Chapter 5

A Bus Allocation Model for Major Industrial Disasters

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Additional information is available at the end of the chapter

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Abstract

The presented research is part of a broader project DIEM-SSP—Disasters and Emergencies Management for Safety and Security in Industrial Plants –aiming at managing major industrial emergencies by considering both medical and engineering/logistics issues. When a disaster occurs, it is necessary to immediately provide relief plans. Many decisions must be made in very short time, which may have a relevant impact on the consequences of the disaster. For an efficient and smart exploitation of available resources, it is necessary to mitigate damages. From a logistics point of view, one of the major issues in the event of a major industrial disaster (fire, explosion or toxic gas dispersion) is to evacuate the external population that can be affected by the disaster to specific evacuation areas. The purpose of the research is to determine the optimal number and allocation of vehicles (buses) which must be involved in order to evacuate the population located in a defined risk area around the emergency site and the optimal location for evacuation areas. For that reasons, a dynamic version of the bus allocation problem is proposed using a mixed-integer programming model.

Keywords: bus allocation, industrial disasters, mixed-integer programming

1. Introduction

The presented research is part of a broader project (DIEM-SSP—Disasters and Emergencies Management for Safety and Security in Industrial Plants) aiming at managing major industrial emergencies by considering both medical and transport/logistics issues. The study of the scientific literature confirms that the severity of a disaster can be highly influenced by the efficacy of the logistics operations during the disaster response phase [1–3]. Since in these circumstances time is crucial, one of the major issues in emergency conditions is to ensure a quick response of the rescue operations [4].

Several authors have analysed the issue of vehicles' allocation in the emergency situation: Stein et al. [5] have studied the effects of a correct emergency vehicle location plan and the response system design on response time performance in a South Africa Urban Emergency Medical Services (EMSs). The authors have used a discrete-event simulation and the results indicate that more decentralised vehicle location has a greater effect.

Yang et al. [6] have proposed the use of urban rail transit (URT) systems in emergency circumstances, as quick and efficient response for evacuation. Using a genetic algorithm (GA), the authors propose a mathematical programming with an indicator constraint model for designing a responsive bus bridging services under URT line emergency. In detail, the authors have analysed the problem considering the distance between the bus parking spots and the URT station as a starting point of a scheduled line.

Zheng [7] has defined an optimal bus-operating model during an emergency evacuation that minimizes the exposed casualty time rather than the operational cost, as a deterministic mixed-integer program. The solution has been based on a Lagrangian relaxation-based algorithm.

Huang et al. (2006) have studied the problem of allocating limited emergency service vehicles (as ambulances and fire trucks): using a mixed-integer linear programming model, they have analysed the effects of demand at Critical Transportation Infrastructure (CTI) nodes and transportation network performance on the optimal coverage to CTIs: authors have used a case study applied on Singapore.

Oran et al. [8] have defined a new formulation of the facility location problem (using MIP solver) and vehicle routing problem with time windows (a tabu search-based metaheuristic algorithm), analysing a set of possible emergency scenarios with limited emergency resources. Results show that this approach is able to serve higher priority locations better than the much utilized maximal coverage location problems.

Muaafa et al. [9] have studied an integrated approach based on a multi-objective optimization model to manage the emergency medical response strategies; it allows both to specify the locations of temporary emergency units and to assess the emergency vehicles to these temporary emergency units. The objectives of the model are to minimize response time and cost of the response strategy.

Wang et al. [10] have proposed an optimal allocation of bus to coordinate the passengers' evacuation from urban rail transit service caused by the unexpected service interruptions in URT corridors. The results show that as the evacuation time window increases, the total evacuation cost, as well as the number of dispatched feeder-buses, decreases.

Meinzer et al. [11] have studied new strategies for dynamic ambulance allocation in emergency conditions. They propose to adopt a continuous optimization of vehicles distribution over the region and dynamic reassignment of fleets.

This work proposes a mixed-integer programming model for buses allocation able to determine the optimal number and allocation of buses, which must be involved in order to evacuate all the population located in a defined risk area around the emergency site and the optimal location for evacuation areas (EAs).

A company operating on the waste oil regeneration sector, located in Italy, has been considered in order to evaluate the performance of the proposed methodology: it deals with a toxic gas dispersion and involvement of the external population within a radius of 3 km from the company.

With respect to other research studies analysed in the state of the art, the innovative approach proposed by this study considers the following aspects:

- The study uses a mixed-integer programming model, less used for emergency vehicle allocation.
- The emergency condition in the application is an industrial disaster with a toxic gas dispersion.

2. A mixed-integer programming model

Although they are recognized problems from the scientific community, research on transportation problems and emergency vehicle management for disaster response operations is emerging only recently [2, 12, 13].

When a disaster occurs, it is necessary to immediately provide relief plans. Many decisions must be made in very short time, which may have a relevant impact on the consequences of the disaster. For an efficient and smart exploitation of available resources, it is necessary to mitigate damages. Many applications of operations research methods to disaster response optimization may be found in the literature. Barbarosoglu G, Arda Y. [14] proposed a two-stage stochastic programming model for transportation planning in a disaster, while a multi-objective model for quick response to emergencies in logistics distribution has been proposed by Liu and Zhao [15]. In Ref. [16], the authors proposed a mixed-integer programming model for facility location in humanitarian relief. Ozdamar and Yi [17] dealt with vehicle dispatch plan for relief and evacuation. Other papers presented studies related to relief operations in a specific type of disaster, such as in Ref. [18], where a decision support system, specific for emergency response in the case of nuclear accident, has been presented, and in Ref. [19], the authors proposed an optimization model for allocating emergency resources after an earthquake. Similar issues may be found in ambulance allocation dispatching, where a limited fleet of ambulances must be allocated to real-time requests. A complete review on this subject may be found in Ref. [20].

We deal with buses allocation for mass evacuation. In detail, considering a case in which, due to toxic gas dispersion, all the population located in a risk area surrounding the emergency site must be evacuated. This area is sub-divided into zones, for each one of which the number of people to be evacuated is known. We consider a set of depots where buses are located, for each one of which, we suppose to know the number of available vehicles of identical capacity (in terms of the number of people which can be carried), and the delay with which the vehicles will be available at that depot. A delay equal to 0 means that vehicles are always located at the depot and that they are immediately available. We consider a set of potential evacuation areas with different capacities. For operational reasons, people from the same zone must be evacuated in the same evacuation point located within the area [21–23].

The goal is to minimize the averaged evacuation time. In particular, for evacuation time of a zone, we intend the time within which all the people from that zone are evacuated.

Before proceeding with the mathematical formulation, we define the parameters, sets and variables of the model.

Model parameters:

- q_i: number of people to be evacuated from zone i
- c: vehicles' capacity
- p_k: delay with which the vehicles are available at depot k
- t_{ij}: travel time between zone i and evacuation area j
- τ_{ik}: travel time between depot k and zone i
- R_k: number of vehicles available at depot k
- C_j: capacity of evacuation area j

Model sets:

- I: set of zones to be evacuated
- J: set of evacuation areas
- K: set of depots

Involved variables:

- Y_{ik}: binary variable taking value equal to 1 if zone i is evacuated by bus located at depot k and 0 otherwise
- Z_{ij}: binary variable taking value equal to 1 if zone i is evacuated to evacuation area j and 0 otherwise
- Y_{ik}: number of vehicles starting from depot k and used to evacuate zone i
- T_i: evacuation time for zone i
- A_i: time within which all vehicles that have been assigned to zone i reach the zone

The mathematical model for buses allocation for mass evacuation can be formulated as follows:

$$\min \sum_{i \text{ in } I} \frac{T_i}{|I|} \tag{1}$$

s.t.

$$\sum_{k \text{ in } K} Y_{ik} \geq 1 \qquad \forall i \in I \tag{2}$$

$$\sum_{j \text{ in } J} Z_{ij} = 1 \qquad \forall i \in I \tag{3}$$

$$\sum_{i\ in\ I} q_i Z_{ij} \leq C_j \forall j \in J \tag{4}$$

$$V_{ik} \leq R_k Y_{ik} \forall i \in I\ \forall k \in K \tag{5}$$

$$\sum_{i\ in\ I} V_{ik} \leq R_k \forall k \in K \tag{6}$$

$$\sum_{k\ in\ K} c * V_{ik} \geq q_i \forall i \in I \tag{7}$$

$$\left(\sum_{k\ in\ K} V_{ik} - 1\right) * c \leq q_i \forall i \in I \tag{8}$$

$$A_i \geq \left(\sum_{k\ in\ K} \tau_{ik} + p_k\right) Y_{ik}\ \forall i \in I \tag{9}$$

$$T_i = \sum_{j\ in\ J} t_{ij}\ Z_{ij} + A_i\ \forall \mathrm{i} \in I \tag{10}$$

$$Y_{ik} \in \{0,1\} \quad \forall i \in I\ \forall k \in K \tag{11}$$

$$Z_{ij} \in \{0,1\} \quad \forall i \in I\ \forall j \in J \tag{12}$$

$$V_{ik} \in \mathrm{Z}^+ \quad \forall \mathrm{i} \in \mathrm{I}\ \forall \mathrm{k} \in K \tag{13}$$

The objective function is to minimize the averaged evacuation time, expressed in Eq. (1). Constraint Eq. (2) imposes that each zone must be served by at least one depot, while constraint Eq. (3) ensures that all the population of a zone must be evacuated to the same evacuation point. Evacuation areas' capacity restriction is satisfied by constraint Eq. (4). Constraint Eq. (5) imposes that a zone may be evacuated by vehicles located at a depot only if it is served by that depot. The number of vehicles used, for each depot, must be lower than the number of available vehicles at that depot, as stated in constraint Eq. (6). Constraints Eqs. (7) and (8) ensure that the number of vehicles used to evacuate a zone is the minimum necessary. For each zone, the arrival time of the last bus is computed by constraint Eq. (9), while the evacuation time is computed by constraint Eq. (10). In fact, the evacuation time of a zone, defined as the arrival time of the last bus, evacuating people from that zone, to the evacuation area, can be computed as the sum of the arrival time of the last bus to the zone plus the travel time between the zone and the evacuation area. Finally, constraints Eqs. (11)–(13) specify the domain of the variables.

It is also interesting to analyse how the solution changes if instead of minimizing the averaged evacuation time, we would minimize the largest evacuation time, defined as the time necessary to evacuate all the zones. In this case, the new objective function results:

$$\min \sum_{i\ in\ I} W \tag{14}$$

subject to constraints Eqs. (2)–(13) and the following additional constraints:

$$W \geq T_i \quad \forall i \in I \tag{15}$$

$$W \in Z^{+} \tag{16}$$

3. Data description

The company is located in Italy and it is the European leading company in the main sector of waste oils regeneration. More than 150 people work for the company. The working activities take place 365 days a year, 24 hours a day, in the two production plants: one in the North of Italy and the other one near Rome.

3.1. Data providing information on the population to be evacuated

The risk area within a radius of 3 km from the emergency site has been divided in 23 potential evacuation zones. For each one, the following information has been defined:

- The number of people to be evacuated: For each zone, the number of people to be evacuated has been calculated considering the total zone size (km^2) and the population density of the zone (inhabitants/km^2) (**Table 1**).
- Collection points' location: For operational reasons, people from the same zone must be evacuated in a specific collection point, identified by its geographical coordinates.
- Distance: Distances between collection points and depots (D) and between collection points and evacuation areas (EAs) have been computed (**Table 2**).

Zones	Inhabitants	Zones	Inhabitants
Zone 1	725	Zone 13	626
Zone 2	422	Zone 14	447
Zone 3	367	Zone 15	775
Zone 4	367	Zone 16	338
Zone 5	442	Zone 17	318
Zone 6	362	Zone 18	218
Zone 7	467	Zone 19	328
Zone 8	343	Zone 20	288
Zone 9	660	Zone 21	745
Zone 10	943	Zone 22	367
Zone 11	278	Zone 23	357
Zone 12	536		

Table 1. List of zones and number of inhabitants to be evacuated.

Zones	D1	D2	D3	EA1	EA2	EA3	EA4	EA5	EA6	EA7	EA8	EA9
Zone 1	2.2	4.7	5.7	10.4	10.3	10.4	9.6	7.2	6	10.5	7.6	6.1
Zone 2	3.5	3.2	8.9	11.7	10.7	10.8	11	8.6	9.3	11.8	8.9	9.3
Zone 3	5	2.7	8	11.2	11.1	11.2	10.4	8.1	8.4	11.3	8.4	8.4
Zone 4	4.4	3.3	8.7	11.9	11.8	11.9	11.1	8.7	9.1	12	9.1	9.1
Zone 5	4	4.1	8.5	12.6	13.1	13.2	11.9	9.5	8.9	12.7	9.8	9
Zone 6	2.9	5.5	7.4	12.1	11.9	12.1	11.3	8.9	7.7	12.2	9.3	7.8
Zone 7	1.8	7.5	6.9	11.6	10.8	10.9	10.9	7.6	6.4	11.7	8.8	6.5
Zone 8	1.6	5	4.8	9.5	9.5	9.6	8.7	6.3	5.1	9.6	6.7	5.2
Zone 9	6.5	0	9.2	8.8	9.3	9.4	8.1	5.7	8.2	8.9	6	10.5
Zone 10	3.4	3.4	5.3	7.3	7.3	7.4	6.6	4.2	6.7	7.4	4.5	6.8
Zone 11	5.3	1.3	8.9	9.6	7.8	7.9	8.9	6.5	9	9.7	6.8	11.3
Zone 12	1.3	6.9	6.3	11	11.1	11.2	10.2	7	5.8	11.1	8.2	5.9
Zone 13	1.6	7	4.9	8.1	7.5	7.8	9.8	5.7	4.5	8.5	7.5	4.6
Zone 14	1.6	6.8	4.7	7.3	7	7.2	9	5	3.8	7.8	6.7	3.9
Zone 15	2.2	7	5.9	7	6.6	6.9	8.7	4.6	3.4	7.4	6.4	3.5
Zone 16	1	6.5	5.2	8.8	7.7	8	10	6.5	5.3	10.8	8	5.4
Zone 17	2.4	5.6	4.3	9.5	9.5	9.6	8.8	6.4	5.7	9.6	6.7	5.8
Zone 18	3.2	5.8	3.1	9.8	6.7	6.8	9	4.7	5.1	9.8	7	6.4
Zone 19	1.8	6.4	4.3	8.6	8.2	8.5	9.6	6.2	5	10.4	7.5	5.1
Zone 20	1.8	6.4	3.5	8.6	8.2	7.1	9.7	62	5	10.5	8	5.1
Zone 21	2.2	6.4	3	7	6.6	6.7	9.6	4.6	5.4	7.6	6.3	5.5
Zone 22	3.1	6.4	2.5	6.4	6.1	6.1	9.6	4	4.4	7	5.8	6.4
Zone 23	3.2	8.1	4.6	5.6	5.3	5.6	7.3	3.3	2.1	6.1	5	2.2

Table 2. Zones and number of inhabitants to be evacuated.

Area	Capacity
Area 1	5000
Area 2	3000
Area 3	2000
Area 4	1000
Area 5	3000
Area 6	5000
Area 7	4000
Area 8	1000
Area 9	1000

Table 3. List of evacuation areas capacity.

3.2. Data providing information on the evacuation area

A set of nine evacuation areas has been identified for each one of which the following information has been collected:

- Location: The location of each area is provided in terms of geographical coordinates.
- Capacity: For each area, it is specified the maximum capacity intended as the maximum number of persons that the area can accommodate (**Table 3**).

4. The case study

In this scenario, we consider a toxic gas dispersion due to which the population within a radius of 3 km from the company must be evacuated.

We defined 23 zones to be evacuated and for each one we supposed to know the number of people to be evacuated.

We consider a homogeneous fleet of 170 vehicles located in three depots. 20 of them are located at Depot 1 and are supposed to be immediately available while the other buses are supposed to be around the city and 50 of them can be available in 20 minutes at each depot (1, 2 and 3). We have defined nine available evacuation areas, each one of them is known with the maximum capacity.

Each zone can be served by buses coming from different depots but, for operational reasons, all the people from the zone must be evacuated to the same evacuation area. Distances between depots and zones and between zones and evacuation areas have been computed with Google Maps. Travel times have been computed considering a travel time equal to 10 Km/h, compatible with a congested urban traffic. We have carried out four tests. In Tests 1 and 2, we have tried to minimize the average evacuation time, while in Tests 3 and 4, we aimed to minimize the total evacuation time, i.e. the time within which all the population is evacuated. Furthermore, Tests 1 and 3 consider all evacuation areas available, while in Tests 2 and 4, evacuation areas 4 and 9 are not available.

Tests outlines are described in **Table 4**.

Test	Evacuation areas	Minimize
1	All	Avg Time
2	No. 4 and 9	Avg Time
3	All	Max Time
4	No. 4 and 9	Max Time

Table 4. Tests outlines.

In **Tables 5** and **6**, we report, for each zone, the area to which it has been evacuated, the evacuation time (expressed in minutes), other than averaged and maximum evacuation time.

In **Tables 7** and **8**, we report the vehicle dispatching resume. In detail, for each zone, we report the number of buses started from each depot to evacuate that zone. Depot 1* concerns vehicles starting from Depot 1 but available after 20 minutes.

Test 1			**Test 2**		
Zone	**Evacuation area**	**Time**	**Zone**	**Evacuation area**	**Time**
1	6	100	1	6	100
2	5	101	2	5	101
3	5	95	3	5	95
4	5	102	4	5	102
5	5	111	5	6	107
6	6	93	6	6	93
7	6	79	7	6	79
8	6	71	8	6	41
9	8	66	9	5	64
10	4	90	10	8	77
11	8	79	11	5	77
12	9	73	12	6	73
13	6	67	13	6	67
14	9	63	14	6	63
15	6	85	15	2	105
16	6	38	16	6	38
17	6	48	17	5	52
18	5	77	18	5	77
19	6	41	19	6	41
20	6	41	20	3	84
21	5	76	21	3	88
22	5	69	22	5	69
23	6	71	23	6	71
	Avg Time	75		Avg Time	77
	Max Time	111		Max Time	107

Table 5. Evacuations area assignment and evacuation time for Tests 1 and 2.

Test 3			**Test 4**		
Zone	**Evacuation area**	**Time**	**Zone**	**Evacuation area**	**Time**
1	6	94	1	6	94
2	7	92	2	5	73
3	5	95	3	5	95
4	8	81	4	6	81
5	6	77	5	6	77
6	6	93	6	6	93
7	6	79	7	6	79
8	6	90	8	6	91
9	4	79	9	7	83
10	5	75	10	8	89
11	5	77	11	2	85
12	6	73	12	6	73
13	1	89	13	6	86
14	6	63	14	6	94
15	9	86	15	5	71
16	6	68	16	3	84
17	6	78	17	5	94
18	5	93	18	5	77
19	5	93	19	6	71
20	6	81	20	3	84
21	5	76	21	7	94
22	8	80	22	5	69
23	6	71	23	6	92
	Avg Time	82		Avg Time	84
	Max Time	95		Max Time	95

Table 6. Evacuations area assignment and evacuation time for Tests 1 and 2.

Comparing results obtained in Tests 1 and 2, we can observe that if two evacuation areas are not available anymore (Test 2), the average evacuation time only increases by 2 minutes (from 75 to 77), which shows the robustness of the system. The same behaviour can be noted in Tests 3 and 4. In this case, even if evacuation areas 4 and 9 are not available, the optimal maximum evacuation time is the same as in the case in which all the evacuation areas are available, and the increment of average evacuation time is very little.

Test 1					Test 2				
Zone	**Depot 1**	**Depot 1***	**Depot 2**	**Depot 3**	**Zone**	**Depot 1**	**Depot 1***	**Depot 2**	**Depot 3**
1	0	0	0	11	1	0	0	0	11
2	0	0	7	0	2	0	0	7	0
3	0	0	6	0	3	0	0	6	0
4	0	0	6	0	4	0	0	6	0
5	0	7	0	0	5	0	7	0	0
6	0	6	0	0	6	0	6	0	0
7	0	7	0	0	7	0	7	0	0
8	0	5	0	0	8	5	0	0	0
9	0	0	10	0	9	0	0	10	0
10	0	0	14	0	10	0	0	14	0
11	0	0	4	0	11	0	0	4	0
12	0	8	0	0	12	0	8	0	0
13	0	9	0	0	13	0	9	0	0
14	0	7	0	0	14	0	7	0	0
15	0	0	0	12	15	0	0	0	12
16	5	0	0	0	16	5	0	0	0
17	5	0	0	0	17	5	0	0	0
18	0	0	0	4	18	0	0	0	4
19	5	0	0	0	19	5	0	0	0
20	5	0	0	0	20	0	5	0	0
21	0	0	0	11	21	0	0	0	11
22	0	0	0	6	22	0	0	0	6
23	0	0	0	6	23	0	0	0	6

Table 7. Vehicles dispatching for Tests 1 and 2.

Comparing Tests 1 and 3, we can observe that, trying to minimize the maximum evacuation time or the average one, we obtain sensibly different solutions but values obtained for both criteria are comparable.

The same behaviour can be noted in Tests 2 and 4.

For what concerns vehicle dispatching, we can observe that in Tests 1 and 2, the optimal vehicle assignment is the same, while in Tests 3 and 4, we obtain a different vehicle assignment. This fact depends on the different objective functions. In fact, when we aim to minimize the maximum evacuation time, there are many feasible vehicle assignment configuration, which may yield to the same objective function value.

Test 3					Test 4				
Zone	**Depot 1**	**Depot 1***	**Depot 2**	**Depot 3**	**Zone**	**Depot 1**	**Depot 1***	**Depot 2**	**Depot 3**
1	0	0	11	0	1	0	0	11	0
2	7	0	0	0	2	7	0	0	0
3	0	0	6	0	3	0	0	6	0
4	6	0	0	0	4	6	0	0	0
5	7	0	0	0	5	7	0	0	0
6	0	6	0	0	6	0	6	0	0
7	0	7	0	0	7	0	7	0	0
8	0	0	0	5	8	0	0	5	0
9	0	0	10	0	9	0	0	10	0
10	0	0	14	0	10	0	0	0	14
11	0	0	4	0	11	0	0	4	0
12	0	8	0	0	12	0	8	0	0
13	0	9	0	0	13	0	0	0	9
14	0	7	0	0	14	0	0	7	0
15	0	0	0	12	15	0	12	0	0
16	0	5	0	0	16	0	5	0	0
17	0	5	0	0	17	0	0	0	5
18	0	0	4	0	18	0	0	0	4
19	0	0	0	5	19	0	5	0	0
20	0	0	0	5	20	0	5	0	0
21	0	0	0	11	21	0	0	0	11
22	0	0	0	6	22	0	0	0	6
23	0	0	0	6	23	0	0	6	0

Table 8. Vehicles dispatching for Tests 3 and 4.

5. Concluding remarks

The state of the art underlines that in the event of a major disaster there is a strong need for decision support tools that give solutions to the allocation problem in a short time interval. From a transport/logistics point of view, the most important decisions that should be made by emergency vehicle managers during a disaster response phase are related to the location and allocation of the emergency vehicles.

A mixed-integer programming model for buses allocation has been calibrated to determine the optimal number and allocation of buses, which must be involved in order to evacuate all the population located in a defined risk area around the emergency site and the optimal location for evacuation areas.

Four different scenarios have been calibrated: in two of them, the average total travel time of buses has been minimized, while in the other two the maximum total travel time of buses has been minimized.

Comparing the scenarios with all zones, the obtained results are different but values obtained for both criteria are comparable; the same aspects have been noted comparing the scenarios without areas No. 4 and No. 9.

Regarding further evolution of the research, interesting developments can be followed expanding and integrating the results of bus allocation model with a route choice model and a route assignment model.

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