Multi-objective Optimization for Coordinating Emergency Resources in Multiple Mass Casualty Incidents

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ABSTRACT

Effective co-ordination between resource-constrained emergency services during multiple mass casualty incidents (MCIs) plays a significant role in the response phase. In such a case, the co-ordination problem needs to be solved, namely the allocation of responders-to-incidents, responders-to-casualties, vehicles to travel to casualties at incident sites and transport casualties to hospitals, and task assignment to responders and vehicles. A Neighborhood Search Algorithm (NSA) is employed to solve the co-ordination problem with the aim of reducing the suffering of casualties, with varying injuries and health classifications. An application of the NSA is enabled using a hypothetical case study of MCIs including three scenarios in a major urban area of the UK. The experiments conducted show the effectiveness of using different approaches to generate an initial response plan and the performance of the NSA in developing a final optimized plan.

Keywords

Co-ordination, Neighborhood Search Algorithm, optimization, scheduling.

INTRODUCTION

A man-made disaster is a deliberate event that can occur without notice in a densely populated area. For example, the London bombing incidents on 7 July 2005 are considered as multiple mass casualty incidents (MCIs) (CTPN, 2019). An MCI results in a number of casualties with varying injuries and health classification, which raises challenges to the emergency services and hospitals in the affected and surrounding area to cope with the extraordinary situation (CTS, 2016). Disaster management is divided into four phases, as shown in Figure 1; each phase has its impact, actions and challenges (WHO, 2007). This paper focuses on the response phase of disaster management.

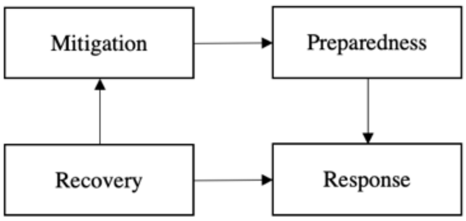


Figure 1. The Four Phases of Disaster Management

The response phase consists of several actions that are activated rapidly during a disaster. It is widely viewed as the most challenging phase due to the importance of the need for co-ordination between the emergency services involved during MCIs. Moreover, there may be a potential lack of resources due to the number of casualties at incident sites (Cabinet Office, 2013). The primary aims of the response to an MCI include saving lives and reducing suffering. Thus, an MCI decision support model is needed to help co-ordinate the emergency services and optimize the allocation and scheduling of resources efficiently. The remainder of this paper is organized as follows. The related work is discussed followed by a description of the model of the co-ordination problem in a multiple MCI. Next, the solution method used to solve the co-ordination problem is introduced. Further, a hypothetical case study is defined, and three scenarios are considered, followed by the results and discussion. Finally, the conclusion and future work are presented.

RELATED WORK

Existing Models in Emergency Response to an MCI

A web-based model has been proposed to solve casualty-to-hospital allocation by providing real-time information regarding estimated driving time, and the capacity as well as location of considered hospitals (Amram et al., 2012). On a similar theme, a mixed-integer programming model has been designed to solve ambulance dispatching, casualty-to-hospital allocation, and treatment ordering problems (Repoussis et al., 2016). In particular, the model aims to improve casualty outcomes by effectively allocating the limited resources during the response. Further, a multi-objective combinatorial optimization model was developed in (Wilson et al., 2016) to solve responder-to-casualty and casualty-to-hospital allocation; this takes into consideration the stochastic nature of casualty health and resource numbers during the response, which leads to dynamic planning. Also, a dynamic optimization model was proposed in (Wex et al., 2013) to allocate and schedule rescue units and to minimize the sum of completion times of incidents. In this model, the assignment and scheduling decisions were updated based on the available information.

Health Profile of Casualties in Mcis

The health profile of a casualty indicates the injuries that he/she may suffer, which could affect his/her vital signs or the ability to walk as indicated in (Ahuja & Bhattacharya, 2004; Atiyeh et al., 2013; Bhalla et al., 2015; NICE, 2014). The health profile of a casualty contributes to categorizing him/her into one of three groups of health classification as a result of the triage process: immediate; urgent; delayed. Immediate indicates a casualty is in a critical condition, urgent signifies a casualty is in a critical condition but less than immediate, and delayed refers to a casualty being in a non-critical condition. In (Aldossary & Coates, 2019; Amram et al., 2012; Repoussis et al., 2016; Wex et al., 2013; Wilson et al., 2016), the health profile of casualties was neglected; however, the health classification was pre-defined and remained the same until the completion of the response. In addition, the model represented in (Wilson et al., 2016) considered whether a casualty is trapped or not. Table 1 signifies the main differences between the existing models and the model presented in this paper.

Table 1. The coordination problem considered in existing models and the proposed model

Models	Co-ordination problem					Scheduling
	Vehicles-to-incidents	Responders-to-incidents	Responders-to-casualties	Vehicles-to-casualties	Casualties-to-hospital	
(Amram et al., 2012)	x	x	x	x	√	x
(Repoussis et al., 2016)	√	x	x	x	√	x
(Wilson et al., 2016)	x	x	√	x	√	√
(Wex et al., 2013)	√	x	x	x	x	√
Proposed in this paper	√	√	√	√	√	√

Contribution of This Paper

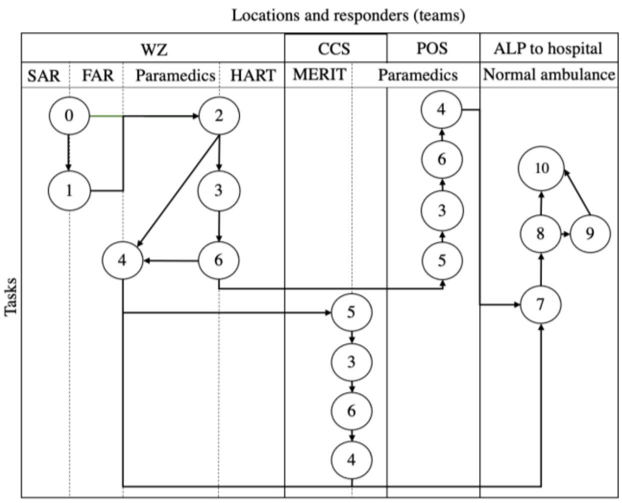
The main contribution of this paper is the design and development of a mathematical optimization model, which includes an approach to develop a 'good' initial emergency response plan prior to a Neighborhood Search Algorithm (NSA) being applied, in order to solve a more comprehensively defined multiple mass casualty incident (MCI) co-ordination problem than seen previously. In particular, the MCI co-ordination problem addressed involves the allocation and scheduling of (a) responders to incidents, (b) responders to casualties, (c) vehicles to travel to casualties at incident sites and transport casualties to hospitals, and (d) tasks to responders and vehicles. The model aims to reduce the suffering of casualties by minimizing three associated objectives, namely the time taken to deliver to hospital the last immediate casualty across all incident sites; the time taken to deliver to hospital the last urgent casualty across all incident sites; the time taken to deliver to hospital the last casualty of any type across all incident sites, i.e. the overall response time. In addition, the model incorporates the design of a comprehensive health profile for casualties, which includes the injuries that each casualty may have and their vital signs and condition. Incorporating such detailed health profiles enables the classification of the casualties' health on-site, updating the classification of casualties' health during the response, and enabling the allocation of the appropriate resources that meet the casualties' needs.

MODEL OF THE CO-ORDINATION PROBLEM IN A MULTIPLE MCI

In order to define the model of the co-ordination problem, a description is given of the MCIs' environment and emergency resources. Subsequently, modelling the casualties' health profiles and the tasks' duration are discussed, and the objectives functions are presented. Finally, model assumptions are stated.

Mcis Environment and Emergency Resources

Given a road network $G = (V, E)$, let V be node set, E be arc set where V represents the considered locations of stations, hospitals, and incident sites and E represents roads. Let $is_1, is_2, \dots, and\ is_{n_{IS}}$ be the incident sites' location set IS, $IS \subseteq V$, where n_{IS} is the number of incident sites, each of which has four associated locations, three of which are static, namely a warm zone (WZ), a casualty clearing station (CCS) and a place of safety (POS), and one is dynamic, i.e. an ambulance loading point (ALP). The purpose of the associated locations will be discussed later in this sub-section. Let $c_1, c_2, \dots, and\ c_{n_C}$ be the casualty set C, where n_C is the number of casualties, with each of them having a number of parameters reflecting his/her health profile. Casualties are distributed between incident sites. Let $h_1, h_2, \dots, and\ h_{n_H}$ be the hospital location set H, $H \subseteq V$ where n_H is the number of hospitals. The capacity of h_i is denoted by CP_{h_i}. Let $as_1, as_2, \dots, and\ as_{n_{AS}}$ be the ambulance stations' location set AS, $AS \subseteq V$, where n_{AS} is the number of ambulance stations. Let $frs_0, frs_1, \dots, and\ frs_{n_{FRS}}$ be the fire and rescue stations' location set FRS, $FRS \subseteq V$, where n_{FRS} is the number of fire and rescue stations. Let $na_1, na_2, \dots, na_{n_{NA}}$ be a set of normal ambulances located at AS that are used to transport paramedics, P, to incident sites, as well as casualties to hospitals, where n_{NA} is the number of normal ambulances. Let $ha_1, ha_2, \dots, ha_{n_{HA}}$ be a set of Hazardous Area Response Team (HART) ambulances located at AS that are used to transport HART teams to incident sites, where n_{HA} is the number of HART ambulances. The HART teams consist of trained personnel who use specialist vehicles, which allow the provision of advanced treatment in hazardous environments. Let $me_1, me_2, \dots, me_{n_{ME}}$ be a set of Medical Emergency Response Incident Team (MERIT) ambulances located at AS that are used to transfer MERIT teams to incident sites, where n_{ME} is the number of MERIT ambulances. The MERIT teams consist of a number of doctors, who have additional skills in a pre-hospital setting. The MERIT teams also involve critical care paramedics who have additional advanced skills compared to the paramedics who work within the normal ambulance teams. Further, let $fe_1, fe_2, \dots, fe_{n_{FE}}$ be a set of fire engines located at FRS that are used to transport Fire And Rescue teams (FAR) to incident sites, where n_{FE} is the number of fire engines. Let $isv_1, isv_2, \dots, isv_{n_{ISV}}$ be a set of incident support vehicles located at FS that are used to transport Search And Rescue teams (SAR) to the incident sites, where n_{ISV} is the number of incident support vehicles. The SAR teams can rescue trapped casualties at an incident site and move them to a CCS or a POS based on the casualties' classifications. The SAR teams are specially equipped personnel when compared to normal fire and rescue teams. The FAR team are equipped personnel to respond to fires, accidents and incidents where there are risks to life and property. The crew capacity of na_i, ha_i, me_i, fe_i, isv_i are denoted as CP_{na_i}, CP_{ha_i}, CP_{me_i}, CP_{fe_i}, CP_{isv_i}. The set of responders is $R = P \cup HART \cup MERIT \cup FAR \cup SAR$. Let T be a set of tasks, which are performed by R. Figure 2 indicates the relationship between tasks related to casualties, locations and responders.



Key table

No	Tasks	Duration (m:s)
0	Find a casualty	2:00
1	Free a casualty	3:00
2	Perform primary triage	0:30
3	Administer on-site treatment	3:00
4	Move a casualty to another location	2:00
5	Perform secondary triage	1:30
6	Prepare a casualty for transportation	1:30
7	Collect a casualty	1:00
8	Transfer a casualty to hospital	Based on the distance
9	Administer treatment in transit	5:00
10	Deliver a casualty to hospital	1:00

Figure 2. The Relationship Between Tasks Related to Casualties, Locations, And Responders

In relation to Figure 2, the ten types of tasks allocated to responders are divided into two groups, namely those they will perform and those they may perform, as presented in Table 2. These two groupings are based on responders' expertise and casualties' needs. Tasks that responders *will perform* will be completed in the actual pre-defined duration of each task. However, tasks that responders *may perform* will take longer (twice as long) than the pre-defined duration due to the lower degree of expertise of the associated responder. In the WZ, there are a number of casualties who might be trapped and thus need to be freed before being triaged. Primary triage, i.e., triage sieve, is required in the WZ to assess the condition of casualties before they receive any treatment. The CCS and POS are locations set up for a number of purposes: (a) to perform secondary triage, i.e., triage sort, due to the possibility of deterioration in casualties' health conditions during the response; (b) to provide further treatment; (c) to prepare casualties for transportation to hospitals. An ALP is the location for ambulances to collect casualties before transporting them to hospitals.

Table 2. Tasks Responders Will Perform or May Perform (Using Numbering in Figure 2)

Responders	Will perform	May perform
SAR teams	0,1	-
FAR teams	4	0,1
HART teams	2,3,6	-
MERIT teams	3,4,5,6	-
Paramedic teams at WZ	4,6	2,3
Paramedic teams at CCS	4,6	3,5
Paramedic teams at POS	3,4,5,6	-
Paramedic teams at ALP and normal ambulances	7,8,9,10	-

Modelling Casualties' Health Profiles

As a result of an MCI, casualties may suffer from one or more injuries, which have been categorized into six groups: head; facial wounds; chest; soft-tissue wounds; extremity; external (Aylwin et al., 2006). The sequence of generating a health profile of each casualty *c* is as shown in Figure 3.

Step 1 — Initialize the binary parameters that represent the injuries that casualty *c* may suffer (except head injury see Step 2) and whether or not he/she is trapped; in each case 0 and 1 indicate no and yes, respectively.

↓

Step 2 — Initialize the integer parameter that represents the head injury where 0, 1, 2 and 3 indicate no injury, severe, moderate and mild injury, respectively.

↓

Step 3 — Based on Step 1 and Step 2, initialize the ability to walk, *AW*, and vital signs parameters (a) the respiratory rate *RR*; (b) pulse rate *PR*; (c) systolic blood pressure *SBP*; (d) Glasgow Coma Score *GCS* which represents motor, verbal, and eyes response.

↓

Step 4 — Determine the triage sieve decision based on *WA*, $RR_{original,c}$ and *PR* to classify casualty *c* into immediate, urgent, or delayed.

↓

Step 5 — Generate $RR_{new,c}$ based on $RR_{original,c}$ *where* $RR_{new,c} = v \text{ x } RR_{original,c}$.

↓

Step 6 — Determine the triage sort decision based on the measured *SBP*, *GCS* and $RR_{new,c}$ to re-classify casualty *c* into immediate, urgent, or delayed using Revised Trauma Score System (RTSS).

Figure 3. The Sequence of Generating the Casualties' Health Profiles

Using the literature as a basis, Table 3 indicates where a relationship exists between the types of injuries and the vital signs in order to initialize Step 1 and 2. Face and soft tissue wound injuries do not affect vital signs; however, they are included in Table 3 for completeness. Only casualties with no injuries or with face and/or soft tissue wound injuries are considered to be able to walk. Table 4 presents the range of the vital sign parameters *RR* (breaths/m), *PR* (breaths/m), and *GCS* to initialize Step 3. The *SBP* is set in the range 30-140 mmHg for all casualties (ALSG, 2012) as it is not affected directly by any type of injuries that have been considered in the presented model, as mentioned in Table 3. In Step 4, a casualty who can walk is classified as delayed. However, for a casualty who is unable to walk, he/she is classified as urgent if *RR* and *PR* are in the range 10-29 and 60-119 (breaths/m), respectively; otherwise, a casualty is classified as immediate (ALSG, 2012).

Table 3. Relationship Between the Types of Injuries and Vital Signs Based on The Literature

Injuries	*AW*	Vital signs			
		RR	***PR***	***SBP***	***GCS***
Head	(NICE, 2014)	-	-	-	(NICE, 2014)
Face					
Chest	(Bhalla, Frey, Rider, Nord, & Hegerhorst, 2015)			-	-
Soft tissue wounds					
Extremity	(Atiyeh, Gunn, & Dibo, 2013)	-	-	-	-
External	(Ahuja & Bhattacharya, 2004)			-	-

Table 4. The Vital Sign Parameters Range Associated with The Type of Injuries

Chest	*RR*	*External*	*PR*	*Head*	*GCS*
0	12-20	0	60-100	0	13-15
				1	13-15
1	1-11 OR 21-40	1	101-190	2	9-12
				3	3-8

In Step 5, $RR_{original,c}$ indicates the value of *RR* of casualty *c* measured at triage sieve, and *v* is a coefficient ∈ [0.1-1.2]. The $RR_{new,c}$ indicates the value obtained at triage sort for the same casualty *c*. Updating $RR_{original,c}$ ensures the associated health classification of *c* is correct at the time of triage sieve. The $RR_{original,c}$ is more likely to improve or stabilize if a casualty is classified as delayed or receives on-site treatment, i.e., $v \in [1.0\text{-}1.2]$. In contrast, $RR_{original,c}$ can deteriorate if *c* is classified as urgent or immediate without receiving treatment, i.e., $v \in [0.1\text{-}0.9]$. Updating the $RR_{original}$ may contribute to a casualty's health classification transitioning from one state to another. In Step 6, scores of 15 and 14 lead to a casualty being classified as delayed and urgent, respectively, whereas all other scores result in a casualty being classified as immediate. In relation to Figure 2, some tasks will be performed only in certain circumstances. For example, casualties will only need to be freed if trapped, on-site treatment at the WZ will only be administered to casualties suffering from severe injuries, such as head and/or external injuries, and they will be moved directly to the ALP to be transferred to the allocated hospital (NICE, 2014). Casualties with chest and/or extremity injuries will only receive on-site treatment either at the CCS or POS based on their health classification (Atiyeh et al., 2013; Bhalla et al., 2015). Further treatment will be given to casualties with chest injuries on the way to hospital (Bhalla et al., 2015).

Tasks' Duration

The actual duration of tasks, except transferring a casualty to the allocated hospital task (i.e., Task 8), is pre-defined due to the absence of such data; these are indicated in Figure 2. To determine the duration of Task 8, a realistic and detailed representation of the geographical area under consideration, along with key locations such as incident sites and hospitals, is required. The GIS data is constructed using Ordnance Survey MasterMap (OSM) (OSM, 2020) and modelled as an undirected graph *G*. OSM's ITN Layer is used as this has sufficient details to determine the route and distance between any two locations, and thus the travelling time between them can be calculated. Dijkstra's algorithm is applied to find the shortest distance between any two locations (Dijkstra, 1959). Due to the absence of data related to the speed of ambulances in MCIs, the data used in (McCormack & Coates, 2015) was adopted to simulate road traffic. This was done by varying vehicle speed according to the day and time of the incident.

Aims and Associated Objective Functions

The model presented in this paper is designed to co-ordinate the emergency services and optimize the allocation and scheduling of resources efficiently. It aims to reduce the suffering of casualties which is measured by minimizing three associated objectives, namely the time taken to deliver to hospital the last immediate casualty across all incident sites f_1 (s); the time taken to deliver to hospital the last urgent casualty across all incident sites f_2 (s); the response time, which is the time taken to deliver to hospital the last casualty of any type across all incident sites f_3 (s). These objectives are measured in minutes and seconds. In the context of this paper, suffering relates to the injuries' that casualties suffer and their corresponding health classification, which may vary during the emergency response.

The associated objective functions f_1 (s), f_2 (s), and f_3 (s) are defined in a lexicographic approach which shows the level of their importance. In the lexicographic approach, the search will be carried out according to the order given to the objective functions. In our case, $f_1(s_{new})$ is compared with $f_1(s_{current})$, if it is improved, the current plan will be replaced with the new one; if no improvement has occurred, the new plan is discarded; if $f_1(s_{new})$ is as same as $f_1(s_{current})$, the same procedure applied to f_1 will be applied to the next objective function and so on (Talbi, 2009). The reason for applying the given sequence is to give priority to the immediate and then urgent casualties during the response as there is a chance of them losing their lives when they are waiting on-site for a responder to assist them (e.g., freed if trapped, treated, and/or transported).

The associated objective functions f_1 (s) and f_2 (s) can be recorded during the calculation of f_3 (s) as the time from the moment of the first journey of each normal ambulance through to the delivery of the final casualty to hospital. To obtain the emergency response time f_3 (s), the workload of each normal ambulance in minutes is determined as indicated in (1),

$$\forall i \; W_{na_i} = \sum_{j=1}^{m} d_{na_i,c_j^{hc}} \tag{1}$$

where i represents the number of normal ambulances from 1 to n_{NA}, m is the number of casualties allocated to normal ambulance na_i, and hc is the health classification of casualty c_j^{hc}.The parameter $d_{na_i,c_j^{hc}}$ denotes the duration of normal ambulance na_i delivering each casualty c_j^{hc} from the assigned incident site to the allocated hospital. Casualties can only be allocated to a hospital providing the capacity of that hospital has not been exceeded. Then, the value of f_3 (s) is obtained by minimizing the maximum workload across all normal ambulances as represented in (2),

$$f_3(s) = min\, max\, W_{na_i} \tag{2}$$

Equations (3) and (4) indicate the times of delivering the last immediate casualty and the last urgent casualty to hospital, respectively.

$$\forall i \; DTI_{na_i} = \sum_{j=1}^{m} d_{na_i,c_j^{hc}} \text{ , where } hc = \text{ immediate} \tag{3}$$

$$\forall i \; DTU_{na_i} = \sum_{j=1}^{m} d_{na_i,c_j^{hc}} \text{ , where } hc = \text{ urgent} \tag{4}$$

The priority of casualties to be transported to the allocated hospitals depends on their health classification. The maximum times of delivering to hospital the last immediate casualty (see (5)) and the last urgent casualty (see (6)) across all incident sites, via a normal ambulance na_i, are both minimized. As a result, suffering is indirectly reduced.

$$f_1(s) = min\, max\, DTI_{na_i} \tag{5}$$

$$f_2(s) = min\, max\, DTU_{na_i} \tag{6}$$

Model Assumptions

A number of assumptions have been made in the model presented in this paper including: (a) casualties are available at each incident site at the beginning of the response; (b) casualties are treated according to their injuries and transported to hospitals based on the priority of their health classification; (c) the health classification of no casualty will deteriorate leading to their life being lost; (d) responders remain at their incident site locations unless they are travelling to a hospital with a casualty, however, the movement between locations to carry casualties to the CCS, POS, or ALP is allowed; (e) immediate casualties must be transferred individually to a hospital by a normal ambulance whereas up to two delayed casualties can be transferred in a single normal ambulance from an incident site to a hospital.

SOLUTION METHOD: 'THE NEIGHBOURHOOD SEARCH ALGORITHM'

The NSA has been developed to solve the co-ordination problem described earlier. The NSA consists of ten structures applied to alter the current plan. These structures are: (1) changing the order of processing one task related to a casualty assigned to a selected normal ambulance, subsequentially, the rest of the tasks assigned to the same ambulance will be shifted up or down in the schedule; (2) allocating a casualty to a different normal ambulance; (3) swapping two casualties allocated to the same normal ambulance; (4) swapping two casualties within different normal ambulances; (5) allocate a casualty from the normal ambulance that has the highest workload to the one with the lowest workload; (6) allocating a casualty to a different hospital; (7) swapping the assigned hospital of two selected casualties; (8) allocating a task related to a casualty to a different responder who is able to perform that task; (9) swapping two selected tasks related to two casualties located at the same associated location, i.e. WZ, CCS, and POS, at an incident site between two responders' schedules; (10) allocate a task related to a casualty from the workload between the responder who has the highest to the one with the lowest where both responders are from the same type of responder and located at the same associated location at an incident site. In each iteration of the NSA, one structure is chosen randomly and applied to the current plan. The new plan generated in each iteration is only accepted when there is an improvement when compared with the current plan using the lexicographic approach mentioned earlier; otherwise, the new plan is discarded. Pseudocode for the NSA is given in Algorithm 1.

Algorithm 1. The Neighbourhood Search Algorithm

```
s_current ← generateInitialPlan ()
s_new ← ∅
converged ← false
while (!converged) do
    structure ← genRandStruc[1, 10]
    S_new ← genNeighborhood (s_current, structure)
    isImproved ← lexicographic(s_new, s_current)
    if (isImproved)
        s_current ← s_new
    else
        converged ← convergence (s_current)
    end if
end while
output(s_current)
```

Four approaches have been established to develop an initial response plan. The approaches include: (a) a fully random task assignment; (b) the same as (a) but with all responders assigned at least one task; (c) the same as (a) but with all responders assigned an equal number of tasks (if possible); (d) using a form of a genetic algorithm (GA) with 100 iterations being applied in each of which tournament selection, crossover, and elitism techniques are used. In this paper, a set of 50 initial response plans were generated using each approach (a) to (d). The best response plan was selected from the generated set of individuals to be the initial emergency response plan, which will be optimized by the NSA. The impact of each approach on the performance of the NSA is discussed in the 'Results and Discussion' section.

CASE STUDY

The case study consists of a number of casualties, with varying condition and injuries, located at multiple incident sites to be attended to by a number of responders from different locations such as ambulance stations, fire and rescue stations and hospitals. In terms of a response, a number of responders will be allocated to each incident site to perform a number of tasks related to casualties. Subsequently, casualties will be delivered to one of a number of hospitals via a number of normal ambulances.

The hypothetical three incidents are assumed to occur on Saturday at 1.00 p.m. at three locations in Birmingham, namely Arena Birmingham (AB), Sunset Park (SP), Think-Tank Science Museum (TSM). Birmingham was chosen as it is the second-largest population centre in the UK, after London. The case study involves: two ambulance stations, namely Immediate Care Medical (ICM) and St John Ambulance Station (SJ); two fire stations, namely West Midlands (WM) and Ladywood Community (LC); two hospitals, namely City Hospital (CH) and Queen Elizabeth Hospital (QEH), each of which has a limited casualty capacity. Figure 4 shows a map of Birmingham city where the top right and bottom left coordinates are (463751, 288244) and (408752, 283527), respectively. Table 5 shows the available emergency service vehicles at each location, with each vehicle accommodating three responders.

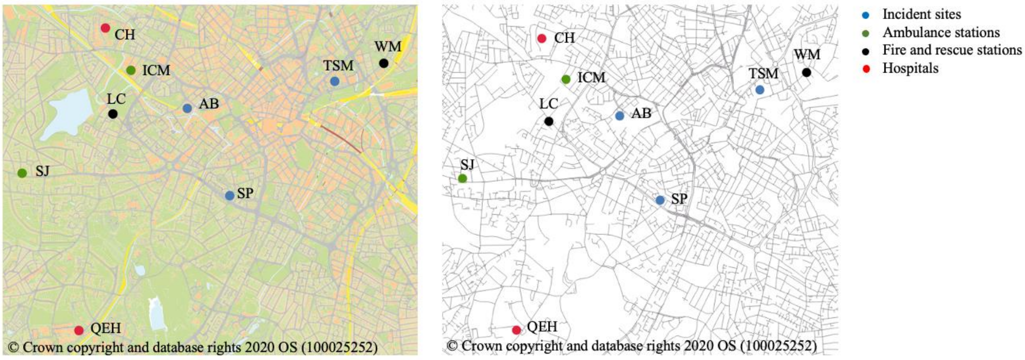


Figure 4. Map of Birmingham. The Topography and Road Network Layer on The Right and Left Images, Respectively

Table 5. Available Vehicles at Labelled Locations in Figure 4

Resources	**ICM**	**SJ**	**QEH**	**CH**		**WM**	**LC**
n_{HA}	2	1	0	0	n_{FE}	2	2
n_{ME}	2	2	0	0	n_{ISV}	2	3
n_{NA}	4	3	1	2			

Three scenarios are considered in which the number of casualties and their injury levels, as well as the hospital casualty capacity, are set to different values as shown in Table 6 and Table 7.

Table 6. The Distribution of Casualties and Their Health Profiles

Scenario	**Incident sites**	**Casualties**	**Trapped**	**Type of injuries**			
				Head	**Chest**	**Extremity**	**External**
1	AB	40	14	32	21	24	20
	SP	20	13	14	10	11	7
	TSM	10	4	10	2	4	7
	Total	70	31	56	33	39	34
2	AB	50	25	33	21	22	25
	SP	30	11	21	14	15	15
	TSM	20	11	14	7	7	14
	Total	100	47	68	42	44	54
3	AB	100	37	71	60	48	48
	SP	50	26	36	22	29	29
	TSM	50	27	36	23	25	26
	Total	200	90	143	105	102	103

Table 7. Casualty Capacity of Hospitals

Scenarios	**CH**	**QEH**
1	50	40
2	70	80
3	90	140

RESULTS AND DISCUSSION

For each scenario, Figure 5 presents the value of each objective function for (i) each of the four approaches to develop the best initial plan and (ii) the associated final plan generated by the NSA. The response times of the initial plans developed by the four approaches corresponds to the largest value of the three objectives, which increases from scenario (a) to (b) to (c) due to the increasing number of tasks associated with those scenarios. Scenario 1 involves 698 tasks associated with 70 casualties distributed between the three incidents sites. In contrast, scenario 2 and 3 contain 1090 and 2003 tasks associated with 100 and 200 casualties, respectively, distributed between three incident sites. In Figure 5, for approach (a), the initial plans developed for scenario 1, 2 and 3 had a response time of 532.75, 651.5 and 1201 minutes, respectively. For approach (b), the response time for scenarios 1, 2, and 3 are 605, 710.5 and 1237.5, minutes, respectively, whereas for approach (c), the three scenarios' response times are 517.5, 644.25 and 1181.5 minutes. Approach (d) generated initial plans for scenario 1, 2, and 3 with response times 480, 595.5 and 963.25 minutes. By comparing the response time of the initial plans generated using all four approaches, it can be seen that approach (d) results in the shortest response time across all three scenarios. To assess the influence of the initial plan on the performance of the NSA in generating an optimized final plan, the execution times of the four approaches and the NSA for the three scenarios were recorded as shown in Table 8.

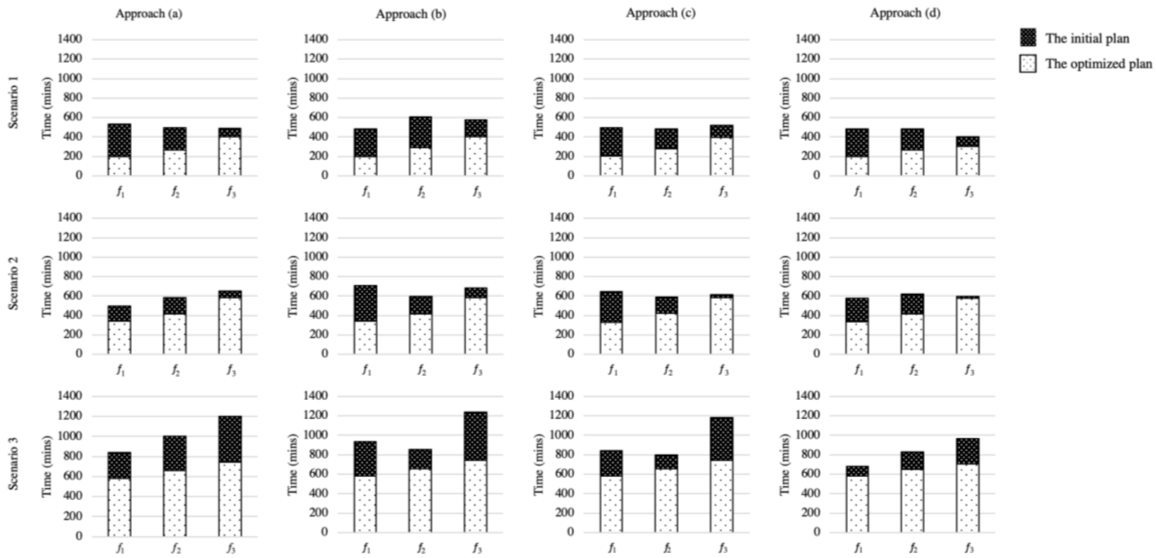


Figure 5. Values of Objective Functions for Each Scenario-Approach Combination

Table 8. The Execution Times of The Four Approaches and the NSA

Scenario	Approach	Execution time (milliseconds) to generate			Diff in %
		Initial plan	NSA optimized plan	Total	
1	a	123	84616	87456	-11
	b	107	87333	84723	-7
	c	140	94536	94676	0
	d	**9389**	**61120**	**70509**	**-29**
2	a	183	119506	119689	-13
	b	193	110037	110230	-21
	c	213	136097	136310	0
	d	**19744**	**79525**	**99269**	**-31**
3	a	434	244362	244796	-23
	b	475	245497	245972	-23
	c	478	307974	308452	0
	d	**30638**	**143782**	**174420**	**-56**

Table 8 indicates that the execution times of the four approaches to generate an initial plan for scenario 1 are less than those for scenarios 2 and 3. This is due to the reason mentioned earlier regarding an increasing number of casualties in each scenario leads to an increase in the number of the tasks associated with casualties. For all scenarios, approaches (a) and (b) generated initial plans faster than (c) and (d). Indeed, approach (d), which uses a form of a GA to generate initial plans, has the greatest execution times. On comparing the execution times of the NSA to optimize the plans generated by the four approaches, it is observed that the NSA optimizes the initial plans generated by approach (d) in the shortest time across all three scenarios; i.e., for scenario 1, 2, and 3, the execution time is 61120, 79525, and 143782 milliseconds, respectively. This observation suggests that using approach (d), which takes the longest execution time to generate an initial plan of the four approaches considered, followed by the NSA, leads to the lowest overall execution time to create an optimized plan. In other words, applying approach (d) to generate the initial plans followed by the NSA for scenario 1, 2, and 3 reduces the total execution time by approximately 29%, 31% and 56%, respectively, when compared to the highest execution times recorded by using approach (c) then the NSA.

In Figure 5, it can be seen that by applying the NSA to the initial plans, the effect of the lexicographic approach on the final optimized plans is clear. As the priority of the proposed model is to optimize f_1, then f_2, and then f_3, the value of f_1 in each optimized plan is the lowest and the value of f_3 is the highest, which represents the response time of the optimized plan. For scenario 1, the final optimized plans developed using the NSA following the application of approaches (a), (b), (c) and (d) to develop initial plans, have similar values of f_1 ranging from 200.2 to 200.4 minutes, and similar values of f_2 varying from 263.4 to 269.1 minutes. However, using the NSA following approaches (a), (b) and (c), the value of f_3 varies from 399.0 to 399.7 minutes, whereas using (d) the value is 300.3 minutes. For scenario 2, using approaches (a) to (d) followed by the NSA, yields values of f_1 and f_2 in the final optimized plans that are almost equal, with the former ranging from 340.2 to 343.4 minutes and the latter from 417.0 to 420.2 minutes. However, the value of f_3 is the lowest using approach (d) followed by the NSA at 578.5 minutes, whereas for the other three approaches range from 582.9 to 583.7 minutes. Similarly, scenario 3 sees the application of approach (d) followed by the NSA yielding the best (lowest) values for all three objection functions. In summary, for all scenarios considered, approach (d) is selected to generate the initial plan due to its ability to develop a good initial plan with the shortest response time. Further, the initial plan generated reduces the execution time taken by the NSA to develop the final optimized plan and achieve a better optimized plan in terms of objective function values.

Due to space limitations, the result of one scenario, i.e., scenario 1, will be discussed in terms of the final optimized plan generated by the NSA. Table 9 shows the distribution of responders between the associated static locations at each of the three incident sites. In the final optimized plan, 39 responders travelling in 13 vehicles, i.e., 3 per vehicle, are allocated to AB. Given that AB has the highest number of trapped casualties, i.e., 14, 9 SAR members and 6 FAR members are allocated from LC to this incident site. Further, 15 responders, travelling in 5 vehicles, are allocated to TSM given that there are 10 casualties of which 4 are trapped. These 5 vehicles are allocated from ICM, WM and CH, which are the closest stations and hospital to the incident site. The incident site SP is attended by vehicles from QEH and all stations except LC, as all vehicles available at this Fire and Rescue station are dispatched to the closer incident site, i.e., AB, which has the highest number of casualties. It is noted that the allocation of responders to incident sites is not only affected by the distance between locations and the number of casualties, but also by the casualties' health profiles. That is, the NSA allocated the responders based on the casualties' needs to ensure that all tasks related to each casualty are completed in the minimum time possible.

Table 9. The Distribution of Responders Between the Associated Static Locations at Incident Sites

Incident sites and associated static locations		AS						FRS				H	
		ICM			SJ			WM		LC		QEH	CH
		HART	MERIT	P	HART	MERIT	P	FAR	SAR	FAR	SAR	P	P
AB	WZ	3	0	0	3	0	0	0	0	6	9	0	0
	CCS	0	0	3	0	3	6	0	0	0	0	0	0
	POS	0	0	3	0	0	3	0	0	0	0	0	0
SP	WZ	0	0	6	0	0	0	6	3	0	0	0	0
	CCS	0	3	0	0	3	0	0	0	0	0	0	0
	POS	0	0	0	0	0	0	0	0	0	0	3	0
TSM	WZ	3	0	0	0	0	0	0	3	0	0	0	3
	CCS	0	3	0	0	0	0	0	0	0	0	0	0
	POS	0	0	0	0	0	0	0	0	0	0	0	3

Table 10 shows the changes in the health classification of casualties between triage sieve in the WZ and triage sort in either the CCS or POS. When performing triage sort, an improvement was seen in the health classification of 7, 2, and 2 casualties at AB, SP, and TSM, respectively. Further, no deterioration was recorded when performing triage sort, reinforcing that casualties received on-site treatment needed to stabilize their conditions.

Figure 6(a) and Figure 6(b) show the total number of casualties received at each hospital and the total number of casualties allocated to each hospital from each incident site, respectively.

Table 10. The Changes in Health Classification of Casualties

Incident sites	Triage sieve			Triage sort		
	Immediate	Urgent	Delayed	Immediate	Urgent	Delayed
AB	23	14	3	20	10	10
SP	11	4	5	10	3	7
TSM	4	4	2	4	2	4

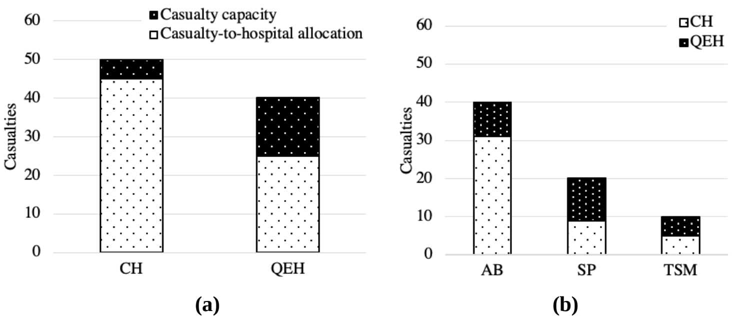


Figure 6. Casualty-to-Hospital Allocation

In Figure 6(a), a total of 45 casualties is allocated to CH and 25 casualties to QEH. In Figure 6(b), a total of 31 casualties is delivered from AB to CH, which takes 21.41 minutes per journey compared to 39.25 minutes per journey to QEH. Due to the distance between either hospital and SP being approximately equal, 11 and 9 casualties are delivered to QEH and CH, respectively. The distance between TSM and QEH is 25.75 km; however, half of the casualties at this incident site have been delivered to QEH despite the available casualty capacity at CH, which is 5.25 km closer to TSM than QEH. This indicates that the NSA is unable to achieve a better final optimized plan even if more than half the casualties located at TSM were delivered to CH, which is due to the plan's overall response time being dependent on the time taken by normal ambulances to deliver casualties from AB and SP to hospitals.

CONCLUSION

Multiple MCIs require many emergency actions to be undertaken quickly during a disaster to cope with the rapid changes in the situation and environment. During the response to multiple MCIs, a number of co-ordination problems need to be solved, namely the allocation and scheduling of vehicles-to-incident sites, responders-to-casualties, vehicles to transport casualties to hospitals, and task assignment to responders and vehicles. In this paper, a comprehensive casualty health profile is considered. Further, an optimization-based approach, incorporating a NSA, to solve the co-ordination problem has been presented. Prior to the NSA being deployed, a number of approaches to develop initial plans have been considered to provide the NSA with a better starting plan to be optimized. A hypothetical multiple MCI has been modelled in which three multiple MCI scenarios are considered. In these scenarios, the number of casualties and their injury levels, as well as casualty capacity of hospitals, vary. For each scenario, the final optimized plan generated by the NSA followed the application of one of four approaches to develop an initial plan, namely (a) a fully random task assignment, (b) the same as (a) but with all responders assigned at least one task, (c) the same as (a) but with all responders assigned an equal number of tasks (if possible), (d) using a form of GA. For all scenarios considered, approach (d) performed best in generating an initial plan with the shortest response time. Further, the initial plan generated using approach (d) reduced the execution time taken by the NSA to develop the final optimized plan and achieve a better optimized plan in terms of objective function values. In the final optimized plan generated for scenario 1, it is noted that the allocation of responders-to-incident sites and responders-to-casualties are not only influenced by the distance between locations and the number of casualties at incident sites but also by the casualties' health profiles.

In terms of future work, the casualties' health profiles will be updated dynamically during the response to multiple MCIs. In addition, multiple MCIs occurring at different times during the response will be introduced. These dynamic changes will require re-scheduling the tasks associated with casualties that were already assigned to responders and re-allocating the normal ambulances that were allocated to travel to certain casualties at incident sites. In addition, re-allocating casualties that have been allocated to certain hospitals is required in consideration of their respective casualty capacity limit. Moreover, due to human error, information regarding the number and location of casualties at incident sites could be incorrect. Thus, the impact of reporting incorrect information to the emergency center on the overall response time is being considered in future work.

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