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EMERGENCY EVACUATION ROUTE FOR THE PASSENGER SHIP

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EMERGENCY EVACUATION ROUTE FOR THE PASSENGER SHIP

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Key words: evacuation route, minimum cost flow.

ABSTRACT

Emergency evacuation of a ship becomes an important issue in case of an accident. In order to present the TITANIC incident in 1912 from recurring again, IMO has stipulated International Convention for the Safety of Life at Sea (SOLAS). The main purpose of this study is to find an optimal personnel evacuation route in order to increase personnel's security at sea. Mathematical programming is the research methodology in this study. After formulating the model and exploring different evacuation scenarios, we compare the results from our minimum cost flow model with that of original evacuation plan. Some suggestions are provided.

I. INTRODUCTION

The passenger ship sailing at sea is like an isolating island, if a ship accident happens, it will cause the loss of human lives. In order to prevent the accidents of Titanic, the Estonia and the Herald of Free Enterprise from recurring again, IMO has stipulated international convention for the Safety of Life at Sea (SOLAS), and revised relevant safe specification of personnel evacuation plan for many times in the Maritime Safety Committee (MSC).

Emergency evacuation of a ship becomes an important issue in case of an accident. The investigation of evacuation processes has been originally applied to building. Many studies have been conducted on the evacuation models. The literature on evacuation models can be generally classified into two categories: analytical models and simulation models. Fig. 1 (Bakuli and Smith [1]) gives a snapshot of different ways in which the evacuation problem has been approached or formulated.

In general, the deterministic model is a simple and useful tool for building evacuation. If the evacuation problem is

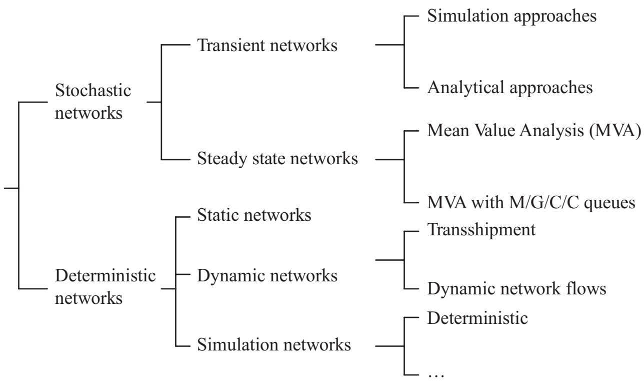

Fig. 1. Morphological diagram of emergency evacuation problem approaches.

formulated by stochastic models, which are more realistic, but also more complex. Major studies to adopt this approach are those of Smith [15, 16] and Lovas [10, 11]. A detailed review for different approaches can be found in Bakuli and Smith's work.

Simulation has been used frequently in emergency evacuation. Weinroth [18] used the GPSS to write a MOBILIZE model for evacuating a complex building on a large campus. Fahy [2] presented EXIT89 model to study the evacuation process in high rise buildings. Tompson and Marchant [17] developed SIMULEX to evaluate the potential evacuation process of a complex building with a high degree of accuracy. The most recent contribution was made by Galea [3] with program EXODUS.

Little research has been devoted to the evacuation from ships. Recently the methodology from building evacuation has been transferred to ship evacuation, taking into account the special circumstances such as ship motion and human behaviors.

The EU research project was launched in 1997. The mustering simulation program EVAC was developed to simulate the mustering operation on passenger vessels based on microscopic method. The motion of each passenger and his interactions with other evacuees were included in the program. However, the dynamic effect and the listing of the ship were not included.

A prototype of maritimeEXODUS was developed (Galea

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[3]). Current version of maritimeEXODUS does not include reliable data to represent the preparation and the deployment of the escape system. MonteDEM is developed (by The Korea Research Institute of Ships and Ocean Engineering and Seoul National University) for assessing the fire safety of ships. The physical characteristics of each person and forces caused by motions can be specified in the MonteDEM.

Factors, such as ship listing and motion, crowd density, and psychological factors, affecting human behavior in ship evacuation have been explored. Lee *et al*. [8] provided a detailed current status and future issues in human evacuation from ships. Park *et al*. [13] presented the IMEX (intelligent model for extrication simulation) which combines dynamics model and human behavior model to overcome some limits of currently used evacuation model.

From the literature review mentioned above, we know that planning of the movement of people is very important to the safety measures, so an appropriate tool is necessary to analyze the optimal evacuation route problem. The main advantage of the system simulation is that it can handle complex scenarios, but the results from the system simulation cannot be used repeatedly. If the evacuation problem is formulated by stochastic models, which are more realistic, but also more complex.

The main purpose of this study is to formulate a simple and efficient mathematical programming model to find an optimal personnel evacuation route in order to increase personnel's security at sea.

The rest of the paper is organized as follows. The next section formulates the mathematical model for our problem. Section 3 introduces the case study. Experimental results are reported in Section 4. Finally concluding remarks and suggestions for future research are provided in Section 5.

II. PROBLEM FORMULATION

In order to simplify our analysis, we made the following assumptions.

(1) The crew will immediately be at the evacuation duty station ready to assist.
(2) Smoke, heat and toxic fire products present in fire effluent are not considered to impact passenger/crew performance.
(3) Family group behavior is not considered in the analysis.
(4) Ship motion, heel and trim are not considered.

In the following we present the relevant notations and the minimum cost flow model:

subscripts:

i, j: denoting the initial point and terminal point of an arc, respectively.
k: index for nodes.
V: the set of nodes.
A: the set of arcs.

decision variable:

$X_{i,j}$: the amount flow in arcs (i, j), i.e., the number of people moving from node i to node j, $X_{i,j} \geq 0$ and integer.

parameters:

$C_{i,j}$: length of arc (i, j), i.e., the travel distance of arc (i, j).
$U_{i,j}$: capacity of arc (i, j), i.e., the number of people of allowed to pass through the arc (i, j).
b_k: net demand at node k, i.e., subtracting the number of people flow out from the number of people flow in at node k.

$$Minimize\ z = \sum_{(i,j)\in A} C_{i,j} X_{i,j}$$

$$subject\ to\ \sum_{(i,k)\in A} X_{i,k} - \sum_{(k,j)\in A} X_{k,j} = b_k \quad (1)$$

$$X_{i,j} \leq u_{i,j} \quad \forall k \in V \quad (2)$$

$$X_{i,j} \geq 0 \quad \forall (i,j) \in A \quad (3)$$

The objective function is to minimize the total cost. The cost is defined as the travel distance in our study. From a system point of view, we want minimize the sum of travel distances on the entire network. Constraints (1) enforce balance of flow at nodes. Flow must be nonnegative to make sense and upper bounds may apply. These requirements lead to constraints (2). Constraints (3) ensure that the number of people on every arc must be nonnegative.

III. CASE STUDY

The case study was conducted based on a Ro-Ro passenger ferry called "TAI WHA" and the ferry usually moors at Port of Kaohsiung, Taiwan. The particular of the ferry is given in Table 1.

There are seven decks of the ferry, including HOLD PLAN, RO-RO DECK, INTERMEDIATE DECK, C DECK, B DECK, A DECK, and NAV BRI DECK. Fig. 3 shows the layout of every deck.

In order to apply our mathematical model, we need to transform the layout of every deck into a network graph. The capacity of source node, the space of the transshipment point, the clear width of stair, corridor and door are important factors affecting the evacuation route. Following the same symbol used by "Tai-Hwa", we summarize the detailed information of the width of stair and door in Table 4 and Table 5, respectively. Furthermore, two sets of symbol are used to denote the capacity of source node and the space of transshipment point. The detailed data are presented in Table 2 and Table 3, respectively.

After taking the number of people of source node, the space of the transshipment point, and the clear width of stair and

Table 1. The particular of "TAI WHA".

M.V. "TAI WHA" Principal Particulars of Combination Ferry/Ro-Ro/Passenger Vessel	
Length over-all------------------ ABT. 120.00 M	**Vehical Capacity**
Length between perpendiculars ----- 107.00 M	Bus--10
Breath moulded--------------------------19.30 M	Sedan---20
Depth moulded---------------------------- 8.00 M	Motorcycle --------------------------------------60
Draft moulded----------------------------- 5.50 M	Cargo Handling Equipment ---10 T Deck Crane
Deadweight------------------------ ABT. 1,500 T	Sperry -------------------------------- in Stabilizer
Gross Tonnage ---------------------------- 8000 T	Bow Thruster------------------------ABT. 9 Tons
Type -------- Twin Screw Driven, Combination ferry/Ro-Ro/Passenger Vessel	Bow & Stern Quarter Ramp
Cargo Capacity ----------------------------- 800 M	Classification China Register of Shipping CR 100 ✠ Ⓔ, CMS ✠, CAS ✠ American Bureau of Shipping ✠ A1 Ⓔ, ✠ AMS, ✠ ACC
Main Engine Type: MAN-B & W 9L 40/45 Max Output Continous Rating---------7,245 ps at 600 rpm Normal Output------------- 6,683 ps at 579 rpm	Complement---------------------------------- 60 P
Speed Max. Trial speed------------- ABT. 22.00 Knots Service Speed-----------------MIN 21.00 Knots Cruising Endurance ------3,000 Nautical Miles	**Entertainment Facilities** Restaurant -----------------------------------100 P Cafeteria -------------------------------------- 80 P Saloon-- 50 P Video Game Room -------------------------- 30 P Swimming Pool Video TV and Stereo System
Passenger Capacity VIP room --------------------------------------- 4 P Special 1st class --------------------------------20 P Special 2nd class--------------------------------40 P General Berthing --------------------------- 140 P High class reclining seat------------------- 700 P Driver room -----------------------------------14 P	
Total --918 P **Peak Season-------------------------------1,204 P**	

Table 2. The capacity of source nodes.

Symbol	Item	Capacity (persons)
m1	Driving room	14
c1	Aft reclining seat	388
c2	Fore reclining seat	312
c3	Crew cabins	22
b1	Saloon	54
b2	Chinese Restaurant	80
b3	Restaurant	98
b4	VIP room	0
b5	Kitchen	2
a1	1st class cabins	40
a2	2nd class cabins	24
a3	General berthing	154
n1	Driving room	1
n2	Crew cabin	5

Fig. 2. The Ro-Ro passenger ferry, "TAI WHA".

door into consideration, we obtain the network graph of our case study. For the convenience of coding in the mathematical model, we reassign the number to the source nodes, doors, transshipment points and stairs. There are 108 nodes in our problem and the comparative table are summarized in Table 6 and the corresponding network graph is shown in Fig. 4. Nodes 107 and 108 denote lifeboats which are the sink nodes.

IV. EXPERIMENTAL RESULTS

Data for this study were gathered from different sources as follows: (1) on-sites visits, (2) architectural drawings, and (3) literature review. Five different scenarios were explored.

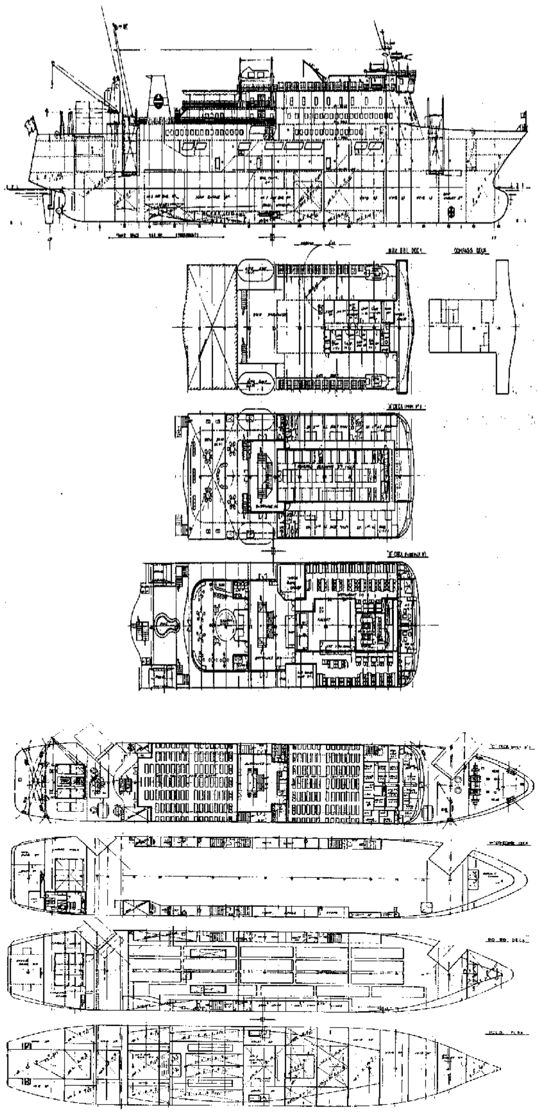

Fig. 3. The layout of every deck.

Table 3. The space of transshipment points.

Symbol	Space (m^2)	Symbol	Space (m^2)
X1	60.63	X8	1.47
X2	106.58	X9	333.62
X3	31.47	X10	58.07
X4	227.18	X11	76.06
X5	110.19	X12	109.26
X6	5.00	X13	172.5
X7	9.17	X14	1.10

Table 4. The clear width of stairs.

Symbol	Width (m)	Symbol	Width (m)
C	1.42*2	E21	2.00
D1	2.00*2	E22	2.00
E11	2.00	M	0.8
E12	2.00	N1	0.7
I	0.75	O	1.0
K	1.5	P	1.0
L	1.5	N2	0.7
D2	2.0*2	Q	0.7

Table 5. The clear width of doors.

Symbol	Width (m)	Symbol	Width (m)
5	1.6	28	0.65
6	1.6	29	1.6
7	1.7	30	1.6
8	1.7	31	1.6
11	1.765	32	0.7
12	1.765	33	1.6
13	1.5	34	0.7
14	0.65	35	1.08
15	0.65	36	1.08
19	1.8	37	0.65
22	1.6	38	0.75
23	1.6	39	0.7
24	1.54	40	0.65
25	1.46	42	0.8
26	0.75		

Table 6. A comparative table.

Symbol	Item	Symbol	Item	Symbol	Item	Symbol	Item
1	door	28	Door	55	door	82	door
2	door	29	Door	56	door	83	door
3	door	30	Door	57	door	84	door
4	transshipment points	31	Door	58	door	85	transshipment points
5	stairs	32	Door	59	door	86	stairs
6	stairs	33	transshipment points	60	door	87	stairs
7	stairs	34	Stairs	61	door	88	stairs
8	door	35	stairs	62	door	89	door
9	cabins	36	stairs	63	door	90	door
10	General Berthing	37	stairs	64	transshipment points	91	door
11	driving room	38	stairs	65	stairs	92	door
12	crew cabin	39	stairs	66	stairs	93	door
13	stairs	40	stairs	67	transshipment points	94	door
14	stairs	41	stairs	68	stairs	95	stairs
15	transshipment points	42	transshipment points	69	stairs	96	stairs
16	door	43	door	70	transshipment points	97	stairs
17	door	44	door	71	stairs	98	stairs
18	door	45	door	72	stairs	99	transshipment points
19	door	46	door	73	transshipment points	100	door
20	door	47	door	74	stairs	101	door
21	door	48	door	75	stairs	102	door
22	door	49	door	76	stairs	103	door
23	door	50	door	77	stairs	104	transshipment points
24	transshipment points	51	door	78	transshipment points	105	door
25	door	52	door	79	door	106	door
26	door	53	transshipment points	80	door	107	lifeboat
27	door	54	door	81	door	108	lifeboat

Table 7. Speed values for speed of passengers and crew.

Type of facility	Condition	Density (p/m^2)	Speed of persons (m/s)	Specific flow (p/ms)
Stairs (down)	Low	< 1.9	1.00	0.54
	Optimum	1.9-2.7	0.50	0.94
	Moderate	2.7-3.2	0.28	0.77
	Crush	> 3.2	0.13	0.42
Stairs (up)	Low	< 1.9	0.80	0.43
	Optimum	1.9-2.7	0.40	0.75
	Moderate	2.7-3.2	0.22	0.62
	Crush	> 3.2	0.10	0.32
Corridors and doorways	Low	< 1.9	1.40	0.76
	Optimum	1.9-2.7	0.70	1.30
	Moderate	2.7-3.2	0.39	1.10
	Crush	> 3.2	0.18	0.55

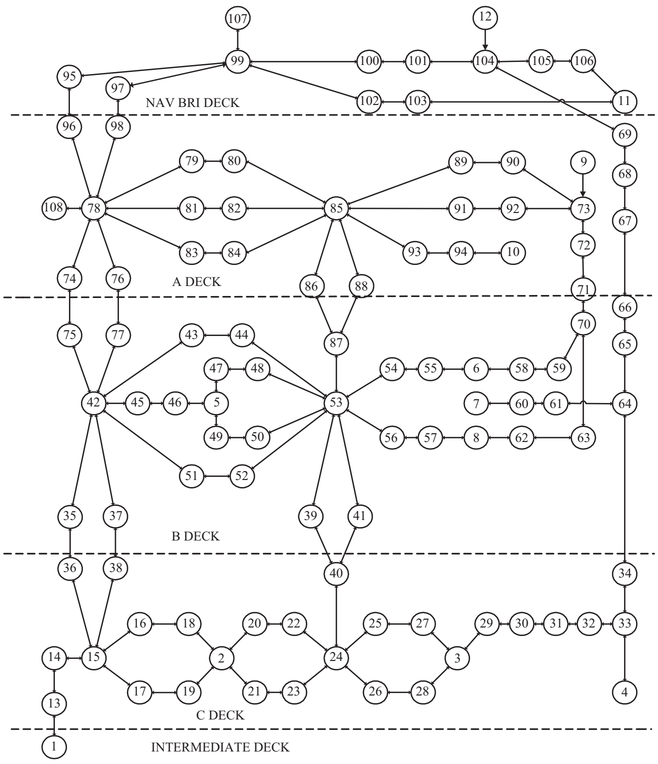

Fig. 4. The network graph of our case study.

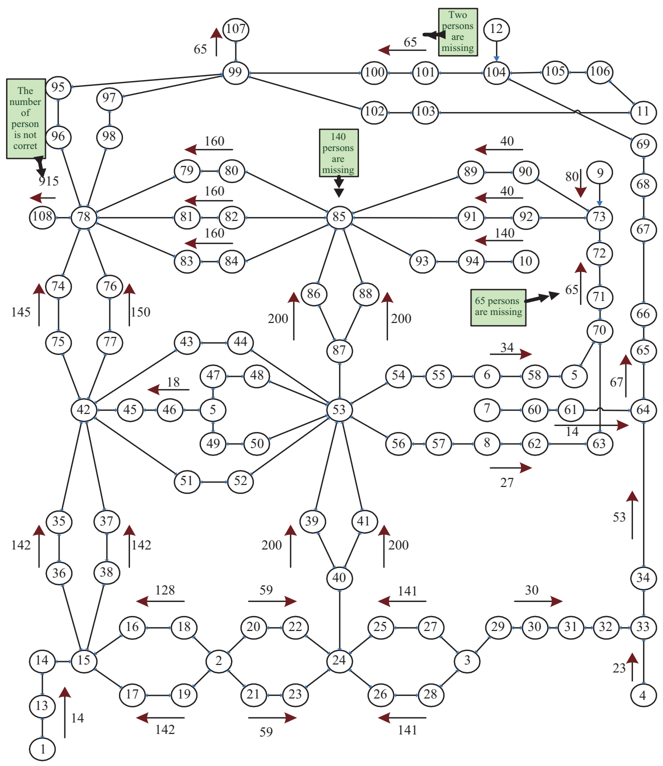

Fig. 5. Some mistakes of current evacuation route of "TAI WHA".

(1) Based on Current Evacuation Route of "TAI WHA" Scenario

The ferry was built in 1989 and the ship building company also provided the evacuation route plan at then. After studying the evacuation route plan thoroughly and summarizing the related information on the network (see Fig. 5), we found some mistakes in the current evacuation route. In Fig. 5, the heavy arrow denotes the escape direction, the corresponding value represents the number of people moving on the arc and some mistakes are indicated by double arrows.

The speed of passengers and crew along the evacuation route depends on the density of persons and on the type of evacuation facility. Table 7 gives speed values for passengers and crew.

The related information of "TAI WHA" and speed values of the crush condition in Table 7 are used to solve the problem. The commercial software CPLEX are adopted in this study and the solution results are summarized in Fig. 6. By comparing the results in Fig. 6 with those in Fig. 5, we find that there is no significant difference between Figs. 5 and 6 except that our model indicate that more people should be evacuated from the central stairs.

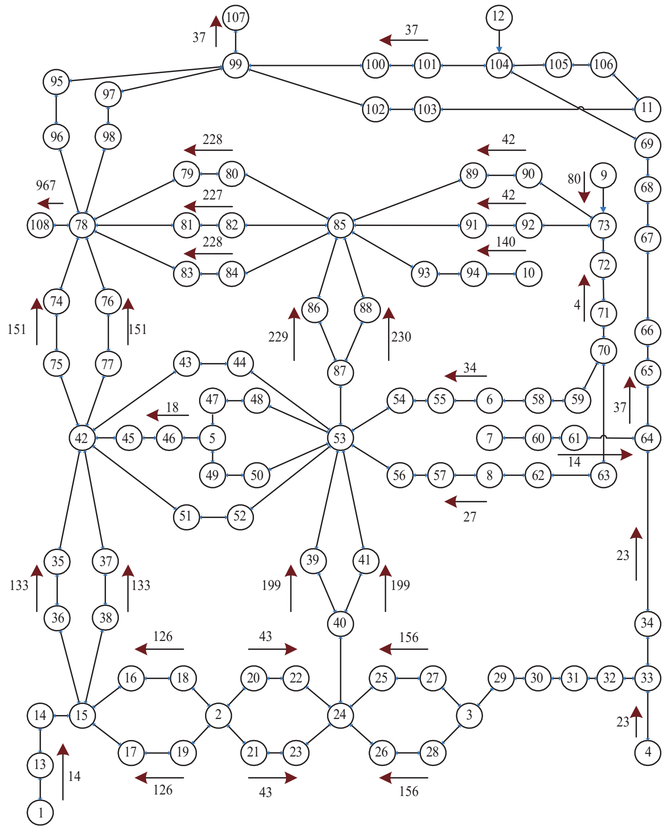

Fig. 6. Proposed evacuation route of "TAI WHA" based on our model.

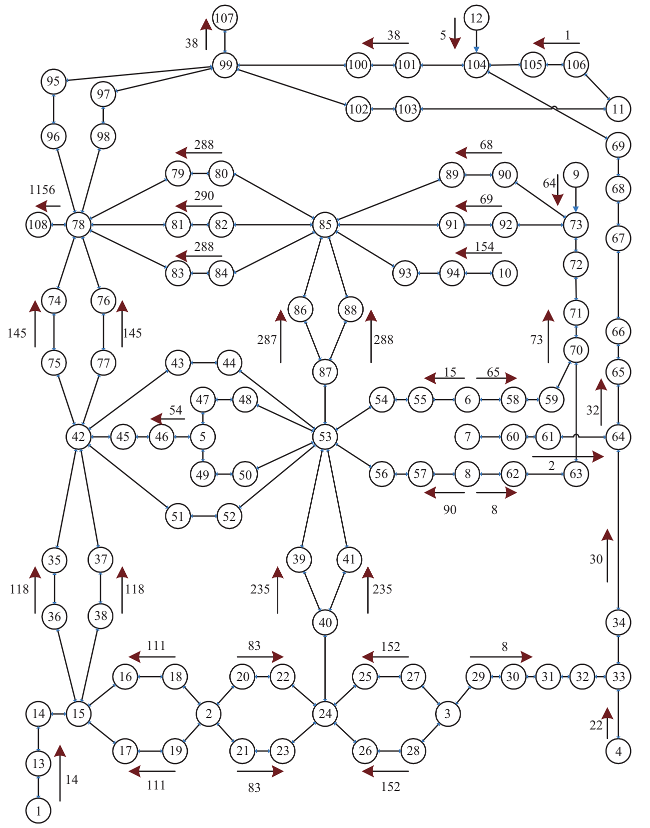

Fig. 8. Proposed evacuation route based on the crush condition.

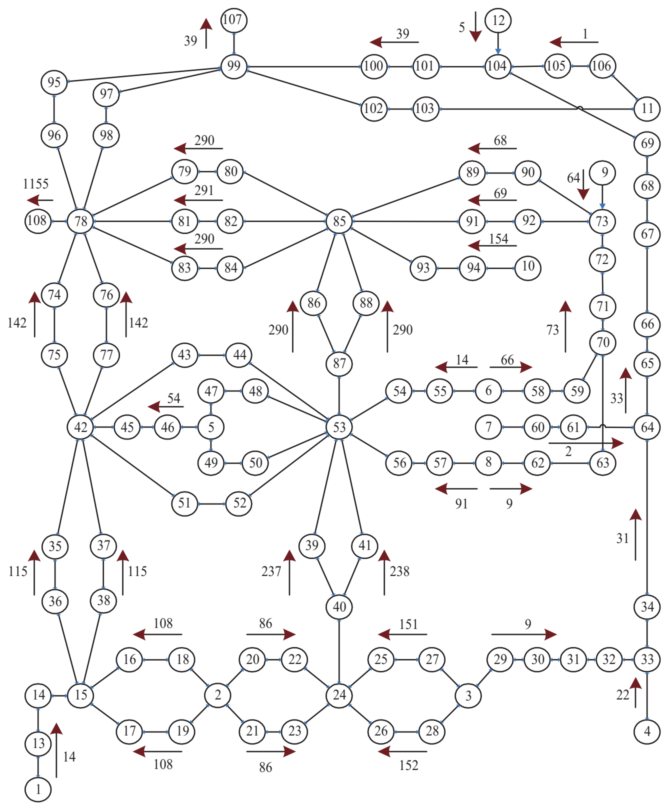

Fig. 7. Proposed evacuation route based on the moderate condition.

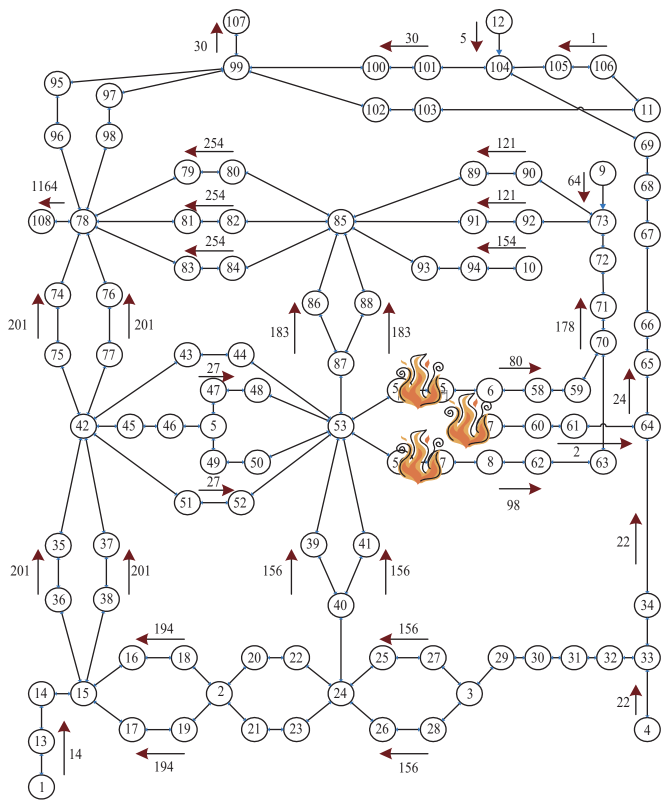

Fig. 9. Proposed evacuation route of the kitchen on fire.

(2) The Moderate Condition Scenario and (3) the Crush Condition Scenario

Combining the moderate condition and the crush condition scenarios together, we want to examine the effect of different people densities on the evacuation route. The evacuation routes of the moderate and crush conditions are shown in Fig. 7 and Fig. 8, respectively.

In general, the evacuation routes are similar between the moderate condition and crush condition except that less people evacuate through central stairs (node 39 and node 41) during the crush condition. Instead of escaping from the central stairs, more people take the stairs on the left side (nodes 35, 36, 37, 38) during the crush condition. The reason for that is the width of stairs on the left side is wider than that of central stairs.

(4) Kitchen on Fire and the Crush Condition Scenario

The kitchen is a place with a high probability to be on fire. For example, grease fires happen when collections of oil or grease on a stove, oven become hot enough to ignite. Grease fires are extremely dangerous because the fuel source is a liquid, and easily splashed. Grease fire can quickly spread to cabinets or other flammable areas of the kitchen.

In this scenario, the kitchen on fire and speed values of the crush condition in Table 8 are used to explore the problem. The results are presented in Fig. 9. From Fig. 9, we can find that the number of people evacuated from the central stairs (node 87 to node 86 and node 87 to node 88) decreases drastically. In stead of taking the central stairs, people evacuate from the stairs on the right side so the number of people on node 71 increases to 178. This evacuation route is reasonable because people tend to move to opposite direction while the escape route is on fire.

V. CONCLUSION

The paper presents a simple and efficient mathematical programming model that identifies the emergency evacuation routes that are available to the passengers for their movements. As for further research, a system that monitors the number of people in a room or place at any point and can solve the optimal evacuation route in real time. These evacuation routes could be indicated in the hallways by signs pointing the way. As room occupations change, so do optimal routes, so that the optimal evacuation route from any given room or place may change as well. Then, the mathematical model developed in this study as well as other models in current literature can evacuate people more efficiently and decrease the loss of lives at sea.

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