_{21}(12)$	$x_{25}(12)$	$x_{32}(12)$	$y_1(12,13)$	$y_2(12,13)$	$y_3(12,13)$	$y_5(12,13)$	
11.1	-1			1											= 0
11.2	1	1	-1		1										= 0
11.3			1			1									= 0
11.4															= 0
11.5		-1					1								= 0
12.1				-1				-1			1				= 0
12.2					-1			1	1	-1		1			= 0
12.3						-1				1			1		= 0
12.4															= 0
12.5							1		1					1	= 0

Completion of the equations for period 13 is on the next page.

	$x_{21}(11)$	$x_{25}(11)$	$x_{32}(11)$	$y_1(11,12)$	$y_2(11,12)$	$y_3(11,12)$	$y_5(11,12)$	$x_{21}(12)$	$x_{25}(12)$	$x_{32}(12)$	$y_1(12,13)$	$y_2(12,13)$	$y_3(12,13)$	$y_5(12,13)$	
13.1											-1				→
13.2												-1			→
13.3													-1		→
13.4															→
13.5														-1	→

Equations for periods 13, 14 and part of those for period 15:

	$x_{21}(13)$	$x_{25}(13)$	$y_1(13,14)$	$y_2(13,14)$	$y_5(13,14)$	$x_{21}(14)$	$x_{25}(14)$	$y_1(14,15)$	$y_2(14,15)$	$y_5(14,15)$	
13.1	-1		1								= 0
13.2	1	1		1							= 0
13.3											= 0
13.4											= 0
13.5		-1			1						= 0
14.1			-1			-1		1			= 0
14.2				-1		1	1		1		= 0
14.3											= 0
14.4											= 0
14.5					-1		-1			1	= 0

Completion of the equations for period 15 is on the next page.

	$x_{21}(13)$	$x_{25}(13)$	$y_1(13,14)$	$y_2(13,14)$	$y_5(13,14)$	$x_{21}(14)$	$x_{25}(14)$	$y_1(14,15)$	$y_2(14,15)$	$y_5(14,15)$	
15.1								-1			→
15.2									-1		→
15.3											→
15.4											→
15.5										-1	→

Equations for period 15, 16 and part of those for period 17:

	$x_{21}(15)$	$x_{25}(15)$	$y_1(15,16)$	$y_2(15,16)$	$y_5(15,16)$	$x_{21}(16)$	$x_{25}(16)$	$x_{52}(16)$	$x_{51}(16)$	$y_1(16,17)$	$y_2(16,17)$	$y_5(16,17)$	
15.1	-1		1										= 0
15.2	1	1		1									= 0
15.3													= 0
15.4													= 0
15.5		-1			1								= 0
16.1			-1			-1			-1	1			= 0
16.2				-1		1	1	-1			1		= 0
16.3													= 0
16.4													= 0
16.5					-1		-1	1	1			1	= 0

Completion of the equations for period 17 is on the next page.

	$x_{21}(15)$	$x_{25}(15)$	$y_1(15,16)$	$y_2(15,16)$	$y_5(15,16)$	$x_{21}(16)$	$x_{25}(16)$	$x_{52}(16)$	$x_{51}(16)$	$y_1(16,17)$	$y_2(16,17)$	$y_5(16,17)$	
17.1										-1			+
17.2											-1		+
17.3													+
17.4													+
17.5												-1	+

Equations for period 17 and 18:

	$x_{21}(17)$	$x_{25}(17)$	$x_{52}(17)$	$x_{51}(17)$	$y_1(17,18)$	$y_2(17,18)$	$y_5(17,18)$	$x_{21}(18)$	$x_{25}(18)$	$x_{51}(18)$	$x_{52}(18)$	$y_1(18,19)$	$y_2(18,19)$	$y_5(18,19)$	
17.1	-1			-1	1										= 0
17.2	1	1	-1			1									= 0
17.3															= 0
17.4															= 0
17.5		-1	1	1			1								= 0
18.1					-1					-1		1			= 0
18.2						-1		-1			-1		1		= 0
18.3												1			= 0
18.4															= 0
18.5							-1		-1	1	1				= 0

The coming periods 19,20 up to 24 has the same pattern or structure as 18 so we will have just copies of the equations in 18. The following are the capacity constraints on the routes and the holy places.

$0 \leq x_{ij}(t) \leq K_{ij}$ if t is odd

$0 \leq x_{ij}(t) \leq L_{ij}$ if t is even

$0 \leq y_i(t,t+1) \leq \min(L_i,K_i,b_i)$

4.2. Objective Function

One of the objectives to be considered is space and routes utilization. The objective is of goal type to ease crowding as much as possible, i.e.

$$(4.2.1)\quad \text{Max} \sum_i |\min(K_i,L_i,b_i) - y_i(t,t+1)| + \sum_{\substack{t \\ \text{odd}}} \sum_{ij} |K_{ij} - x_{ij}(t)| + \sum_{\substack{t \\ \text{even}}} \sum_{ij} |L_{ij} - x_{ij}(t)|$$

Maximizing this function alone will allow for overcrowding of holy sites and we will be maximizing a convex function, but with the capacity constraints

$x_{ij}(t) \leq L_{ij}$, $x_{ij}(t) \leq K_{ij}$ and

$y_i(t,t+1) \leq \min(K_i, L_i, b_i)$

that will not happen and the objective function will be transformed into the following equivalent linear function.

$$(4.2.2)\quad \text{Min} \sum_t \sum_i y_i(t,t+1) + \sum_t \sum_{ij} x_{ij}(t)$$

Hence the model for the Hajj internal movement will minimize the linear function in (4.2.2) subject to all the constraints in section 4.1.

The above model could be updated if conditions on the routes and the holy sites are changed. It could be formulated in terms of shorter periods for example on an hourly basis if detailed monitoring of the Hajj internal movement is needed.

Another objective function to be considered is

$$\text{Min} \sum_t \sum_{i=1}^{n} |\min(K_i, L_i, b_i) - y_i(t,t+1)| + \sum_{\substack{t \\ \text{odd}}} \sum_{ij} |K_{ij} - x_{ij}(t)|$$

$$+ \sum_{\substack{t \\ \text{even}}} \sum_{ij} |L_{ij} - x_{ij}(t)|$$

This is of a goal type objective and this with the constraints in section 4.1 can be transformed into a larger pure network.

Other objectives and constraints may also need consideration, e.g., the role of individual contractors ("Mutwafeen") may need more explicit consideration.

5.0 Numerical Example and Conclusions

The following example is solved to test the model and to draw general policy conclusions. The example was constructed using [4] a study done by the Hajj Research Center at Jeddah. Using this study and some personal judgement, the following data on road and town capacities is obtained.

Routes capacities:

Routes	Day	Night
Jeddah to Makkah	0 to 200,000	0 to 150,000
Makkah to Muna	0 to 500,000	0 to 400,000
Makkah to Medina	0 to 200,000	0 to 150,000
Makkah to Arafat	0 to 900,000	0 to 700,000
Muna to Arafat	0 to 800,000	0 to 700,000
Muna to Makkah	0 to 250,000	0 to 200,000
Medina to Makkah	0 to 100,000*	0 to 150,000

*when 2-way traffic

Capacity Of	No. of Pilgrims
Jeddah	300,000
Makkah	1,000,000
Muna	600,000
Arafat	2,000,000
Medina	1,000,000

$P_1 = 200{,}000$; $P_2 = 800{,}000$; $P_3 = 400{,}000$; $P_5 = 200{,}000$; $P_4 = 0$

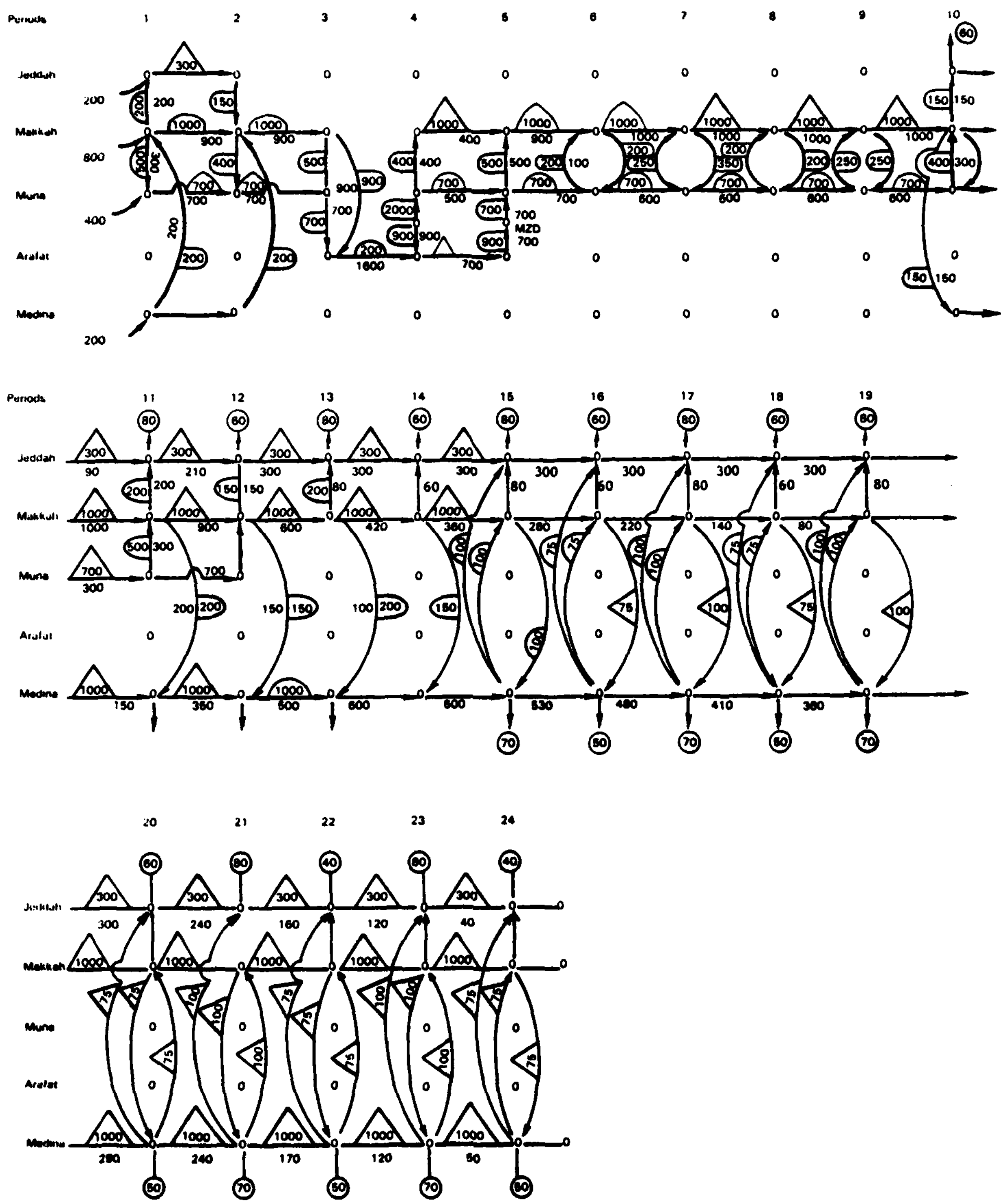
This example was solved and the flows given by the optimal solution is in Figure 3.

We conclude from the model and the above example that it would be possible for the authority to schedule the pilgrims internal movement without overcrowding routes and towns and most important within the religious constraints by which the Hajj is defined. One very important point is to consider the impact of dividing the pilgrims into two groups,one group visiting Medina before the Hajj, the other group after the Hajj. This will ease the transportation in two ways, before and after the Hajj. The model also shows that when the pilgrims leave their departure strictly dependent on the capability of the ports' upgrading. The ports will help in smoothing the Hajj process.

Finally, this "internal" model needs to be extended to include the "external" parts of arrival and departure in more detail. This can be accomplished easily.

FIGURE 3

Optimal Solution of The Example



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Dynamic capacitated network model, goal programming, Hajj, pilgrims, policy analysis.

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This paper develops a dynamic capacitated network model for planning the movements of pilgrims in the Hajj, one of the world's largest mass movements, according to religious ritual. The model develops a scheduling plan in order to minimize traffic congestion and the overcrowding of the holy sites. The model is effective in producing background for general policy decisions for the Hajj transportation.

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