An optimisation-based decision support model to dynamically coordinate the pre-hospital response of emergency services' resources to multiple mass casualty incident

by

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A thesis presented for the degree of

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This thesis is dedicated to

my mother Aisha.

A Thesis Presented for the Degree of
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Abstract

Effective coordinated responses to Mass Casualty Incidents (MCIs), which can occur suddenly and without notice, play a vital role in saving lives and reducing suffering. MCIs can result in a number of casualties with different levels of injury severity, requiring immediate lifesaving intervention. The complexity involved in responding to MCIs increases significantly due to the dynamic nature of such events as new information becomes available during the response. New information may include 1) an update on the number of casualties at an incident site, 2) identifying any casualties with deteriorating health requiring immediate lifesaving interventions, 3) the occurrence of a new incident site or sites as the response unfolds, resulting in additional casualties requiring lifesaving interventions, and/or 4) the response to an incident site or sites is completed, resulting in a number of emergency responders becoming available to be deployed to another incident site or sites.

Due to the importance of effective coordinated responses to MCIs, this thesis develops a novel dynamic optimisation-based decision support model to coordinate the emergency services' response to MCIs. The model comprises a pre-hospital response framework (PHRF) and an MCI environment, and a coordination and management interface that facilitates information exchanges between the environment and framework. The PHRF consists of optimisation-based algorithms, including a greedy heuristic algorithm, a genetic algorithm, and a neighbourhood search algorithm. The application of these algorithms results in the generation of a pre-determined attendance (PDA) response plan followed by an initial optimised post-PDA response plan, and then optimised post-PDA response plans based on new information that becomes available as the MCI response unfolds. Within the PHRF, an approach has been developed to manage the seamless transition from one optimised post-PDA response plan to another. Collectively, the aforementioned plans provide a continuous, coordinated response of the emergency services' resources to be implemented in the MCI environment. The PHRF is coupled with an MCI environment that provides a realistic road network of the affected geographical area at which the actual key locations, including incident sites, ambulance stations and fire and rescue stations, and hospitals, are accurately identified. In addition, comprehensive health profiles of casualties are modelled, which can be used dynamically to simulate casualties' health, including their deterioration, during the response to MCIs.

In relation to the application of the decision support model, two case study areas have been considered to simulate the coordinated emergency response to multiple MCIs. Central London represents the first case study area considered and was chosen due to it being a densely populated area, coupled with having a significant number of emergency resources and hospitals. Further, in recent times, it has been subjected to a number of MCI 'terrorism' events, including the 2005 London bombings. Birmingham city centre was selected for the second case study area due to being the UK's second most populous city, and this area enables the consideration of the emergency response to a different city layout and locations of emergency services' resources and hospitals. As a result of the model's application, key findings are reported. Also, the results generated from the model are verified using grounding and calibration techniques. In addition, based on an evaluation of the performance of the model, its strengths and weaknesses are identified.

Finally, areas of possible future work are recommended to improve the developed decision support model.

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List of Abbreviations

ACPO	**A**ssociation of **C**hief **P**olice **O**fficers
ALP	**A**mbulance **L**oading **P**oint
AMP	**A**dvanced **M**edical **P**ost
ART	**A**daptive **R**easoning **T**echnique
BAS	**B**loomsbury **A**mbulance **S**tation
BA	**B**irmingham **A**rena
BCH	**B**irmingham **C**ity **H**ospital
BFS	**B**illesley **F**ire **S**tation
BL	**B**lood **L**oss
BM	**B**ritish **M**useum
BNS	**B**irmingham **N**ew **S**treet
BP	**B**lood **P**ressure
CC	**C**ommand and **C**ontrol
CCS	**C**asualty **C**learing **S**tation
CHP	**C**annon **H**ill **P**ark
CWH	**C**helsea and **W**estminster **H**ospital
DFS	**D**owgate **F**ire **S**tation
DSRM	**D**esign **S**cience **R**esearch **M**ethodology
E	**E**xperiment
EFS	**E**uston **F**ire **S**tation
EOC	**E**mergency **O**perational **C**entre
ES	**E**mergency **S**ervices
EUS	**E**mbankment **U**nderground **S**tation

FAR	**F**ire **a**nd **R**escue
FAS	**F**ulham **A**mbulance **S**tation
FFS	**F**ulham **F**ire **S**tation
FLA	**F**orward **L**oading **A**lgorithm
GA	**G**enetic **A**lgorithm
GCS	**G**lasgow **C**oma **S**cale
GH	**G**uy’s **H**ospital
GHA	**G**reedy **H**euristic **A**lgorithm
GIS	**G**eographical **I**nformation **S**ystem
HART	**H**azardous **A**rea **R**esponse **T**eam
HFS	**H**ighgate **F**ire **S**tation
HMFS	**H**ay Mills **F**ire **S**tation
HP	**H**yde **P**ark
HPC	**H**ealth **P**rofile of **C**asualty
HZ	**H**ot **Z**one
KCH	**K**ing’s **C**ollege **H**ospital
LAS	**L**ondon **A**mbulance **S**tation
MCI	**M**ass **C**asualties **I**ncident
MERIT	**M**edical **E**mergency **R**esponse **I**ncident **T**eam
MS	**M**anagement **S**cience
NHS	**N**ational **H**ealth **S**ervice
NSA	**N**eighbourhood **S**earch **A**lgorithm
NS	**N**eighbourhood **S**tructure
OAS	**O**val **A**mbulance **S**tation
OC	**O**xford **C**ircus

OKRFS	**O**ld **K**ent **R**oad **F**ire **S**tation
OR	**O**peration **R**esearch
OS	**O**rdnance **S**urvey
PDA	**P**re-**D**etermined **A**ttendance
PFS	**P**addington **F**ire **S**tation
PFS	**P**eckham **F**ire **S**tation
PHRF	**P**re-hospital **R**esponse **F**ramework
POS	**P**lace **o**f **S**afety
PR	**P**ulse **R**ate
QEH	**Q**ueen **E**lizabeth **H**ospital
QGIS	**Q**uantum **G**eographical **I**nformation **S**ystem
RCD	**R**equirements of **C**oordination **D**ecision
RLH	**R**oyal **L**ondon **H**ospital
RME	**R**equirements of **M**odelling an MCI **E**nvironment
RPM	**R**espiration, **P**ulse, and **M**otor response
RR	**R**espiratory **R**ate
SAR	**S**earch **a**nd **R**escue
SD	**S**tandard **D**eviation
SFS	**S**oho **F**ire **S**tation
SJWAS	**S**t **J**ohn’s **W**ood **A**mbulance **S**tation
SMH	**S**t **M**ary’s **H**ospital
SP	**S**unset **P**ark
START	**S**imple **T**riage **a**nd **R**apid **T**reatment
STM	**S**acco **T**riage **M**ethod
TRTS	**T**riage **R**evised **T**rauma **S**core

TSA	**T**abu **S**earch **A**lgorithm
UCH	**U**niversity **C**ollege **H**ospital
VND	**V**ariable **N**eighbourhood **D**escent
WAAS	**W**aterloo **A**mbulance **S**tation
WAES	**W**estminster **A**mbulance **S**tation
WBAS	**W**est **B**romwich **A**mbulance **S**tation
WBFS	**W**est **B**romwich **F**ire **S**tation
WMAS	**W**est **M**idlands **A**mbulance **S**tation

List of Nomenclature

IS	A set of incident sites.
is_i	A single incident site, where i is the index of that incident site.
n_{is}	The total number of incident sites.
l_{is_i}	The location of incident site is_i
C	A set of casualties.
c_q	A single casualty, where q is the index of that casualty.
n_c	The total number of casualties at all incident sites.
C_{is_i}	A set of casualties at incident site is_i, where $C_{is} \subseteq C$.
AS	A set of ambulance stations.
as_j	A single ambulance station, where j is the index of that ambulance station.
n_{as}	The total number of ambulance stations in the affected geographical area.
FS	A set of fire and rescue stations.
fs_k	A single fire and rescue station, where k is the index of that fire and rescue station.
n_{fs}	The total number of fire and rescue stations in the affected geographical area.
ER	A set of emergency responders of all types.
er_n	A single emergency responder, where n is the index of that emergency responder.
n_{er}	The total number of emergency responders at all ambulance stations and fire and rescue stations.
ER_{per}	A set of emergency responders of a particular type per, where $ER_{per} \subseteq ER$.
per	The type of an emergency responder or a set of emergency responders, where $per \in \{\text{SAR}, \text{FAR}, \text{HART}, \text{paramedic}, \text{MERIT}\}$.
n_{er,as_j}^{per}	The number of emergency responders of type per initially located at ambulance station j.
n_{er,fs_k}^{per}	The number of emergency responders of type per initially located at fire and rescue station k.
EV	A set of all emergency vehicles of all types.
ev_p	A single emergency vehicle, where p is the index of that emergency vehicle.

n_{ev}	The total number of emergency vehicles located at all ambulance stations and fire and rescue stations.
EV_{pev}	A set of emergency vehicles of a particular type pev, $pev \in \left\{\begin{matrix}\text{HART ambulances, MERIT ambulances, standard ambulances,} \\ \text{fire engines, incident support vehicles}\end{matrix}\right\}$.
n_{ev,as_j}^{pev}	The total number of emergency vehicles of a particular type pev initially located at ambulance station as_j.
n_{ev,fs_k}^{pev}	The total number of emergency vehicles of a particular type pev initially located at fire and rescue station fs_k.
H	A set of hospitals.
h_m	A single hospital, where m is the index of that hospital.
n_h	The total number of hospitals in the affected geographical area.
c_q^{hi}	The severity of the head injury of casualty c_q.
c_q^{fi}	Signifies if casualty c_q suffers from facial wounds.
c_q^{ci}	Signifies if casualty c_q suffers from a chest injury.
c_q^{si}	Signifies if casualty c_q suffers from soft tissue wounds.
c_q^{bi}	The severity of the burn injury of casualty c_q.
c_q^{ei}	The severity of the extremity injury of casualty c_q.
c_q^{RR}	The respiratory rate of casualty c_q.
c_q^{PR}	The pulse rate of casualty c_q.
c_q^{SBP}	The systolic blood pressure of casualty c_q.
$c_{q,t}^{BL}$	The blood loss of casualty c_q.at time t
c_q^{GCS}	The degree of consciousness of casualty c_q.
c_q^{t}	Signifies if casualty c_q is trapped at the incident site.
c_q^{phc}	The health classification of casualty c_q based on performing a primary triage (Triage Sieve).
c_q^{shc}	The health classification of casualty c_q based on performing a secondary triage (Triage Sort).
c_q^{w}	Signifies if casualty c_q is abile to walk.
TC	A set of all tasks associated with all casualties at all incident sites.

$tc_{s,q}^{pr}$	A single task associated with casualty c_q, where *pr* refers to the index of the preceding task associated with casualty c_q that must be completed to allow a particular emergency responder to process task tc_s.
n_{tc}	The total number of tasks associated with all casualties at all incident sites.
$n_{er,is,t}^{per}$	The number of emergency responders of each particular type per, who are considered for reallocation to a new incident site.
$n_{c,is,t}$	The number of casualties at new incident site is that occurred at time t.
$\sum_{w=0}^{w=l} rc_{is_w,t}$	The total number of remaining casualties at another incident site or sites at which the response is still ongoing at time *t* where *l* is the number of other incident sites.
$n_{er,t}^{per}$	The number of emergency responders of type per, who are available at time t, across all other incident sites with tasks yet to be completed.
$n_{er,is_v,t}^{per}$	The number of emergency responders of each particular type per to be reallocated to each new incident site, is_v, where *v* represents the index of the new incident sites.
$\sum_{v=0}^{v=z} n_{c,is_v,t}$	The total number of casualties located at all new incident sites that occurred at time t, where z is the number of new incident sites that occurred at time t
n_{er,is_v,t_2}^{per}	The number of emergency responders of each particular type per to be reallocated to each new incident site, is_v, at time t_2, where *v* is the index of new incident sites under consideration and t_2 is the time at which the most recent new incident occurred.
n_{c,is_v,t_2}	The number of casualties at the new incident site is_v at time t_2
$\sum_{w=0}^{w=l} rc_{is_w,t_2}$	The total number of remaining casualties at other incident sites at which the response is still ongoing at time t_2 and *l* is the number of other incident sites.
$\sum_{v=0}^{v=z} n_{c,is_v,t_2}$	The total number of casualties at new incident sites at time t_2 yet to be allocated to emergency responders, and z is the number of the most recent new incidents that occurred.
n_{er,t_2}^{per}	The number of emergency responders of a particular type per, who are available at time t_2, across all other incident sites with tasks yet to be completed.
$f_1(\mathrm{x})$	The arrival time to the assigned hospital of the final immediate casualty across all incident sites.
$f_2(\mathrm{x})$	The arrival time to the assigned hospital of the final urgent casualties across all incident sites
$f_3(\mathrm{x})$	The total processing time of all casualties.
$f_4(\mathrm{x})$	The emergency response time

tc^{ct}_{s',c^I_q}	The completion time of the final task s'associated with the final immediate casualty c_q across all incident sites.
tc^{ct}_{s',c^U_q}	The completion time of the final task s'associated with the final urgent casualty c_q across all incident sites.
pt_{c_q}	The processing time of each casualty.
tc^{st}_{s,c_q}	The starting time of the first task s associated with casualty c_q (locating a casualty at an incident site (Task 0)).
tc^{ct}_{s',c_q}	The completion time of the final task s' associated with casualty c_q (unloading casualties from a normal ambulance once he/she has arrived at the assigned hospital (Task 9)).
$tc^{ct}_{s',c_{q'}}$	The completion time of the final task s' associated with the final casualty $c_{q'}$ of any health classification across all incident sites.

Chapter 1. Introduction

Mass casualty incidents (MCIs) can occur in a short time and cause widespread damage to infrastructure, humans, fauna, and flora [1]. Examples of such events include the coordinated terrorist attacks in September 2001, where the World Trade Centers (WTC) in lower Manhattan, New York, were targeted. This attack resulted in significant damage to both buildings that subsequently collapsed [2], over 25,000 people being injured with varying degrees of severity, almost 3000 deaths, and significant disruption to infrastructure and property of the surrounding area [3]. A more recent MCI was the 7/7 London bombings of July 2005 in the UK, where four coordinated terrorist attacks targeted commuters using London’s public transport network during the morning rush hour. The London attack resulted in 52 deaths, more than 700 people being injured, and the destruction of the transport network in central London, resulting in mass disruption across the entire city [4]. A further example was the coordinated terrorist attack in Paris in November 2015, where six attacks were planned almost simultaneously, lasting approximately 30 minutes across multiple locations. The attack included gunmen and suicide bombers, resulting in 138 deaths, wounding hundreds, and more than 100 being seriously injured [5]. All these examples are considered MCIs [6].

MCIs typically occur in densely populated urban areas, frequently in places where people visit, congregate, or pass through [7], and therefore result in mass casualties. Although MCIs can occur anywhere, the most common locations include shopping centres, markets, retail stores, stadiums, schools, universities, airports, hotels, high streets, places of worship, rail stations, parks, and other public locations. In Section 1.1, the motivation for the thesis is presented, followed by the aim and objectives in Section 1.2. In Section 1.3, the contribution of the presented research is identified. In Section 1.4, the selected research methodology is discussed. Subsequently, the structure of the thesis is presented in Section 1.5.

1.1 Motivation

The UK national terrorism threat level has been substantial since 2019 and increased to be severe in 2020, indicating that a terrorist attack is highly likely to occur [7]. After the London bombings, the London Ambulance Service reported a number of failures [8], including:

- a lack of communication that resulted in a failure to deploy the precise number of ambulances to the different incidents;
- a lack of essential supplies and equipment at the incident sites;
- a failure to dispatch ambulances to hospitals from the incident site, resulting in delays in transporting casualties to hospitals.

Therefore, it is crucial that the decision-making process which coordinates the emergency services' resources in an MCI event is improved so as to avoid future failures.

Due to the significant number of casualties involved in MCIs, local emergency services and hospital treatment capabilities can potentially become overwhelmed. In this context, the term 'emergency services' refers to ambulance and fire and rescue services. In the immediate aftermath of an MCI, many rapid and interrelated decisions need to be made — from the initial allocation of emergency resources to delivering the casualties to hospitals [6]. The decisions that need to be made require a prior and obvious understanding as regards coordinating the roles of emergency services effectively and utilising the limited number of resources efficiently. However, the rationale for making these decisions is likely to change over time as the MCI response unfolds. The dynamic changes in the information received pose a challenge for decision-makers to make rapid and effective operational decisions [9] and for emergency resources and hospitals in the affected area to cope with new information [7, 10]. There is no doubt that experience accrued from previous incidents is a critical ingredient in an effective and successful emergency response. However, the development of a decision support model that best comprehends the nature of an MCI and thus allows for coordinating the response of emergency services' resources will allow decision-makers to explore and simulate all possible scenarios that may occur during an MCI event.

1.2 Aim and objectives

This research aims The primary objective of this study is to enhance the process of decision-making in the context of effectively coordinating the resources of emergency services during real-time responses to MCIs. The coordination of emergency services resources in mass casualty incidents can be facilitated through the development of a dynamic decision support model, taking into account the limitations that have been identified in the existing models. Therefore, this research seeks an answer to the following research question:

To what extent can the ***interrelated decisions*** *in coordinating the response of the* ***emergency services' resources*** *to* ***multiple near-simultaneous*** *MCIs in a* ***realistic and complex environment*** *be assisted through the use of a dynamic optimisation-based model?*

The term *interrelated decisions* indicates that such decisions have to be determined based on other decisions. For example, which incident site should a particular responder be sent to is directly related to a decision about which casualty that responder will be assigned to upon arrival at the incident. A further discussion of such decisions will be presented in Chapter 4, Section 4.3.

The term *emergency services' resources* involve a number of multiple fire and rescue stations and ambulance stations in which several types of resources, including different types of emergency responders with various levels of expertise and knowledge and different types of emergency vehicles, are located.

The term *multiple near-simultaneous* MCIs refers to a number of incidents that may occur at exactly the same time (i.e., simultaneously) or in close succession (i.e., semi-simultaneously). In such cases, an additional set of casualties needing lifesaving and/or medical interventions are introduced, requiring the reallocation of emergency responders and rescheduling their schedules.

The *realistic MCI environment* includes modelling the road network using Geographic Information Systems (GIS) data of the MCI-affected geographical area. By using the GIS data, the actual location of ambulance, and fire and rescue stations, hospitals, and incident sites can be specified, and the distance between these locations can be determined. Furthermore, the realistic MCI environment includes modelling the incident sites, ambulance and fire and rescue stations and associated emergency responders and vehicles, hospitals, and casualties and tasks associated with them based on the literature. However, police services have not been considered in the decision support model presented in this thesis because they are not directly related to casualties at incident sites.

The MCI environment is *complex* in terms of coordinating the emergency services' resources of various types and responsibilities in a dynamic MCI environment and dealing with the new information that is revealed as the response to MCIs unfolds, requiring updating the current response plan.

In order to address the research question stated above, there are three sub-questions that should be addressed throughout this research.

RQ1) How are emergency resources coordinated through the response to MCIs, and what information is needed by decision makers to coordinate this response?

RQ2) To what extent can existing decision support models for this response be improved with dynamic optimisation-based modelling?

RQ3) How can such modelling assist with multiple near-simultaneous MCIs?

The following objectives need to be met to achieve the aim of the research:

1) Identify and review previously published models, with a specific focus on identifying a suitable approach that ensures a coordinated emergency response during the response to an MCI.
2) Identify the limitation in previously published models relating to the coordination of the emergency service resources in MCIs.
3) Identify and develop an enhanced understanding of the role that emergency services play in responding to MCIs.
4) Identify the interrelated decisions that are important when coordinating emergency service resources during in MCIs.
5) Model a realistic MCI environment, including:
    - the road network of an MCI-affected geographical area using GIS data. The road network must also include important information relating to the actual locations of ambulance, fire and rescue stations, hospitals, incident sites and the various routes between all of the above.
    - the locations of incident sites, including the number of casualties with a range of injuries, from life-threatening to non-life threatening.
    - the locations of ambulance, fire and rescue stations, including the different emergency vehicles located at these sites.
    - the locations of ambulance, fire and rescue stations, including emergency responders with a variety of expertise and knowledge at these sites.
    - the locations of the hospitals where casualties will be allocated to.
    - a comprehensive and dynamic casualty health profile that is able to represent the current health status of casualties based on previously published literature.

- identify the specific tasks related to each casualty, such as the need to be rescued or requiring urgent treatment based on their injuries, using previously published literature. Such an approach ensures that an emergency responder with suitable expertise and knowledge is able to manage the casualty, and the time required to complete the tasks associated with each casualty can be incorporated into the developed decision support model.

6) Develop a decision support model that is able to model real-time events based on the MCI as it unfolds.
7) Identify and define suitable experiments that can be incorporated into the developed decision support model to assess the developed model's efficacy.
8) Simulate the pre-defined experiments and generate results that can then be discussed while highlighting novel and important findings.
9) validate the developed decision support model to assess the reliability of the results generated and assess the generalisability of the findings.
10) evaluate the efficacy of the developed decision support using evaluation techniques.

1.3 Contribution

The original and significant contribution to knowledge of this study is to develop a dynamic model that includes a mathematical optimisation model to solve the coordination problem in the emergency response to multiple evolving MCIs, with the aim of modelling the MCI environment more comprehensively and realistically than previous models in the domain of MCIs. The model continually and effectively coordinates the emergency responders and vehicles of ambulance, and fire and rescue stations and efficiently allocates, reallocates, schedules, and reschedules these limited resources. The original and significant contribution of the present research is thus five-fold: 1) modelling a realistic GIS-based environment; 2) modelling incident sites and considering a dynamic occurrence of incidents during the response to MCI; 3) modelling casualties with varying levels of severity of injuries and simulating their health dynamically using comprehensive health profiles; 4) modelling interrelated tasks associated with casualties; 5) dynamically reallocating the emergency resources and rescheduling of response plans as the MCI response unfolds.

A realistic GIS-based MCI environment

The MCI environment includes a GIS-based representation of any area of the UK currently under consideration, which enables defining the road network of the chosen area and indicating the actual numbers and locations of hospitals, and ambulance and fire and rescue stations located in that area. Furthermore, various types of emergency vehicles and responders are initially located at these stations. Emergency responders with various levels of expertise, knowledge, and interrelated responsibilities are considered at these stations.

Dynamic occurrence of incidents

Multiple incident sites are considered to occur at exactly the same time, in close succession, and/or a single new incident occurs sequentially, introducing new sets of casualties, requiring lifesaving and/or medical interventions. As the occurrence of new incident sites can arise at any time as the response unfolds, the complexity of coordinating the emergency response increase.

Casualties with varying levels of severity of injuries.

Casualties are initially located at incident sites. The model employs comprehensive and dynamic casualties' health profiles to enable the status of casualties' health to be dynamically simulated during the response to MCIs. The health profile of a casualty refers to the current health status of a casualty. It includes information related to injuries, vital signs and degree of consciousness, triage decisions, and other important parameters.

Interrelated tasks associated with casualties.

Interrelated tasks associated with casualties are modelled to be undertaken by emergency responders at incident sites. Each type of emergency responder can administer a number of specific tasks depending on his/her type, knowledge, and degree level of expertise. The duration of these tasks varies between emergency responders and is computed based on the type and degree level of expertise of emergency responders and/or severity level of injury of casualties.

Dynamic reallocation of the emergency services' resources and rescheduling of response plans.

The model continually allows dynamic reallocation of the emergency responders and rescheduling of their tasks to cope with the rapid and frequent changes in information pertaining to incident sites as the MCI response unfolds to reflect the situation at hand. For example, the occurrence of new incidents, the deterioration of casualties' health, and the completion of the response to incident sites. The developed dynamic decision support model ensures the continuity of executing the optimised response plans by minimising the transition time between successive optimised response plans that have been generated to reflect the situation at hand. The term 'transition time' refers to the time when emergency responders may have no scheduled tasks to undertake due to the reallocation and rescheduling processes.

1.4 Research methodology

The research presented in this thesis follows the Design Science Research Methodology (DSRM) proposed in [11]. The DSRM is widely advocated in scholarly research publications as it incorporates principles, practices, and processes required to conduct such research [12]. The DSRM consists of six phases: (1) problem identification and motivation; (2) objectives of a solution; (3) design and development; (4) demonstration; (5) evaluation; (6) communication. The flow chart of the DSRM is presented in Figure 1.1.

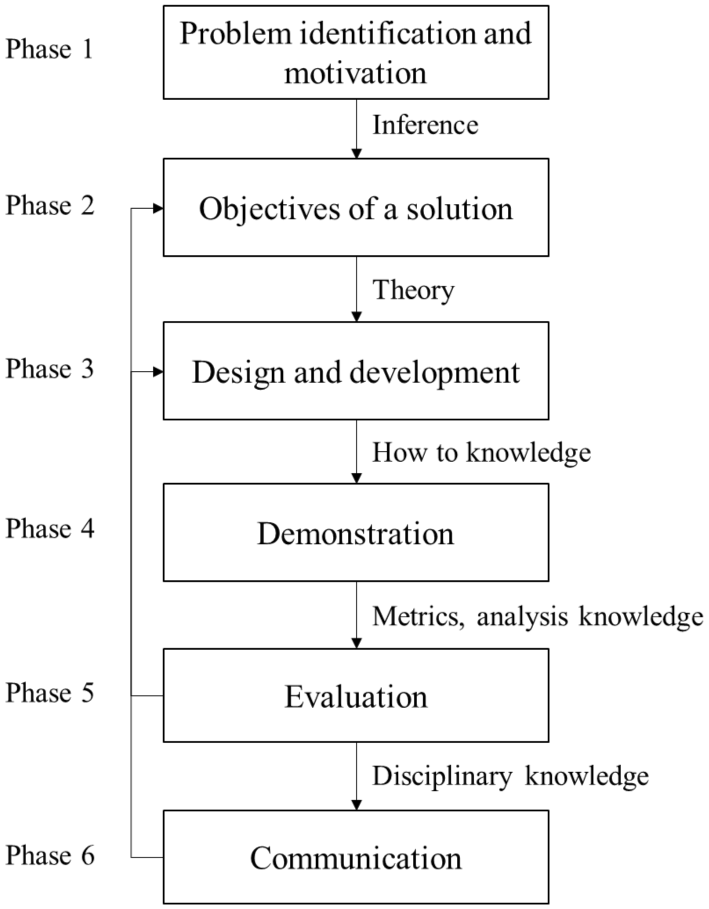


Figure 1.1: The Design Science Research Methodology (based on [11]).

In Phase 1, the research problem is defined, and the importance of the research is highlighted. Prior knowledge of the problem and the awareness of the importance of devising a solution to the problem is required. In Phase 2, the objectives of a solution are derived from defining the research problem and knowledge of what is feasibly achievable. Knowledge of the state of such a problem and current solutions is required. In Phase 3, the proposed and designed solution is provided, in which a research contribution is embedded, requiring an understanding of the theory behind the proposed solution. In Phase 4, a demonstration of the use of the proposed solution in solving one or multiple instances of the problem is provided. Implementing the proposed solution using case studies and experiments is essential in this phase. Prior knowledge of applying the proposed solution to the problem is required. In Phase 5, the solution is evaluated to measure how well the proposed solution solves the problem. In Phase 6, the defined problem and its importance, the proposed solution and its contribution to knowledge, and the rigour of its design are documented in a scientific form, for example, a thesis or article. The DSRM allows reference back to earlier phases, in particular from Phase 5 or Phase 6 back to Phase 2 or Phase 3, depending on the nature of the research.

1.5 Thesis structure

This thesis comprises thirteen chapters, including the introduction. A brief description of the contents of each chapter, including the linkages between chapters (mapped with the phases of the chosen research methodology), is presented in Figure 1.2.

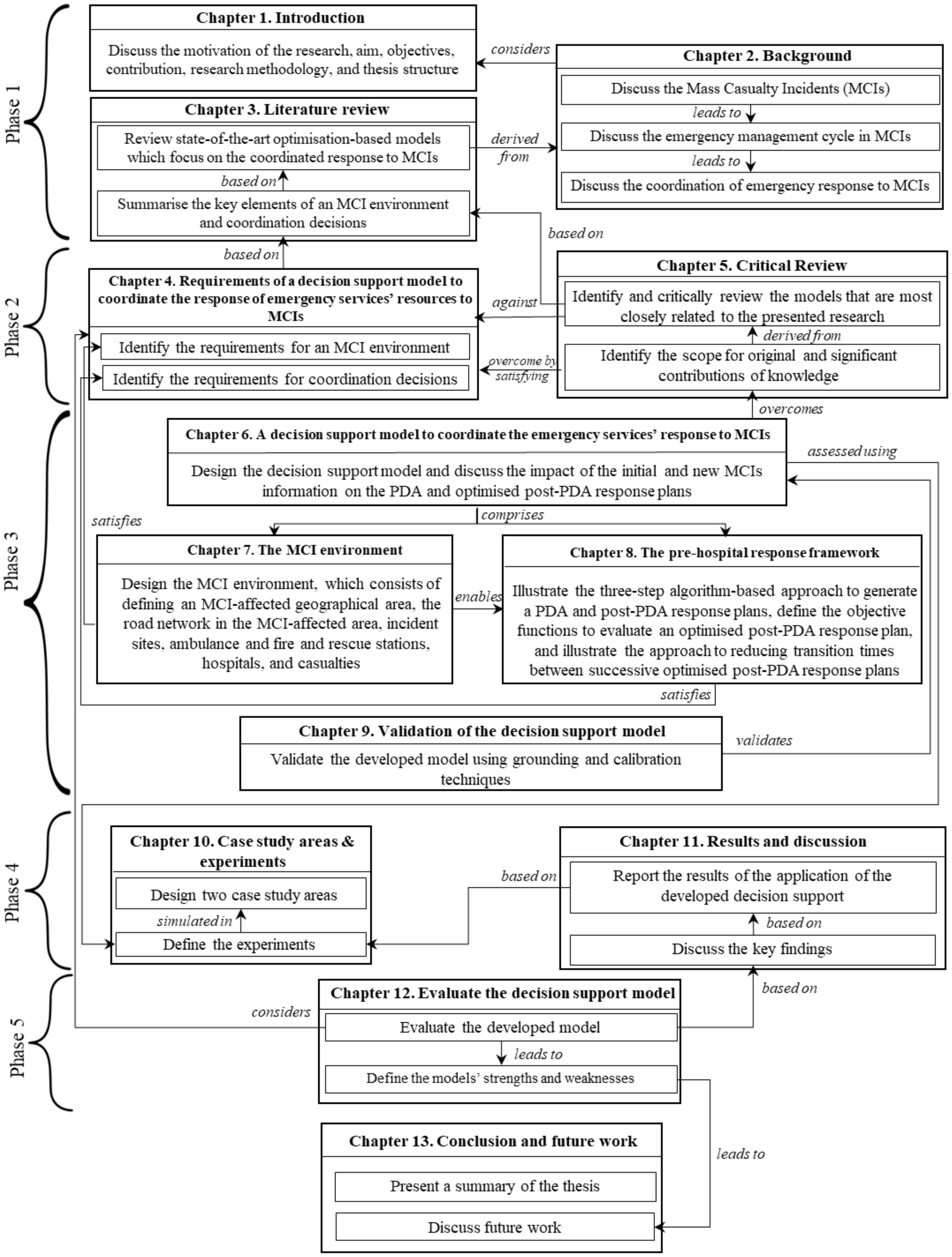


Figure 1.2: Thesis structure.

Phase 1 - Problem identification and motivation (related to Chapters 2 and 3)

- Chapter 2 partially addresses **RQ1** by providing an understanding of the terms MCI, response, and coordination in the context of emergency response to MCIs. Furthermore, Chapter 2 discusses the types and complexity of MCI supported with examples.
- Chapter 3 reviews state-of-the-art optimisation-based models which focus on the coordinated response to MCIs in order to identify the key elements of an MCI environment required to develop a decision support model to coordinate the response of emergency services' resources to MCIs. This chapter, in conjunction with Chapter 2, fully addresses **RQ1.**

Phase 2 - Objectives of a solution (related to Chapters 4 and 5)

- Chapter 4 aims to define the requirements of modelling an MCI environment and coordination decisions for a decision support model to coordinate the response of emergency services' resources to MCIs based on the key elements of an MCI environment and the coordination decisions identified in Chapter 3. This chapter partially defines **RQ2** and **RQ3**.
- Chapter 5 aims to evaluate the models reviewed in Chapter 3 and identifies a subset of models that most closely relate to the key elements identified in Chapter 3. Then, the subset of models is critically reviewed against the requirements defined in Chapter 4. As a result of the critical review, an original and significant contribution to knowledge in this research area is defined. This chapter completes the definition of **RQ2** and **RQ3**.

Phase 3 - Design and development (related to Chapters 6 to 9)

- Chapter 6 presents a novel decision support model to coordinate the response of emergency services' resources to MCIs, which comprises a pre-hospital response framework (PHRF) and an MCI environment and a coordination and management interface that facilitates information exchanges between the environment and framework. The development of the decision support model considers the literature reviewed in Chapter 4 and aims to overcome the limitation defined in Chapter 5.
- Chapter 7 presents the design of the MCI environment of a decision support model to coordinate the response of emergency services' resources to MCIs based on the requirements of modelling an MCI environment defined in Chapter 4.
- Chapter 8 presents the three-step algorithm-based approach within the PHRF of the decision support model, which has been designed to generate a pre-determined attendance

(PDA) response plan, an initial post-PDA response plan, and optimised post-PDA response plans based on initial or newly available information as the MCI response unfolds. The three-step algorithm-based approach is designed based on the requirements of coordination decisions defined in Chapter 4. In addition, it defines the objective function used to evaluate the optimised post-PDA response plan. Furthermore, this chapter presents the design of the approach to reducing the transition times between successive optimised post-PDA response plans due to the dynamic changes in the MCI environments that require generating new optimised post-PDA response plans that reflect the situation at hand.

- Chapter 9 validates the developed decision support presented in Chapters 6 to 8 using two validation techniques: grounding and calibration. This chapter, in conjunction with Chapters 6, 7 and 8, fully addresses **RQ2**.

Phase 4 - Demonstration (related to Chapters 10 and 11)

- Chapter 10 defines two case study areas representing two Mass Casualty Incident (MCI) environments and designs a number of experiments to simulate the coordinated emergency response to MCIs in two cities in the UK: central London and Birmingham city centre. The experiments defined in this chapter are used to assess the application of the decision support model presented in Chapters 6 to 8.
- Chapter 11 presents the results of the application of the decision support model presented in Chapters 6 to 8 from sixteen experiments defined in Chapter 10. Furthermore, in this chapter, the key findings will be discussed, which, in conjunction with Chapter 10, fully addresses **RQ3**.

Phase 5 – Evaluation (related to Chapter 12)

- Chapter 12 assesses the decision support model presented in chapters 6 to 8 against the requirements defined in Chapter 3 and defines the model’s strengths and weaknesses.

Conclusion and future work

- Chapter 13 concludes the work presented in this thesis and outlines the research’s original and significant contribution to knowledge. Furthermore, based on the evaluation of the model presented in Chapter 12, the limitations of the model presented in this thesis are identified, and promising avenues for further research are discussed.

1.6 Summary

This chapter presented the motivation for the research as well as the corresponding aim and objectives. The aim of the presented research has been discussed, which is to develop an optimisation-based dynamic model to coordinate the emergency response to multiple MCIs. The study’s originality and significant contribution to knowledge were highlighted, and the structure of the thesis was discussed. The DSRM was chosen to structure the thesis. Additionally, this chapter illustrated the work presented in this thesis and showed the linkage between the chapters. The next chapter will present the background of MCI events and discuss the challenges faced by emergency services during the response to MCI.

Chapter 2. Background

2.1 Introduction

Events that occur suddenly and without notice, resulting in a number of casualties who are likely to suffer from a variety of serious injuries that exceed the resources of the emergency services in a specific geographical area, are referred to as Mass Casualty Incidents (MCIs) [13, 14]. Each casualty affected during the MCI could require rescue from the incident site, triage at the incident site, and a set of specific medical and lifesaving interventions provided by emergency responders. The involvement of multiple agencies, including ambulance and police services, fire departments, and hospitals, combined with the ever-evolving environment of an MCI and a variety of information sources relating to casualties, can all significantly increase the complexity and difficulty of MCI responses [14]. This chapter aims to discuss **RQ1**, which was initially introduced in Chapter 1 and is restated below.

How are emergency resources coordinated through the response to MCIs, and what information is needed by decision makers to coordinate this response?

This chapter discusses the various definitions of an MCI from various sources, including those of the UK Cabinet Office [7], the Association of Chief Police Officers [15], and the National Health Service [16]. Furthermore, in this chapter, the different types of MCIs that can occur and their associated complexity will be discussed, with examples included for illustrative purposes (Sections 2.2.1 and 2.2.2). This chapter will also provide an introduction relating to the emergency management cycle, which consists of mitigation, preparedness, response, and recovery (Section 2.3). The complexity of initiating an MCI will also be discussed with the viewpoints of emergency responders on the ground, including surgeons and physicians who have participated in the response to MCIs [17, 18]. Insight from emergency responders involved on the ground in an MCI is invaluable for acknowledging the challenges MCIs can cause and how these are different from those caused by daily incidents [10]. Insight from emergency responders also identifies the need for a deeper understanding of disaster principles and management, as well as the necessity of well-developed preparedness plans, which is the focus of this thesis. Therefore, this chapter presents a particular focus on the response phase to discuss the term ‘coordination’ in the context of emergency responses to MCIs (Section 2.4).

2.2 Mass casualty incidents

The UK Cabinet Office defines MCIs as incidents resulting in a number of casualties on a scale that exceeds the capacity of emergency resources and overwhelms emergency services and hospitals [7]. Similarly, the Association of Chief Police Officers defines MCIs as emergency events or situations with severe consequences where special arrangements are required to be implemented by one or multiple services [15]. For the National Health Services, an MCI is an emergency event or situation that results in serious damage to human life or causes a large number of fatalities or injuries, necessitating the implementation of special arrangements [16]. However, others claim that the number of casualties resulting from an incident and/or the scale of the incident itself is by themselves insufficient to determine whether or not that incident constitutes an MCI [13]. For example, an incident causing a *large number of casualties* with *no or minor injuries* who manage to self-evacuate and which can be handled by hospitals without the need for any other services, is not considered an MCI. In contrast, a *large number of casualties* with *severe injuries* requiring lifesaving interventions from multiple services is considered an MCI. Similarly, if there is a *lack* of emergency resources when a small-scale incident occurs, which has caused relatively *few casualties*, the incident is also deemed an MCI because the number of casualties exceeds the capacity of emergency services' resources [19, 20]. However, *large-scale* incidents which result in *no or minor injuries* are not considered MCIs. These examples confirm that the severity of the injury of casualties, the number of casualties, and the extent of available emergency services' resources are important factors in determining the incident as an MCI. As indicated in [21], the main characteristic that distinguishes an MCI from an everyday incident is the number of casualties that exceeds the capacity of the available emergency services and overwhelms local hospitals.

2.2.1 Types of an MCI event

Indeed, MCIs differ in nature, size, and their impact on society and the local infrastructure. Nonetheless, they may also share certain characteristics, such as dealing with a large number of casualties. In the past, many MCIs occurred that required extraordinary resources and efforts from multiple organisations and agencies [22] (listed ascendingly in Table 2.1). The MCIs presented in Table 2.1 have been considered the most catastrophic and complex MCIs that have occurred globally from the 20th century up to the present [22-25]. Such MCIs can be a reference for local and regional emergency services and agencies around the world to learn from the mistakes made in the past, improve their response to similar incidents, or help mitigate similar consequences [22].

Table 2.1: The most catastrophic MCIs in history (1918- the present) (based on [22-25]).

Location	Type of MCI	Year	Fatalities	Injured
Worldwide	Spanish Flu disease	1918	100,000,000	500,000,000
Ethiopia, Africa	Famine	1983-1985	Over 1,000,000	
Bhopal, India	Chemical	1984	11,000	550,000
Chernobyl, Ukraine	Chemical	1986	Over 80	2,000,000
Lockerbie, UK	Terrorist attack	1988	Over 250	-
Baltic Sea, Europe	Shipwreck	1994	Over 850	-
New York, USA	Terrorist attack	2001	3,000	Over 25,000
Europe	Heatwave	2003	Over 70,000	-
London, UK	Terrorist attack	2005	52	Over 700
Indian Ocean	Earthquake	2004	Over 230,000	-
Kashmir, northern Pakistan	Earthquake	2011	90,000	110,000
West Africa	Ebola virus disease	2013-2016	Over 11,000	Over 28,000
Worldwide	Coronavirus disease	2020- the present	Over 6,000,000	Over 550,000,000

The data presented in Table 2.1 highlights that the types of MCI varied in nature, from natural incidents to man-made incidents [1, 13]. Natural incidents result from natural phenomena such as floods, volcanoes, hurricanes, or earthquakes, which are described as self-propagating in terms of the consequences of illness and diseases, homelessness, and famine [13]. Man-made incidents, particularly terrorist attacks, can occur suddenly in places where a large number of people are present [1]. In countries such as Iraq and Afghanistan, frequent terrorist attacks have resulted in a high number of deaths and injuries over the past two decades [26]. Historically, the UK has been less prone to natural disasters than other countries [10]. However, approximately three to four terrorist incidents necessitating extraordinary resources occurred in the UK every year from 1966 to 1996 [13]. On the 3rd of November 2020, the UK national terrorism threat level increased from substantial to severe, which refers to a highly likely attack [7].

2.2.2 Complexity of an MCI

The complexity of an emergency event can be described using the terms simple, compound, compensated or uncompensated [1, 13]. A simple incident refers to an incident that does not affect the infrastructure but overwhelms local hospitals [13]. An example is the Beslan school massacre in 2004, which was a terrorist attack that occurred in Beslan, North Ossetia-Alania, Russia, resulting in more than one thousand hostages, including more than 700 children, and more than 300 deaths, including 186 children and 31 attackers [27]. A compound incident refers to an incident that damages infrastructure, such as buildings and road network, and overwhelms the emergency services and medical capacity [28]. An example is the London bombings in 2005, which was a terrorist attack that occurred in central London, England, where four coordinated terrorist attacks targeted commuters who used London's public transport network during the morning rush hour. The attacks resulted in 52 deaths and more than 700 people being wounded, besides the destruction of the transport network [4]. A compensated incident describes an incident that does not overwhelm the emergency services but damages infrastructure [13]. The response to such an incident can be managed by additional resources, such as a helicopter with a stabilised camera platform for aerial photography and technical and humanitarian assistance [2]. An example is the New York World Trade Centre attack in 2001, a terrorist attack that occurred in lower Manhattan, New York, where two coordinated terrorist attacks targeted The World Trade Centers (WTC), notably the two tallest buildings in the complex, causing both towers to collapse [2]. The WTC was a 16-acre commercial complex that consisted of seven tall buildings, a large plaza, and an underground shopping mall. The attacks resulted in over 25,000 injured, almost 3000 deaths, and massive disruption to infrastructure and property [3]. An uncompensated incident describes an incident that exceeds the capacity of emergency services, overwhelms hospitals, and cannot be managed by additional resources. An example is the 2007 South Asian floods, multiple concurrent floods in South Asia, particularly in Bangladesh, Bhutan, India, Nepal, and Pakistan. The flood resulted in over 2000 deaths, around 20 million people were displaced, and over 30 million people were affected by flooding, which is considered the worst flooding in history [29].

As mentioned in Chapter 1, densely populated urban places can be a target for MCIs. Such places may not necessarily be busy at all times – the density may vary depending on the time of the day or could be temporary, such as a football match. However, they remain an attractive target for MCIs to harm a large number of people [30]. The consequences of an attack on densely populated urban places can be noticed in one or all of the following [7].

- An increase in the number of fatalities and casualties with severe injuries.
- Significant damage to property and infrastructure.
- Significant damage to the economy, particularly via disruption to businesses and tourism.
- An increase in the demand for emergency services' resources.
- Disruption to essential services, particularly transport, health and education in the affected area.

2.3 Emergency management cycle in MCIs

The emergency management cycle refers to the organisation of emergency resources and their responsibilities toward emergencies [31]. Under Section 1 of the UK's Civil Contingencies Act 2004, the term 'emergency' describes an event or situation that threatens the nation's people, environment, or security [10]. The emergency management cycle is divided into four phases: mitigation, preparedness, response, and recovery. Each phase has its own impact, actions, and challenges [19, 32]. The association between the four phases is shown in Figure 2.1. The first two phases are the pre-event response, and the latter two phases are the post-event response [33]. The pre-event response involves predicting and investigating potential hazards and creating mitigation action plans. The post-event response starts when an incident occurs.

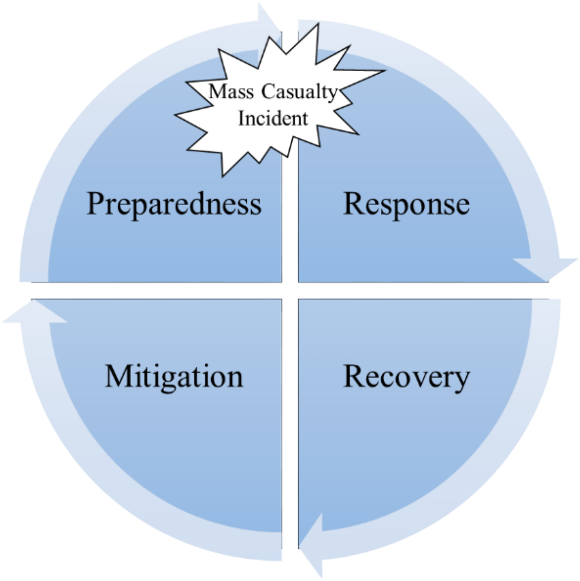


Figure 2.1: Four phases of the emergency management cycle, along with where an MCI event exists (based on [34]).

2.3.1 Mitigation phase

The mitigation phase is a set of ongoing processes that include planning, strategising, and implementing sustained activities prior to an incident [31]. The final product of this phase is a hazard mitigation plan, a document that defines arrangements and policies that are put into action in order to reduce vulnerability to hazards, which leads to sustainable communities [31]. The plan can be implemented as a stand-alone document or as integrated activities of the local emergency operations plan [32]. Effective mitigation aims to prevent future disasters, reduce the likelihood of hazards, and eliminate or reduce the long-term impact on people and property [13]. The mitigation phase involves activities such as preventing the use of high-hazard areas, land use control, establishing building codes and zoning requirements, and barrier construction. Such activities require collaboration from a number of organisations to research, plan, and implement to achieve sustainable communities [31]. Any failure will lead to vulnerable communities not being adequately prepared for environmental disasters (see, for example, [35-38]).

2.3.2 Preparedness phase

The decision to assign the necessary emergency resources to the incidents with the most need is a challenging problem. Accurate information regarding casualties and incidents may not be available in the immediate aftermath of an incident, leading to an unclear picture for emergency services [39]. Effective preparedness in the pre-disaster stage, including the development of effective evacuation plans, will lead to effective emergency response and aid the management of potential disasters [19, 40]. Furthermore, organisations and services are responsible for exercising MCI preparedness in order to maintain their teams' readiness for any challenges that such incidents may present. The readiness is achieved by combining discussion-based and operation-based exercises tailored to meet the needs of practitioners involved in response to MCIs [41]. In general, exercising for MCIs preparedness is resource intensive due to the repetitive and iterative nature of these exercises. Nevertheless, it is essential for practitioners to be exposed to such incidents to become familiar with dealing with similar incidents and increase their confidence in response to such incidents [13, 24]. In addition, exercising for MCIs preparedness allows for continually improving preparedness plans. The importance of the preparedness phase lies in achieving a fast, effective and efficient response [42]. Previously published research, such as [42, 43], focused on studying the importance of involving multiple sectors. Others focused on assessing the preparedness plan and the readiness of healthcare sectors in dealing with certain diseases [44, 45].

As part of emergency preparedness in the UK, a Pre-Determined Attendance (PDA) response is designed based on past mass casualty incident experience and approved by experts on the basis of their knowledge [13]. The PDA refers to the initial response to MCIs in which the type and number of resources and specialists, and the type of equipment, which needs to be sent have been agreed upon in advance [13, 46, 47].

2.3.3 Response phase

Declaring an MCI triggers an emergency response from each emergency service, including the ambulance, and fire and rescue, and police services. Although each of these services has specific responsibilities and roles in response to an MCI, saving casualties' lives is the primary objective of all services. Other objectives common to all services include [13]:

- prevent escalation;
- reduce suffering;
- protect environment;
- protect property;
- bring normalcy back;

- facilitate enquiries.

In the pre-hospital response to MCIs, emergency responders from the ambulance service, fire and rescue service, and police play a critical role in dealing with casualties since they can save lives and reduce fatalities. The pre-hospital response to MCIs covers the period from deploying the first emergency vehicle to the allocated incident site (i.e., activating the PDA response plan) to delivering the last casualty to the allocated hospital [6]. The objective of providing medical and/or lifesaving interventions during the response to MCIs is ‘the greatest good for the greatest number of casualties’, which contrasts with the objective of ordinary medical interventions, ‘the greatest good for the individual patient’ [40].

As per the PDA response, the first team that arrives at the incident site is responsible for collecting information regarding the incident site to declare the incident and start the emergency response. The PDA report contains information regarding the incident location, the number of casualties, their initial health condition, and the need for additional emergency responders and vehicles. The PDA report is not expected to be complete; it is based on what can be seen through the window of the first arriving emergency vehicle and, therefore, is commonly called the ‘window report’ [6]. It aims to indicate the need for emergency resources; therefore, any delay in the PDA report will cause a delay in the pre-hospital response, which may negatively affect the casualties at the incident sites [6, 13].

During the response to an MCI, casualties are triaged, treated if they need, and transported to hospitals. Triage is a process used to quickly assess and prioritise casualties for medical treatment based on the severity of their injuries or medical conditions. Triage typically involves classifying casualties into one of four health classifications: immediate urgent, delayed, or expectant [13, 48].

- Immediate casualty refers to a casualty in a life-threatening condition that requires immediate medical interventions; however, the time is not determined;
- Urgent casualty refers to a casualty in a life-threatening condition but less than an immediate casualty and requires medical interventions within 2-4 hours;
- Delayed casualty refers to a casualty in a less serious or non-critical condition;
- Expectant casualty refers to casualties who have a poor likelihood of survival or those with signs of impending death.

The response phase is widely viewed as the most challenging phase due to the importance of the need for coordination between the emergency services involved in response to MCIs and dealing with the potential lack of resources [10, 49]. Failure to respond to MCIs can lead to catastrophic consequences for casualties, emergency responders, residents, families, and communities for an extended period [50].

2.3.4 Recovery phase

Once the response to an MCI is declared complete, indicating that all casualties were delivered to or collected to be transported to the assigned hospitals from the incident site, the incident will transition from the response to the recovery phase. In the recovery phase, a set of long-term and short-term actions are carried out to rehabilitate the damaged area and restore the infrastructure, including water, electricity, and sewer systems. The long-term actions aim to return the normalcy as quickly as possible or at least to an acceptable level. The long-term actions include defining action plans to obtain new resources, rebuilding damaged structures, and repairing economic damages [19]. The short-term actions include restoring essential services such as search and rescue [31]. A lack of research addressing the recovery phase can be noticed [9]. Previously published research, such as [51, 52], focused on the recovery phase after natural disasters; however, the type of incident was not specified in [53-55].

The above discussion demonstrates that the four phases are not independently isolated from each other. Rather, the emergency management cycle is a continuous process in which multiple services and organisations are likely to implement specific arrangements and activities simultaneously in several phases. Given that the coordination of the emergency response to MCIs in the context of preparedness is the focus of the research presented in this thesis, the study is framed from the point of time when MCIs occur to the point when the final casualty is delivered to the assigned hospital.

2.4 Coordination of emergency response in MCIs

Coordination has been a long-standing interest of researchers [56]. Coordination theory has been proven to be an effective and successful theory in coordinating people, resources, and tasks in multiple fields [56, 57]. From the coordination theory perspective, the term ‘coordination’ is defined as managing dependencies between activities. The term ‘dependency’ refers to the interdependence of people, resources, and tasks. First come/first serve and priority order are examples of mechanisms for managing dependency with regard to coordination theory [58]. This creates distinctive challenges in coordinating available resources when all emergency services are suddenly required to work together and coordinate their activities [59]. However, the pressure on such emergency services increases due to the lack of accuracy in the available information and the high demand for up-to-date information regarding MCIs [14]. Therefore, coordinating emergency services during the response to MCIs is critical and subject to severe time pressure [13, 14, 60, 61].

Emergency responders, including surgeons and physicians, who have participated in response to MCIs admit to underestimating the difficulties and associated challenges that they encountered in achieving an effective coordinated emergency response [17, 18]. Insight from emergency responders identifies the need for a deeper understanding of disaster principles and management, as well as the necessity of well-developed preparedness plans. The Greater London Authority reported that the emergency response to the London bombings was complicated and difficult due to the involvement of multiple casualties at multiple locations, multiple emergency services, and local agencies. They emphasised that the coordination of such services and agencies was important in a hazardous situation where communications between them were difficult, further events were uncertain and unexpected, and the causes of such events were unclear [8]. Further, the Metropolitan Police described the situation aftermath of the London bombings as chaotic, where information regarding the nature of the incident, the number of casualties and fatalities, and the actual location of the bombings was unclear [8].

The coordination challenges caused by MCIs differ from those caused by daily incidents [10]. During MCIs, in a short period of time, emergency services and hospitals with limited resources available face a large number of casualties suffering from injuries with varying levels of severity requiring rapid lifesaving and/or medical interventions. The effective coordination of the limited available emergency services that respond to an MCI is vital if as many casualties as possible are to be saved [13]. Specifically, coordination challenges may arise due to (1) the limited number of responders initially located at the numerous emergency service stations, each of which can undertake a number of specific tasks [14, 59, 62], and (2) a high demand on local hospitals and emergency resources in a short period of time [40]. The dynamic changes in the MCI information as the response progresses, which require that the response plan is continuously updated to reflect the changing situation at hand, poses a further challenge [2].

To sum up, the coordination problem identified in response to MCIs is related to managing the activities of multiple emergency services where multiple types of emergency responders and vehicles are required to respond to multiple incident sites with casualties in varying degrees of severity as so to save lives and reduce suffering. This statement emphasises the importance of effective coordination between emergency services to lead to effective emergency response and meet the objectives of the response to MCIs previously discussed in Section 2.3.3.

2.5 Summary

This chapter partially addressed RQ1 by discussing the various definitions of an MCI from different perspectives, including the UK Cabinet Office, the Association of Chief Police Officers, and the National Health Services. Further, the types and complexity of an MCI event were discussed and supported with examples. Then, the emergency management cycle was illustrated, which consists of four associated phases, namely mitigation, preparedness, response, and recovery, each of which was discussed individually. The term ‘coordination’ was explained, and the challenges faced by emergency services responding to MCIs were discussed. As indicated in this chapter, the research presented in this thesis focuses on coordinating the emergency response in MCIs, particularly man-made incidents in densely populated urban places, in the context of preparedness. The next chapter will provide a state-of-the-art review of related models in the domain of emergency response to MCIs.

Chapter 3. Literature review

3.1 Introduction

Effective emergency response is crucial for mitigating the impacts that Mass Casualty Incidents (MCIs) have on public health, safety, and infrastructure [40] whilst achieving the primary objective of all emergency services, saving the lives of casualties [13]. Richard et al. [63] identified the potential for decision support models to facilitate the coordination of responses to MCIs and other major incidents. The development of decision support models for coordinating the response of emergency services to MCIs can be essential for providing automaticity regarding informed coordination decisions and supporting emergency service decisions in real-life MCIs [14, 63]. Decision support models aim to provide a comprehensive view of an MCI event based on simulations of various scenarios to enable emergency services to understand the incident site and therefore facilitate effective decision-making during the response to an MCI [56]. In addition, by analysing the simulated scenarios, emergency services can identify potential risks and develop strategies to mitigate them, which may be beneficial for the preparation and planning of potential MCIs [40]. Furthermore, these models are able to determine the optimal allocation of the available resources, which may avoid wasting resources and contributes to a reduction in any delays for medical intervention, and reduce mortality, and morbidity during and in the aftermath an MCI event. This chapter provides a continuation of the exploration of **RQ1**, which was restated in Chapter 2.

This chapter aims to review state-of-the-art optimisation-based models (Section 3.2), which focus on the coordinated response to man-made incidents in densely populated urban areas [61, 62, 64-75]. However, the models presented in [61, 67-75] fall outside the definition of man-made incidents, although they do cover some relevant elements of any type of such incidents, including modelling the road network, emergency resources, and casualties. Moreover, the aforementioned models may only implicitly involve the coordination of emergency responses to MCIs. However, there is no explicit mention of coordination itself. This chapter aims to identify and discuss the key elements required to develop a decision support model for the coordination of emergency response to MCIs (Section 3.3).

3.2 Optimisation decision support model in response to MCI

Optimisation models focused on the coordinated response to man-made incidents [62, 64-66] are reviewed in Section 3.2.1. This is followed in Section 3.2.2 by a review of models concerning the coordinated response to natural incidents [61, 67-70]. Finally, Section 3.2.3 reviews other optimisation models [71-75] in which the type of incident covered is not defined. The review focused on providing insights into these models in terms of: 1) the coordination problem for which a solution is sought; 2) the method was developed to solve the coordination problem; 3) the elements of the MCI environment taken into account; 4) the coordination decisions that were covered; 5) the objective functions that were defined; 6) the key results that were obtained.

3.2.1 Man-made incident or incidents

Repoussis et al. [64] proposed a mixed integer programming model to solve the coordination problem of assigning casualties to ten hospitals from a single incident site. Furthermore, it aimed to solve the treatment ordering problem at hospitals. Two types of either ‘immediate’ or ‘urgent’ casualties were considered. The definitions of casualty health classifications, including immediate and urgent, were provided in Chapter 2 (Section 2.3.3). Ambulance vehicles were assumed to be available at the incident site when an incident occurred to transport casualties to the allocated hospitals. The location of the incident site and hospitals were assumed to be in an unrealistic road network. The mixed integer programming model aimed to minimise the overall response time, which was defined as the delivery of the last casualty from the incident site to the assigned hospital. A two-step approach was employed, beginning with a constructive heuristic followed by a tabu search algorithm (TSA). A constructive heuristic was employed to generate the initial solution, equivalent to an initial response plan. This solution consisted of tasks for the transportation of casualties from the incident site to the assigned hospitals and the subsequent treatment tasks in hospitals. The TSA was developed to search for further improvements in the solution to achieve the aims of the model, which minimises the overall response time. The authors examined the influence of the number of hospitals and ambulances on the overall response time using 50 scenarios. They observed that the response time decreased when the number of ambulances increased while the numbers of hospitals and casualties were kept constant. For example, the response time for the delivery of ten casualties to four hospitals decreased from 108 to 99 minutes when the number of ambulances increased from three to four. It was further observed that the response time doubled from 99 to 178 minutes when the number of casualties doubled from 10 to 20 while the numbers of ambulances and hospitals were kept constant. Meanwhile, the response time decreased when the number of hospitals increased, but the numbers of ambulances and casualties were kept constant. For example, the response time to transport 30 casualties to the assigned hospitals using 20 ambulance vehicles decreased from 122 to 107 minutes when the number of hospitals increased from 8 to 10.

Wilson et al. [65] proposed a multi-objective optimisation model to solve the coordination problem of allocating tasks to emergency responders, namely Search and Rescue (SAR), Hazardous Area Response Team (HART), and Mobile Emergency Response Incident Team (MERIT) responders whose initial locations were not specified. The model was also used to determine the optimal allocation of casualties to hospitals. A realistic road network representation of central London was modelled using the GIS data of the area under consideration. Two objective functions were considered in attempting to minimise the expected number of fatalities before delivery to hospitals as well as suffering, where the latter term indicates how quickly casualties at the incident sites could be delivered to hospitals. A two-step approach was designed, with a constructive heuristic followed by a variable neighbourhood descent (VND) algorithm. The constructive heuristic was developed to create the initial schedules of emergency responders, and the VND algorithm was developed to alter the initial schedules of emergency responders based on the information available and to allocate casualties to hospitals. They found that the constructive heuristic was unable to deal with the dynamic nature of the MCI environment, which led to schedules quickly becoming irrelevant as more information became available. Real-time scheduling was also examined using the VND algorithm, and it was concluded that the search-based approach was appropriate for real-time use since it improved the values of two objective functions.

Hawe et al. [66] proposed a multi-agent-based model to solve the coordination problem of the allocation of emergency services' resources, including fire engines, firefighters, ambulances, and paramedics initially located at their respective station locations, to two incidents at the Gateshead Interchange and Royal Quays. The proposed model in the work of Hawe et al. was also developed to determine the optimal allocation of immediate and urgent casualties to hospitals. An integrated transport network layer was utilised to model the road network of Newcastle-upon-Tyne. Hawe et al. [66] aimed to minimise the arrival time at the hospital of the last immediate casualty. In their proposed model, nine fire and rescue stations and nine ambulance stations were included. Two ambulance stations were located approximately equidistantly from the incident sites so that the best allocation of emergency resources at these two locations to two incident sites could be determined. Nine different resource allocation strategies were defined, and for each strategy, the number of emergency vehicles allocated to each incident site was specified. The results presented in [66] showed that the allocation of 12 ambulances to each incident site was found to be the best strategy to perform the tasks associated with 15 casualties at each location or 16 and 14 casualties at Gateshead Interchange and Royal Quays, respectively. The arrival times at the hospital of the last immediate casualties from the Gateshead Interchange (15 casualties) and Royal Quays (15 casualties) were 3799 and 3308 seconds respectively, whereas the arrival times at hospital of the last immediate casualty among 16 from the Gateshead Interchange and 14 from Royal Quays were 4037 and 3246 seconds respectively. The findings of the multi-agent-based model highlighted that a higher proportion of the emergency vehicles were allocated to the incident site where a higher proportion of immediate casualties were located.

Amram et al. [62] proposed a web-based simulation model to solve the coordination problem of allocating to two hospitals casualties whose initial health classification was unspecified and who were originally located at two incident sites. Casualties were transported to hospitals via ambulances which were assumed to be available at the incident site when an incident occurred. In the proposed model, real-time information regarding hospital capacity was considered, and a realistic representation of a road network in Vancouver was employed. Amram et al. [62] aimed to minimise the time taken to transfer casualties to hospitals and, thus, to reduce the number of fatalities. In the proposed model, casualties were dynamically allocated to hospitals based on real-time information regarding driving time from an incident site to the allocated hospital, the level of trauma services available at the allocated hospital, and the hospital's capacity. Such information was updated every 10 seconds. The results of the model demonstrated the effect of real-time information on the allocation of casualties to hospitals. Most casualties at the two incident sites were allocated to the closest hospital, which had yet to reach its capacity. This hospital was nine minutes from the first incident site and seven minutes from the second. However, the second hospital was 20 minutes away from the first incident site and 15 minutes away from the second incident site. It was found that the closest hospital reached its maximum capacity one hour after the response to the incident began. Consequently, the remaining casualties yet to be allocated to hospitals from both incident sites were allocated to the more remote hospital, which reached its maximum capacity later.

Rauner et al. [75] developed a discrete-event simulation policy model to determine the best allocation of emergency resources, including medical staff and ambulances, to severely or slightly injured casualties at advanced medical posts (AMPs). The term AMP refers to a small field hospital set up in a location near an incident site to provide treatment to casualties prior to their transportation to hospitals. Emergency resources were assumed to be available at the incident site when an incident occurred. Each AMP had its own equipment to be used by the allocated medical staff to treat casualties. Two settings – manual and automatic player mode – were available to the user to choose from in order to initialise the response to a man-made incident. In manual mode, the user was able to allocate medical staff to casualties at AMPs. Updated information regarding the number of casualties waiting to be treated at AMPs and the capacity of each AMP was displayed to the user to assess allocation decisions made. In automatic player mode, the real-time allocation of medical staff to casualties at AMPs was employed to create a response without any interaction with the user. The model was designed with the aim to minimise the number of fatalities and the response time, which is the time from the start of the rescue to the time at which the last casualty was delivered to the assigned hospital. Three different types of incident were examined in this study: a collapsed stadium roof, a train accident, and a gas explosion. It was found that the type of incident affected the time needed to complete the emergency response. The response to the largest incident in terms of size, the collapse of a stadium roof, was completed in 403 minutes. Meanwhile, the response to a train accident was completed in 398 minutes due to the remote location of the accident. Finally, the emergency response to the gas explosion was completed in 218 minutes, which was the shortest compared to the other types of incident due to the simple structure of the incident with no crash or building collapse. Various instances were defined to investigate the most important factors in reducing the number of fatalities and the response time. Rauner et al. [75] found that without triaging casualties at AMPs, a lower response time can be achieved (280.37 minutes), but the number of fatalities increased to approximately 24, whereas releasing medical staff from AMPs to transport casualties to hospitals reduced the response time but increased the number of fatalities. However, when medical staff remained at AMPs to triage and treat casualties, the number of fatalities decreased, but the response time increased.

3.2.2 Natural incident or incidents

Rauchecker and Schryen [67] developed a linear integer programming model to solve the coordination problem of allocating specialised and non-specialised rescue units to natural incident sites, where neither the initial locations of rescue units nor incident types were specified. A specialised rescue unit was trained to perform one task, including treating casualties, extinguishing fires, or searching for and rescuing casualties at an incident site. However, a non-specialised rescue unit was able to perform two to three of the aforementioned tasks. The linear integer programming model aimed to minimise the weighted sum of the completion times of the tasks assigned to all rescue units at all incident sites. A heuristic branch-and-price algorithm was developed to determine the best allocation of rescue units to incident sites based on the traffic density and the presence of specialised and non-specialised rescue units. However, no information was given regarding the modelling of traffic density since the layout of the road network was ignored. In [67], four different scenarios were defined in which there were between 10 and 40 incident sites, and the number of rescue units was assumed to be less than or equal to the number of incident sites. The results of the four scenarios showed that the execution time of the linear integer programming model was impacted by the ratio of the number of incident sites to rescue units. With 40 incident sites and 30 to 40 non-specialised rescuers, the average execution time was approximately two seconds. However, with 40 incident sites and 20 non-specialised rescue units, the execution time increased to 56 seconds.

Li et al. [68] developed an integer programming model to solve the coordination problem of allocating rescue units to three earthquakes in Ludian County, China. The model aimed to maximise the degree of matching between the skills of rescue units and the assigned tasks. The degree of matching was calculated using weights assigned to each type of experience required to perform a particular task and the time needed to complete it. The higher the degree of matching rescue units, the more optimal the solution would be. However, the authors emphasised that records of the histories of rescue units were important if a realistic solution was to be generated. The rescue units were initially stationed at three unspecified locations, and the road network of the MCI-affected area was not defined. Instead, the travel times between the initial locations of the rescue units and the incident sites were pre-defined. The rescue units considered in [68] were assumed able to perform six tasks according to different levels of experience in searching for casualties, providing medical care to casualties, immunisation, escorting critical casualties, psychological counselling and health education, and setting up temporary settlement sites. Li et al. [68] provided an example to explain the use of the proposed model in allocating rescue units to incident sites.

Rezapour et al. [61] developed an integer programming model to solve the coordination problem of allocating emergency responders, namely SAR and medical units, to tasks associated with immediate and delayed casualties initially located at an earthquake site in the New Madrid Seismic Zone in Illinois, USA. The model aimed to maximise the number of expected survivors. The initial locations of emergency responders were not specified, but the travel times to the incident site were pre-defined. In the integer programming model, two allocation approaches were applied, which involved the fair or optimal allocation of emergency responders to tasks associated with casualties. In fair allocation, the emergency responders were divided proportionally between immediate and delayed casualties at the incident site so that the workloads of emergency responders remained fairly equitable. In optimal allocation, however, the emergency responders were allocated to tasks associated with immediate and delayed casualties using the ‘streaming without overflow’ treatment strategy. This strategy requires determining the optimal number of emergency responders needed to undertake tasks associated with casualties of each health classification at an incident site. In order to evaluate such a strategy, a number of combinations were considered, which consisted of 11 values of a mixed ratio from 0.0 to 1.0 inclusively, indicating the average ratio of immediate casualties to the total number of casualties. The authors observed that increasing the number of emergency responders decreased their workload at the incident site and maximised the number of expected survivors. In contrast, decreasing the number of emergency responders increased their workload at the incident site, which resulted in substantial deteriorations in casualties’ health and increased mortality. Furthermore, they observed that the ratio of immediate casualties to the total number of casualties did not lead to significant changes in the number of expected survivors when the number of emergency responders was kept constant.

Sung and Lee [70] developed a branch-and-price algorithm to determine the best allocation of immediate and delayed casualties to ambulances and then to hospitals after a natural disaster. The developed algorithm aimed to maximise the expected number of survivors. In [70], the initial locations of ambulance vehicles were unspecified; however, the travel times between the initial locations of ambulances to the incident site and from the incident site to hospitals were unspecified. Long waiting times of casualties at the incident site before transportation to assigned hospitals caused a deterioration in their survival probability, which was calculated using the survival probability function proposed in the previously published study [76]. The survival probability function considered three scenarios, pessimistic, moderate, and optimistic, in relation to the initial survival probability of casualties, low, moderate, and high, respectively. In all scenarios, the survival probability of immediate casualties was assumed to deteriorate faster than delayed casualties over time. The authors compared the findings generated using the branch-and-price algorithm and those from simple heuristics constructed based on immediate-first or delayed-first priority rules. The results of the comparison showed that the immediate-first heuristic generated a worse solution under the pessimistic scenario compared to the solution generated using the branch-and-price algorithm. However, the immediate-first heuristic performed better under the optimistic scenario, and the solution generated was claimed to be close to optimal, although no quantitative data was provided. In contrast, the delayed-first heuristic performed better than the immediate-first heuristic under the pessimistic scenario. The authors discussed this outcome with emergency medical services practitioners, who disagreed with its significance. Practitioners believed that immediate casualties always warranted higher priority, and thus more casualties could be saved. The authors stated that the survival probability function proposed by Mills et al. [76] for immediate casualties was one of the main reasons for the worse performance of the immediate-first heuristic in the pessimistic scenario. Furthermore, the authors indicated that the reason for the disparity in the findings was that no priority was given to any health classification of casualties in their defined objective function, which was merely defined to maximise the number of casualties who survived.

Wang et al. [72] developed an agent-based model to determine the best allocation of immediate, urgent or delayed casualties at an incident site after an earthquake to 15 hospitals; however, the locations of hospitals were unspecified. The agent-based model employed realistic data regarding the available emergency resources, including ambulances and hospital beds. However, information relating to travel times between the incident site and hospitals was assumed. Ambulances were modelled to transport two casualties with the same health classification (urgent or delayed) or only one immediate casualty. The model aimed to minimise the time elapsing from the start of the response to when all casualties were delivered to hospitals and all relevant treatment tasks associated with these casualties at hospitals were completed. The survival probability for each casualty was defined using the same survival probability function cited above [76]. In [72], a number of real-time allocation of casualties to hospitals strategies were examined. The findings of implanting the agent-based model highlighted that the allocation of casualties to the hospital nearest to the incident site with the lightest schedule of incoming casualties was the worst, generating a plan with a high number of fatalities (66.2%) due to the long waiting times at the assigned hospitals for definitive treatment. Furthermore, this policy did not consider hospital capacity, leading to the allocation of casualties to hospitals without sufficient capacity to treat them; therefore, these casualties must be sent to another hospital, which may lead to higher death rates. In contrast, the number of fatalities was reduced by 47.7% when casualties were allocated to hospitals based on their capacity.

3.2.3 Undefined type of incident or incidents

Su et al. [69] proposed a linear integer programming model to solve the coordination problem of allocating emergency resources whose types and locations were unspecified to multiple incidents which were also unspecified. The travel times between the initial locations of the emergency resources to the incident sites were assumed, and each incident required a pre-defined number of emergency resource units, each of which was assigned a pre-defined cost associated with the total spending on the purchase, storage, and maintenance of the emergency resources used at each incident. Allocation decisions of emergency resources to incident sites are made based on the severity of incidents and the travelling times from the initial locations of the emergency resources to incident sites; however, no information was provided about how incident severity was defined. The linear integer programming model aimed to minimise the total arrival times of emergency resources to the allocated incident sites and the total cost of those resources. In this model, a heuristic algorithm was developed to determine the best allocation of emergency resources to incident sites. The algorithm was implemented dynamically and statically, and the results were compared in terms of execution time. Two scenarios were considered with either 20 emergency resources and six incident sites or 20 emergency resources and 20 incident sites. It was found that the dynamic allocation process was efficient when the number of emergency resources was more than the number of incident sites, in which case the requirements of any incident site could be satisfied immediately. In contrast, the dynamic allocation process was more complex when the number of emergency resources was equal to the number of incident sites, where the requirements of any incident site may not be satisfied immediately because the required emergency resources might not be available. The execution times of the static model for both scenarios were 7.07 and 7.3 seconds, respectively, whereas those of the dynamic model were 5.69 and 6.5 seconds.

Lodree et al. [71] developed a discrete-time finite horizon stochastic dynamic programming model to allocate medical staff to treat casualties at an incident site. The medical staff were assumed to be available at the incident site when the incident occurred. The model aimed to minimise the delay in treating casualties which, in turn, would minimise total deprivation costs, as suggested by Holguín-Veras et al. [77]. The solutions generated by Lodree et al. were examined for situations with or without a medical staff assignment policy in place, as suggested in previous research [78, 79]. An assignment policy indicates that priority in allocating medical staff was given to immediate casualties (whose number was unspecified) until all those casualties had been treated. The medical staff would subsequently be reallocated to the lower priority casualties (urgent and then delayed). However, the results of the study presented in [71] showed that the assignment policy did not result in the best allocation of medical staff to casualties. This was because the deprivation costs increased by 52.32% compared to the solutions generated without following such a policy, indicating a significant delay in providing treatment to casualties. The results without the policy suggested that sufficient medical staff should be assigned to casualties based on their needs.

Bae et al. [73] developed an agent-based model to determine the optimal allocation of immediate or urgent casualties at an incident site to five hospitals at which a number of ambulances were located. The model aimed to maximise the expected number of survivors. In this model, a number of geospatial details were considered, including the road network in Vancouver, the locations of five hospitals, and a single incident site. Furthermore, immediate and urgent casualties were given high priority for transportation to hospitals, whereas delayed casualties were given lower priority. Each casualty was assumed to suffer from one of two types of injury, and the deterioration in casualties' health was based on pre-defined survival curves for casualties with each type of injury. Two types of ambulance were modelled: a level 1 ambulance staffed by emergency medical technicians with high expertise in dealing with casualties in an MCI and a level 2 ambulance with emergency medical technicians with a lower expertise level. The efficiency of the generated solution was evaluated using the ratio of the expected number of survivors to the expected number of casualties who would survive if medical interventions were provided. The largest and smallest efficiency values were calculated as 50.5% and 24.6%, respectively, from 18 scenarios relating to differences in efficiency caused by varying expertise levels among medical staff at hospitals.

Rolland et al. [74] developed hybrid meta-heuristics to allocate personnel (whose type was unspecified) to tasks at an incident site (the number and locations of which were unspecified), aiming to minimise the mismatching costs of personnel in terms of the lack of appropriate training of the personnel for the tasks assigned. Assigning tasks to unsuitable personnel increased the costs associated with personnel mismatch. Rolland et al. [74] developed a forward loading Algorithm (FLA) and TSA. The FLA was used to assign tasks to personnel with the lowest mismatch costs being prioritised. The TSA was used to search for a better starting time for tasks that had already been assigned to personnel or to search for new personnel to perform tasks that had already been assigned to others. Rolland et al. [74] used 35 experiments to evaluate the performance of their algorithms. For each experiment, one algorithm was utilised, which was executed 50. The authors concluded that in complex scenarios involving 6 personnel and 75 tasks, the TSA performed best in 83% of the experiments. Nevertheless, the FLA performed best in simple scenarios involving only four personnel and 19 tasks.

3.3 Summary of the models reviewed

This section aims to identify the key elements of the MCI environment and coordination decisions considered in the models reviewed in this chapter. The term 'MCI environment' refers to the geographical area affected in which an incident occurs, and the key locations, including emergency resources, hospitals, and incident sites, are determined. The term ‘coordination decisions’ refers to the decisions that have to be made rapidly during the responses to MCIs.

3.3.1 Key elements of an MCI environment

In the models reviewed in this chapter, 5 key elements were considered in modelling the MCI environment in the literature reviewed:

1) road network [62, 64-66, 72, 73];
2) incident sites [61, 62, 64-75];
3) emergency services’ resources [61, 62, 64-73, 75];
4) hospitals [62, 64-66, 70, 72, 73, 75];
5) casualties [61, 62, 64-66, 70-75].

Some of the models reviewed in this chapter [62, 64-66, 72, 73] modelled the road network of the area of interest in which an incident or incidents occurred. Multiple ambulance stations and fire and rescue stations were considered in responses to MCIs in only one study [66]. The types of responder considered in the existing models reviewed in this chapter are medical staff or medical units [61, 71, 74, 75], rescue units [67, 68], firefighters [66], and SAR [61, 65], HART [65], and MERIT responders [65]. Meanwhile, ambulance vehicles are the only emergency vehicles used to transport casualties to allocated hospitals in the models reviewed in this chapter [62, 64-66, 70, 72, 73, 75]. Furthermore, multiple hospitals were considered in some models [62, 64-66, 70, 72, 73, 75]. The types of incidents considered in the models reviewed in this chapter are man-made incident or incidents [62, 64-66], natural incidents [61, 67-70], and unspecified incidents [71-75]. Casualties’ health was classified as either immediate or urgent [64, 66, 73, 74], immediate or delayed [61, 70], immediate, urgent or delayed [65, 71, 72], and severely or slightly injured [75]. However, in one study [62], the health classification of casualties was unspecified, while in two models [67, 68] no casualties were modelled.

3.3.2 Key elements of coordination decisions

Emergency resource allocation is the most common challenge encountered in making coordination decisions during the response to MCIs, as indicated in two studies [14, 56]. The key coordination decisions considered in the literature concern the following allocation decisions.

- Allocating emergency responders to tasks associated with casualties at an incident site or sites statically [61, 65, 66, 68, 69] or dynamically [65, 67, 71, 72, 74, 75].
- Allocating standard ambulances to casualties at an incident site statically [70].
- Allocating casualties to hospitals statically [64, 66, 70, 73] or dynamically [62, 65, 72, 75].

3.4 Summary

This chapter, in conjunction with Chapter 2, fully addressed **RQ1**. it has reviewed published optimisation models that have focused on coordinated responses to MCIs in terms of: 1) the coordination problem for which a solution is sought; 2) the method developed to solve the coordination problem; 3) the elements of the MCI environment considered; 4) the coordination decisions addressed; 5) the objective functions defined; and 6) the key results obtained. Following this, the models reviewed have been summarised and the key elements of an MCI environment and key coordination decisions were identified. The identified key elements of an MCI environment are the road network, incident sites, emergency services' resources, hospitals, and casualties. Further, the identified key coordination decisions concern the allocation of: emergency responders to incident sites; vehicles to casualties at the incident site; emergency responders to tasks at an incident site or sites, and casualties to hospitals. Each allocation process may be conducted in a static or dynamic manner. The key elements identified in this chapter are considered to be the basis for the definition of the key requirements for a decision support model to coordinate the emergency response to MCIs that will be discussed in Chapter 4.

Chapter 4. Requirements of a decision support model to coordinate the response of emergency services' resources to MCIs

4.1 Introduction

Developing decision support models is one of the most important computational approaches for analysing complex problems, evaluating alternatives, and selecting the most appropriate course of action to take [14, 63]. The use of decision support models to coordinate the response of emergency services to mass casualty incidents (MCIs) allows them to identify and mitigate potential risks and make well-informed decisions that are consistent with the primary objective of emergency response, which is to save lives [13]. Defining the specific requirements for a model from existing decision support models ensures that the design of this model aligns with the emergency services' objectives, which in this thesis is to save lives and reduce suffering. Furthermore, defining a model's requirements ensures that any limitations of a developed model can be identified. This chapter does not directly engage with RQs outlined in Chapter 1. Instead, it focuses on providing definitions and explanations for **RQ2** and **RQ3**.

The aim of this chapter is to define the requirements for a decision support model to simulate and coordinate the response of emergency services to MCIs in relation to 1) the requirements of modelling an MCI environment (Section 4.2) and 2) the requirements of coordination decisions that are made throughout MCIs (Section 4.3). The specific requirements required for a decision support model are defined based on the key elements of an MCI environment and the coordination decisions that have been identified in the literature in Chapter 3 (Section 3.3).

4.2 Requirements of modelling an MCI environment

In a decision support model, modelling an MCI environment is essential in terms of enabling the simulation of the coordinated response to MCIs.

4.2.1 Road network

Modelling the road network of an MCI-affected geographical area as accurately and realistically as possible is useful in determining the key locations of interest. These locations are the incident sites at which casualties are initially located, the ambulance and fire and rescue stations at which emergency responders and vehicles are initially located, and hospitals. It should be noted that references are cited in the definitions of RMEs in order to indicate that the need for that requirement has been recognised in the models reviewed in Chapter 3.

- RME1 – Model a realistic road network of an MCI-affected geographical area [65, 66, 73].

In addition, a detailed representation of a realistic road network in the MCI-affected geographical area in which incidents may occur, including the use of the Geographic Information System (GIS) data, is essential to determine the distance between any two key locations of interest. The distance obtained from the GIS data of the MCI-affected geographical area is used to aid in making coordination decisions that require transporting emergency responders from their current location to another; these coordination decisions are discussed in Section 4.3.

- RME2 – Extract the accurate distance between key locations of interest in the MCI-affected geographical area [65, 66, 73].

The travel times of emergency vehicles between any two locations of interest should then be determined. These can be calculated using the distances obtained from GIS data and the specified speed of emergency vehicles. The accurate definition of the travel times of emergency vehicles between any two key locations of interest enables a credible simulation of the movements of these vehicles.

- RME3 – Define credible travel times of emergency vehicles [73].

A direct association between RMEs 1-3 can be noticed. The modelling of a realistic road network of the MCI-affected geographical area enables the identification of the key locations of interest. When accurate distances between any two key locations of interest have been obtained using GIS data, credible travelling times between these locations can be calculated based on the accurate distances obtained and the defined speed of emergency vehicles.

4.2.2 Incident sites

An incident site refers to the location where an MCI event has occurred. Single or multiple incidents may occur at any time, and they often happen unexpectedly. Incidents may occur in densely populated urban areas such as shopping malls, parks, football stadiums, and train stations, as indicated in Chapter 1.

- RME4 – Define the number and specify the locations of incident sites in the MCI-affected geographical area [62, 64, 66, 72, 73].

An MCI event can result in a number of casualties with different levels of severity, needing lifesaving and/or medical interventions undertaken by different types of emergency responder.

- RME5 – Define the number of casualties at each incident site [62, 66, 72, 73, 75].

An incident site consists of four zones: a hot zone (HZ), a Casualty Clearing Station (CCS), a Place of Safety (POS), and an Ambulance Loading Point (ALP) in accordance with previously published reports [61, 64]. An HZ denotes the existence of a high risk to life and health in the location where casualties are initially found [10, 13]. An CCS is set up in a safe area at the incident site but away from the HZ so that advanced treatment can be provided [4]. A POS and ALP are located at a suitable distance from the HZ [16]. The POS is set up to provide first aid treatment, whereas the ALP is set up where casualties are assembled before being transported to hospitals [6, 13]. Each zone has its own specifications concerning the following factors:

1) lifesaving and/or medical interventions (advanced treatment at the CCS and first aid at the POS) are provided to casualties;
2) the type of emergency responders in attendance who can deal with casualties.

Based on this, the zones associated with each incident site should be defined.

- RME6 – Specify the location of the four zones at each incident site [61, 64].

Multiple MCIs may occur in close succession or sequentially over a period of time. In such cases, more than one set of casualties may be introduced, requiring lifesaving and/or medical interventions. This requires a dynamic reallocation of emergency responders and rescheduling of their tasks to cope with the rapid and frequent changes in information pertaining to incident sites as the MCI response unfolds to reflect the situation at hand. Further details concerning how a decision support model should deal with the dynamic nature of MCIs are provided in Section 4.2.

- RME7 – Account for the dynamic occurrence of MCIs in which additional sets of casualties need lifesaving interventions are introduced.

4.2.3 Emergency services' resources

Emergency services, including ambulance and fire and rescue services, must respond to MCI events immediately after they occur by sending their associated emergency resources to the incident site or sites in order to save lives and reduce suffering. Emergency responders initially located at ambulance and fire and rescue stations require transportation to incident sites using various types of emergency vehicles. The requirements related to modelling ambulance stations and the associated emergency resources, namely emergency responders and vehicles, are discussed first, followed by the requirements pertaining to modelling fire and rescue stations and their associated emergency resources.

Ambulance stations, emergency responders, and vehicles

The number and locations of ambulance stations in the MCI-affected geographical area which are considered in response to MCIs must be defined.

- RME8 – Define the number and specify the locations of ambulance stations in the MCI-affected geographical area [66].

There are various types of emergency responder at each ambulance station. Each type of emergency responder has different specialities, which refer to the ability to perform particular tasks associated with casualties in particular zones, namely the HZ, CCS, POS, and ALP at an incident site, as defined in Section 4.2.2. For example, Hazardous Area Response Team (HART) responders have been trained to perform particular tasks associated with casualties at an HZ, whereas Medical Emergency Response Incident Team (MERIT) responders have been trained to perform particular tasks associated with casualties at a CCS. The definitions of HART and MERIT responders are provided in Chapter 3. Different degrees of emergency responders' expertise in dealing with casualties at MCIs are considered. The degree of expertise refers to the level of knowledge and experience that the emergency responder has in relation to undertaking particular tasks associated with casualties. For example, HART responders have been trained to respond to MCIs; thus, the levels of knowledge and experience of a HART responder will be higher than those of a paramedic responder.

- RME9 – Specify the type of emergency responders located at each ambulance station.
- RME10 – Define the number of emergency responders of each type located at each ambulance station.
- RME11 – Define the degree of expertise of each type of emergency responder located at ambulance stations.

At each ambulance station, there are various types of emergency vehicles; each type has a particular purpose in terms of use and capacity. The requirements of modelling emergency vehicles are as follows:

- RME12 – Specify the type of emergency vehicle located at each ambulance station.
- RME13 – Define the purpose of the use of each type of emergency vehicle at each ambulance station.
- RME14 – Define the capacity of each type of emergency vehicle at each ambulance station.
- RME15 – Define the number of each type of emergency vehicle at each ambulance station.

Fire and rescue stations, emergency responders, and vehicles

The requirements of modelling the fire and rescue stations, emergency responders, and emergency vehicles are defined as follows:

- RME16 – Define the number and specify the locations of fire and rescue stations located in the MCI-affected geographical area.
- RME17 – Specify the type of emergency responders at each fire and rescue station.
- RME18 – Define the number of emergency responders of each type located at each fire and rescue station.
- RME19 – Define the degree of expertise of each type of emergency responder at the fire and rescue stations.
- RME20 – Specify the types of emergency vehicle at each fire and rescue station.

- RME21 – Define the purpose of the use of each type of emergency vehicle at each fire and rescue station.
- RME22 – Define the capacity of each type of emergency vehicle at each fire and rescue station.
- RME23 – Define the number of emergency vehicles at each fire and rescue station.

4.2.4 Hospitals

Hospitals are required to receive casualties transferred from incident sites, sharing the same aims with those of the emergency services to save lives and reduce suffering. Since the present study focuses on pre-hospital responses, the hospitals involved in responses to an MCI are considered destinations for ambulance vehicles that transfer casualties from incident sites after having delivered appropriate lifesaving and/or medical interventions. Thus, the number and location of the hospitals involved should be considered when modelling hospitals.

- RME24 – Define the number and specify the locations of hospitals located in the affected geographical area.
- RME25 – Define the casualty capacity level of each hospital.

4.2.5 Casualties

An MCI results in a number of casualties with different levels of severity of injuries. Casualties at an incident site may suffer from one or more injuries that may affect their lives. Thus, a comprehensive health profile for each casualty should be considered in order to differentiate between casualties at an incident site. The term ‘health profile of a casualty’ refers to the current casualty’s health, including information related to his/her injuries, vital signs, and other important information. In the health profile of each casualty, a number of parameters should be determined, for example, the severity level of injuries that the casualty may have suffered as a result of an MCI.

- RME26 – Model a realistic and comprehensive health profile for each casualty.

Modelling health profiles enables the status of casualties’ health to be dynamically simulated during the response to MCIs.

- RME27 – Simulate the status of casualties’ health dynamically [65, 70, 72, 73, 75].

The tasks associated with each casualty and the nature of performing these tasks should be determined. All the identified casualties at an incident site should be triaged and transported to hospitals after receiving any necessary on-site treatment. Casualties who are trapped at an incident site should be released and treated if necessary. The duration of each task depends on the degree of expertise of the emergency responders to which the task has been allocated and the health profile of the casualty involved.

- RME28 – Define the tasks associated with casualties and the sequence of their performance by emergency responders.
- RME29 – Define the duration of each task associated with a casualty.

4.3 Requirements of coordination decisions

When it comes to managing MCIs, coordination decisions play a critical role in ensuring an effective response. In order to manage these incidents successfully, emergency services must work together closely, with clear communication and well-coordinated efforts. The key to this coordination lies in making timely, effective decisions based on the situation at hand. In this section, the coordination decisions that emergency services need to make in response to MCIs will be discussed, particularly those associated with pre-determined attendance (PDA) response and post-PDA response.

4.3.1 Pre-determined attendance response

After an MCI event has occurred, the emergency services must respond immediately, and the emergency resources involved should be appropriately coordinated in order to save lives and reduce suffering. The first coordination decision to be made relates to the determination of the types and numbers of emergency responders who should be sent to undertake a particular number of tasks associated with casualties located at each incident site as part of the PDA response, which is discussed in detail in Chapter 2 (Section 2.3.3). A PDA response refers to the initial response to MCIs in which the types and number of emergency resources required to be sent to each incident site have been agreed upon in advance. The tasks allocated to emergency responders should be scheduled, and the nature of these tasks should be maintained, as discussed in Section 4.2.5 (RME28). Tasks scheduling refers to each task being assigned starting and completion times, taking into consideration the nature of tasks related to each casualty so that on completion of a specific task, the next task-dependent task can be performed. Note that, in the following requirements, the term ‘best’ indicates the most effective response plan, which can be obtained using a suitable optimisation-based algorithm with associated pre-defined objective functions.

- RCD1 – Determine the best allocation and scheduling of emergency responders to undertake tasks associated with casualties located at incident sites for the PDA response plan.

4.3.2 Post- pre-determined attendance response

The PDA response involves the emergency responders gathering and reporting the necessary information about the incident upon their arrival at the site to which they have been allocated to. Based on such information, more emergency responders may be sent to an incident site as part of the post-PDA response. The types and numbers of these extra emergency responders not involved in the initial PDA response and should be sent to undertake tasks associated with casualties at incident sites are determined as part of the initial post-PDA response plan. Tasks assigned to emergency responders in the PDA response plan should be preserved. Moreover, the duplication and overlapping of tasks associated with casualties must be avoided. Thus, based on requirement RCD1, the next requirement can be defined:

- RCD2 – Determine the best allocation and scheduling of tasks associated with casualties for the initial post-PDA response plan.

The term ‘initial post-PDA response plan’ refers to a response plan yet to be optimised using a suitable optimisation-based algorithm with associated pre-defined objective functions. The initial post-PDA response plan conducts a preliminary determination of the tasks to be undertaken by each emergency responder, the particular hospital each casualty will be sent to, and the ambulance vehicle that should be used to transfer each casualty. Then, an appropriate optimisation-based algorithm is applied to optimise the initial post-PDA response plan, thus generating the optimised post-PDA response plan. The combination of the PDA and optimised post-PDA response plan represents the pre-hospital response plan, which covers the period from the deployment of the first emergency vehicle (representing the point of activation of the PDA response plan) to the delivery of the last casualty to the allocated hospital [6].

As the response unfolds, more information related to the MCI may become available. This requires further coordination decisions to be made and updated in a dynamic manner to reflect the evolution of MCI. It is expected that four scenarios may occur at any time during the response to MCIs, in which case there will be a need for dynamic coordination decisions to be made. In Scenario 1, the information reported following the PDA response can be updated at any time during the execution of the optimised post-PDA response plan. The number of casualties reported can be fewer or more than the actual number encountered at an incident site. Subsequently, emergency responder schedules must be updated to involve tasks associated with newly discovered casualties or to remove tasks associated with erroneously reported casualties. In Scenario 2, additional incidents may occur at any time while the response to other incidents is still ongoing, resulting in a new set of casualties who require lifesaving and/or medical interventions, as discussed in (Section 4.2.2). In Scenario 3, the response to any incident might be completed at any time as the response to MCI unfolds, leading to a number of emergency responders and vehicles becoming available for reallocation to other incident sites where the response is still ongoing. In Scenario 4, the health of casualties may deteriorate due to delays in providing the lifesaving interventions required at incident sites, as discussed in Section 4.2.5 (RME27). In all of these scenarios, the interruption of tasks associated with casualties being processed must be avoided even if new information regarding the MCI has become available. In order to deal with the dynamic nature of an MCI, the following requirement must therefore be considered:

- RCD3 – Dynamically schedule and allocate (if required) all tasks yet to be started in order to reflect the evolving MCI for the optimised post-PDA response plan, considering the aim to achieve a seamless transition from one optimised post-PDA response plan to another with minimal transition time.

The implementation of the optimisation-based algorithm may be required at any time during the execution of the optimised post-PDA response plan, which might lead to an interruption in the execution of the most recent plan, which is called ‘transition time’. As a result, emergency responders may have no scheduled tasks to be undertaken during the period when the optimisation-based algorithm is being applied to generate a new optimised post-PDA response plan. This issue must be tackled to ensure a seamless transition from one optimised post-PDA response plan to another with as minimal transition time as possible.

4.4 Summary

This chapter partially defined and explained **RQ2** and **RQ3**. It has defined the key requirements for a decision support model to coordinate the response of emergency services' resources to MCIs. The requirements related to modelling an MCI environment were defined as RME1-RME29. Furthermore, three requirements for making coordination decisions were determined as RCD1-RCD3. The nature of these requirements foregrounds the need for a decision support model to coordinate the emergency response to MCIs. In the next chapter, the models reviewed in Chapter 4 that most closely relate to decision support to coordinate the emergency response to MCIs with respect to the key elements identified in Chapter 3 and the requirements defined in this chapter 4 are identified and critically reviewed against these requirements. As a result, the scope for an original and significant contribution to knowledge in this research can be identified.

Table 4.1 states the requirements of modelling an MCI environment (RME1-RME29) and the requirements relating to the coordination decisions (RCD1-RCD3) in a decision support model to be used to coordinate the emergency response to MCIs. Table 4.1 is included for ease of reference, and the letters 'RN', 'IS', 'ESR', 'H', and 'C' indicate the road network in the MCI-affected geographical area, incident sites, emergency services' resources, hospitals, and casualties, respectively.

Table 4.1: Requirements for a decision support model to coordinate the response of emergency services’ resources to MCIs.

Key elements		Requirements		Section
Modelling an MCI environment	RN	RME1	Model a realistic road network of an MCI-affected geographical area	4.2.1
		RME2	Extract the accurate distance between key locations of interest in the MCI-affected geographical area	
		RME3	Define credible travel times of emergency vehicles	
	IS	RME4	Define the number and specify the locations of incident sites in the MCI-affected geographical area	4.2.2
		RME5	Define of the number of casualties at each incident site	
		RME6	Specify the location of the four zones at each incident site	
		RME7	Account for the dynamic occurrence of MCIs in which additional sets of casualties need lifesaving interventions are introduced	
	ESR	RME8	Define the number and specify the locations of ambulance stations in the MCI-affected geographical area	4.2.3
		RME9	Specify the type of emergency responders located at each ambulance station	
		RME10	Define the number of emergency responders of each type located at each ambulance station	
		RME11	Define the degree of expertise of each type of emergency responder located at ambulance stations	
		RME12	Specify the type of emergency vehicle located at each ambulance station	
		RME13	Define the purpose of the use of each type of emergency vehicle at each ambulance station	
		RME14	Define the capacity of each type of emergency vehicle at each ambulance station	
		RME15	Define the number of each type of emergency vehicle at each ambulance station	
		RME16	Define the number and specify the locations of fire and rescue stations in the MCI-affected geographical area	4.2.3
		RME17	Specify the type of emergency responders located at each fire and rescue station	
		RME18	Define the number of emergency responders of each type located at each fire and rescue station	
		RME19	Define the degree of expertise of each type of emergency responder located at fire and rescue stations	
		RME20	Specify the types of emergency vehicle located at each fire and rescue station	
		RME21	Define the purpose of the use of each type of emergency vehicle at each fire and rescue station	
		RME22	Define the capacity of each type of emergency vehicle at each fire and rescue station	
		RME23	Define the number of emergency vehicles at each fire and rescue station	
	H	RME24	Define the number and specify the locations of hospitals located in the affected geographical area	4.2.4
		RME25	Define the casualty capacity level of each hospital	
	C	RME26	Model a realistic and comprehensive health profile for each casualty	4.2.5
		RME27	Simulate the status of casualties’ health dynamically	
		RME28	Define the tasks associated with casualties and the sequence of their performance by emergency responders	
		RME29	Define the duration of each task associated with a casualty	

MCI, mass casualty incident; RME, requirements of modelling MCI environment; RN, road network in the MCI-affected geographical; IS, incident sites; ESR, emergency services’ resources; H, hospitals; C, casualties.

Table 4.1: Requirements for a decision support model to coordinate the response of emergency services' resources to MCIS (cont.).

Key elements of	Requirements		Section
Coordination decisions	RCD1	Determine the best allocation and scheduling of emergency responders to undertake tasks associated with casualties located at incident sites for the PDA response plan	4.3
	RCD2	Determine the best allocation and scheduling of tasks associated with casualties for the initial post-PDA response plan	
	RCD3	Dynamically schedule and allocate (if required) all tasks yet to be started in order to reflect the evolving MCI for the optimised post-PDA response plan, considering the aim to achieve a seamless transition from one optimised post-PDA response plan to another with minimal transition time	

RCD, requirements of coordination decisions.

Chapter 5. Critical review

5.1 Introduction

State-of-the-art optimisation-based models are commonly used to simulate emergency responses to man-made and natural incidents in densely populated urban areas [63]. In this thesis, optimisation-based models have been reviewed in Chapter 3 to provide specific requirements that ensure the optimisation of any decision support model being developed and that the developed decision support model can be applied to MCIs (Chapter 4). The aim of this chapter is to present a critical review of existing models related to decision support models to coordinate the emergency response of an MCI with respect to the requirements identified earlier in this thesis (Chapter 4). Section 5.2 presents an initial evaluation of the models reviewed in Chapter 3 (Section 3.2) against the key elements defined in Chapter 3 (Section 3.3) regarding a) an MCI environment and b) the coordination of decisions throughout the MCI. As a result of the initial evaluation, a subset of models is identified most closely related to the aforementioned key elements. Subsequently, in Section 5.3, the subset of identified models is critically reviewed against the requirements defined in Chapter 4 for developing a decision support model to coordinate the response to MCIs. Consequently, the scope of original and significant contributions of knowledge to the academic literature in this research is defined in Section 5.4. This chapter provides a continuation of the process of providing definitions and explanations for **RQ2** and **RQ3**.

5.2 Initial evaluation of the reviewed models

An initial evaluation of the models reviewed in Chapter 3 (Section 3.2) against the key elements of 1) an MCI environment (i.e., five key elements; Chapter 3, Section 3.3.1) and 2) coordination decisions (i.e., four static and four dynamic key elements; Chapter 3, Section 3.3.1) is presented. The initial evaluation aims to identify the reviewed models most closely related to the key elements (Table 5.1).

Table 5.1: A summary of the initial evaluation of the reviewed models.

Reviewed model	Type of MCI	Key elements of an MCI environment					Key elements of coordination decisions							
							Static				Dynamic			
		RN	IS	ESR	H	C	R-IS	R-T	C-H	C-A	R-IS	R-T	C-H	C-A
[65]	M	✓	✓	✓	✓	✓	✗	✓	✗	✗	✗	✓	✓	✗
[61]	N	✗	✓	✓	✗	✓	✗	✓	✗	✗	✗	✗	✗	✗
[70]	U	✗	✗	✓	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗
[64]	M	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗
[62]	M	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✗	✓	✗
[66]	M	✓	✓	✓	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗
[67]	N	✗	✓	✓	✗	✗	✗	✗	✗	✗	✗	✓	✗	✗
[68]	N	✗	✓	✓	✗	✗	✓	✓	✗	✗	✗	✗	✗	✗
[69]	N	✗	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗	✗	✗
[71]	U	✗	✓	✓	✗	✓	✗	✗	✗	✗	✗	✓	✗	✗
[72]	U	✓	✓	✓	✓	✓	✗	✗	✗	✗	✗	✓	✓	✗
[73]	U	✓	✓	✓	✓	✓	✗	✗	✓	✗	✗	✗	✗	✗
[74]	U	✗	✓	✗	✗	✓	✗	✗	✗	✗	✗	✓	✗	✗
[75]	U	✗	✓	✓	✓	✓	✗	✗	✗	✗	✗	✓	✓	✗

MCI, mass casualty incident; RN, road network in the MCI-affected geographical; IS, incident sites; ESR, emergency services' resources; H, hospitals; C, casualties; R-IS, allocating emergency responders to an incident site or sites; R-T, allocating emergency responders to perform tasks; C-H, allocating casualties to hospitals; C-A; allocating casualties to emergency ambulances; M, man-made incidents; N, natural incidents; U, undefined incidents; tick, a key element has been addressed in the reviewed model; cross, a key element has not been addressed in the reviewed models; highlighted rows, models are identified warranting further investigation in terms of a critical review and discussion against the requirements defined in Chapter 4.

In terms of the key elements of an MCI environment, Table 5.1 shows that 13 models include IS and ERS, whereas 6, 8 and 11 consider RN, H and C, respectively. In contrast, in terms of the reviewed models, 6 [62, 64-66, 72, 73] include all key elements of an MCI environment, whereas 4 [67-69, 74], 3 [61, 70, 71] and 1 [75] consider 2, 3 and 4 key elements, respectively. None of the reviewed models considers 0 or 1 of the key elements of an MCI environment.

For the key elements of static coordination decisions, Table 5.1 shows that three, four, four, and one of the reviewed models consider R-IS, R-T, C-H, and C-A, respectively.

Furthermore, in terms of the reviewed models, five [61, 64, 65, 69, 73], 2 [68, 70], and 1 [66] consider one, two, and three of the four key elements of static coordination decisions, whereas six reviewed models [62, 67, 71, 72, 74, 75] consider none of the key elements.

In terms of the key elements of dynamic coordination decisions, Table 5.1 shows that none of the reviewed models considers R-IS and C-A. However, six [65, 67, 71, 72, 74, 75] and four [62, 65, 72, 75] of the reviewed models considered R-T and C-H, respectively, whereas none of them considered R-IS or C-A. Moreover, in terms of the reviewed models, none of them considers all the key elements of dynamic coordination decisions, whereas seven [61, 64, 66, 68-70, 73], four [62, 67, 71, 74] and three [65, 72, 75] of them consider zero, one, and two of the key elements, respectively.

In relation to Table 5.1, the reviewed models deemed most closely related to the key elements of (a) an MCI environment and (b) the static and dynamic coordination decisions are defined as those that include consideration of almost half of the key elements, more specifically those that include consideration of at least 6 of the 13 key elements. Thus, for the purpose of this chapter, seven [62, 64-66, 72, 73, 75] of 14 reviewed models are identified (highlighted in Table 5.1) as warranting further investigation in terms of a critical review and discussion against the requirements defined in Chapter 4. However, for completeness, the remaining seven of the 14 reviewed models listed in Table 5.1 are briefly investigated in Appendix A.

5.3 Critically review the identified models against the defined requirements

In this section, the seven models identified in Section 5.2 are investigated in terms of a critical review against the requirements of modelling an MCI environment and coordination decisions.

5.3.1 Modelling the road network of an MCI-affected geographical area

Related to RME1, '*model a realistic road network of an MCI-affected geographical area*', the road network of the affected geographical area in which an MCI occurs should be considered, as indicated in Chapter 4, in order to:

- identify the key locations, including ambulance stations, fire and rescue stations, incident sites, and hospitals;
- determine the actual distance between any two key locations;
- define the travel times of emergency vehicles credibly;

- aid the decision to allocate to incident sites and hospitals the available emergency responders and vehicles located at ambulance stations or fire and rescue stations.

The common presentation of the road network in the identified models, including [62, 64-66, 72, 73], is a graph. In the previously published models [62, 65, 66, 73], a realistic representation of the road network was considered in which the actual key locations, including incident sites, emergency services' resources, including ambulance stations and fire and rescue stations, and/or hospitals, were identified as nodes in the road network. Accordingly, the models presented in [62, 65, 66, 73] fully satisfy RME1. However, in the model presented in [64, 72], an unrealistic representation of the road network is considered where unreal locations, including incident sites, ambulance stations, and/or hospitals, in the road network were modelled as nodes. Thus, these models can be viewed as partially meeting RME1. The work of Rauner et al. [75] did not pay attention to modelling the road network of the affected geographic area, given that emergency resources, including medical staff and emergency vehicles, were assumed to be available on-site immediately when the MCI occurred. However, the transportation of casualties to hospitals was considered in this model. Consequently, the work of Rauner et al. [75] did not satisfy RME1.

RME2 is '*extract the accurate distance between key locations of interest in the MCI-affected geographical area'.* The GIS data of the affected geographic area in which an MCI occurs was considered to determine the actual distances between any key locations in central London [65], Vancouver [62], Newcastle-upon-Tyne [66], and South Korea [73]. These models fully satisfy RME2. However, in [62, 72], the actual distances between the defined key locations in the road network were pre-defined. Further, in the models presented in [64, 75], no attention was given to defining the distances between key locations; rather, the travelling times of emergency vehicles between key locations were pre-defined. Consequently, the models presented in [62, 64, 72, 75] can be viewed as not meeting RME2.

According to RME3, '*define credible travel times of emergency vehicles*', the satisfaction of RME1 and RME2, in addition to defining the speed of the emergency vehicles, are required to determine the travel time between any two key locations in the road network under consideration. In the previously published models [62, 73], the travelling time of emergency vehicles between any two locations in the road network was calculated using the speed of emergency vehicles and the actual distance obtained from the GIS data. Further, in the study of Wilson et al. [65], the median travel time between any two key locations was calculated based on the actual distance obtained from the GIS data due to the absence of the travel times of emergency vehicles in emergency events in the UK. In the previously published models [62, 72], the travel times required for emergency vehicles to travel between any two key locations in the road network were calculated based on a pre-defined distance and a pre-defined speed of ambulance vehicles. In previously published models [64, 75], the travelling times required for emergency vehicles to travel between any two key locations were pre-defined. However, in the work of Hawe et al. [66], no information is given regarding how the travel time between any two key locations was calculated.

Indeed, modelling a realistic road network of the affected geographical area in which an MCI occurs, considering the actual key locations and the GIS data, is essential to determine the accurate distances between any two key locations. Further, defining the speed of emergency vehicles and considering the accurate distances determine the travelling time incredibly. Thus, an unrealistic representation of the road network as in [62, 64, 72], pre-defined distances as in [62, 72], pre-defined travel times as in [64, 75], or using median travel times as in [65] are not appropriate assumptions for modelling a realistic and accurate road network of the affected geographical area where an MCI occurs. Road traffic in the affected geographical area changes throughout the day [80, 81], making these assumptions no longer applicable and not credible. Consequently, only one of the identified models [73] fully satisfies REM3, whereas six of them, including [62, 64-66, 72, 75], can be viewed as not satisfying RME3.

5.3.2 Modelling incident site

RME4 is '*define the number and specifications of the locations of incident sites in the MCI-affected geographical area*'. Two incident sites were assumed to have occurred in the North-East of England at two locations: an underground metro station and an outlet shopping centre in the work of Hawe et al. [66] and two incident sites in Vancouver: Broadway and Waterfront SkyTrain stations in the work of Amram et al. [62]. Further, one incident site was assumed to have occurred in New York Stock Exchange in lower Manhattan [64], D. L. Lawrence Convention Centre in downtown Pittsburgh, United States [72], the World Trade Centre in Korea [73], and an unspecified location [75]. In the work of Wilson et al. [65], the locations of three incident sites were assumed to have occurred in central London; however, their actual locations were not specified. Accordingly, the models presented in [62, 64, 66, 72, 73] fully satisfy RME4. However, the models presented in [65, 75] can be viewed as partially satisfying RME4.

RME5 is ‘*define the number of casualties at each incident site*’. The total number of casualties was specified at *all* incident sites in [62, 64, 66, 72, 73, 75] but not in the work of Wilson et al. [65], taking into account that a single incident site was considered in [64, 72, 73, 75]. The highest number of casualties considered in these models was 150 in the work of Wang et al. [72], and the lowest was 21 in the work of Amram et al. [62]. However, the number of casualties at *each* incident site was not specified in [62, 65, 66], given that these models considered multiple incident sites. Consequently, four of the identified models [64, 72, 73, 75] fully satisfy RME5, whereas the models presented in [62, 65, 66] did not satisfy such a requirement.

RME6 is ‘*specify the location of the four zones at each incident site*’. The modelling of the four zones (i.e., an HZ, CCS, POS, and ALP) associated with each incident site was neglected in [62, 66, 72, 73, 75]; the reader is referred to Chapter 4, Section 4.2.2 for more details related to the four zones. The CCS was set up to provide on-site treatment for trapped casualties only in the model of Wilson et al. [65]. However, this is unrealistic since the CCS is set up to provide advanced treatment for all immediate and urgent casualties. In addition, the POS is set up to provide first aid only for delayed casualties, as indicated in a previous study [13]. The definitions of the health classification of casualties, including immediate and urgent, were provided in Chapter 2, Section 2.3.3. Accordingly, none of the identified models fully satisfies RME6. Only two identified models [64, 65] can be viewed as partially meeting RME6. In contrast, the models presented in [62, 66, 72, 73, 75] did not satisfy RME6.

RME7 is ‘*the dynamic occurrence of incident sites in which additional sets of casualties need lifesaving interventions are introduced*’. Modelling multiple incidents occurring semi-simultaneously was presented in the work of Wilson et al. [65]. Seven SAR responders and 18 ambulances were deployed (initial locations were unspecified) to respond to three incident sites occurring within 15 seconds from the beginning of the response. In the previously published models [64, 72, 73, 75], only one incident site was assumed to have occurred. Therefore, the dynamic occurrence of MCIs was not applicable in these models. However, in the two studies [62, 66], the dynamic occurrence of MCIs is ignored, in which all incident sites were assumed to co-occur. Accordingly, only one of the identified models [65] fully satisfies RME7, whereas six of them [62, 64, 66, 72, 73, 75] did not meet RME7.

5.3.3 Modelling emergency services' resources

As stated in Chapter 4, the term emergency services' resources in this thesis refers to ambulance and fire and rescue stations in the MCI-affected area, as well as the emergency responders and vehicles initially stationed at these locations. RME8 is '*define the number and specify the locations of ambulance stations in the MCI-affected geographical area'*. In the work of Hawe et al. [66], nine ambulance stations in Newcastle-upon-Tyne were considered: Market Lane Ambulance Station, Sheriff Hill Ambulance Station, Netherby Drive Ambulance Station, Sandyford Road Ambulance Station, Debdon Gardens Ambulance Station, Hadrian Hospital Ambulance Station, Hawkey's Lane Ambulance Station, Parkside House Ambulance Station, Boldon Lane Ambulance Station. In the work of Wang et al. [72], six ambulance stations distributed over the Pittsburgh region were considered, but the actual locations of these stations were not given. However, modelling ambulance stations were not considered in [62, 64, 65, 73, 75]. Consequently, only one of the identified models [66] fully satisfies RME8, and the model presented in the work of Wang et al. [72] can be viewed as partially satisfying RME8. However, the models presented in [62, 64, 65, 73, 75] did not satisfy RME8.

RME9 is '*specify the type of emergency responders at each ambulance station*'. Multiple types of emergency responder were considered, including HART and MERIT responders [65], paramedic responders [66], and medical staff [72, 75]. The initial locations of these types of emergency responder were only specified in [66], unspecified in [65, 72], and assumed to be available on-site immediately when the MCI occurred in [75]. Consequently, only the model presented in [66] fully satisfies RME8, whereas the models presented in [65, 72, 75] can be viewed as partially satisfying RME9. In previously published models [62, 64, 73], no attention has been given to modelling emergency responders. Thus, these models did not satisfy such a requirement.

RME10 is '*define the number of each type of emergency responders at each ambulance station*'. The number of emergency responders of each type at each ambulance station must be determined to accurately and efficiently allocate the available emergency responders at these stations to incident sites. However, no knowledge is provided regarding the number of emergency responders at each ambulance station in all the identified models. Consequently, none of the identified models satisfies RME10.

RME11 is '*define the degree of expertise of each type of emergency responder at ambulance station*s'. Each type of emergency responder initially located at ambulance stations has a significant role in an MCI with regard to casualties, a point which should not be ignored. However, the degree of expertise of emergency responders is neglected in the seven identified models [62, 64-66, 72, 73, 75]. Emergency responders of each type were considered identical, and no meaningful difference between emergency responders' expertise was observed. Consequently, none of the identified models satisfies RME11.

RME12 is '*specify the type of emergency vehicle at each ambulance station*'. Ambulance vehicles were considered in [62, 64-66, 72, 73, 75]. Further, HART ambulances and MERIT ambulances were considered in [65]. Ambulance vehicles were located at nine ambulance stations, as in the work of Hawe et al. [66], or five hospitals, as in [62, 64, 65, 73]. Moreover, a common assumption is found in the previously published studies [72, 75], whereby ambulance vehicles were assumed to be available at the incident site or sites when the MCI occurred. This assumption is unrealistic and requires more attention from researchers as it could affect the overall response to an MCI. Accordingly, only one model [66] fully satisfies RME12, whereas the models presented in [62, 64, 65, 73] can be viewed as partially satisfying RME12. In contrast, the models presented in [72, 75] did not satisfy such a requirement.

RME13 is '*define the purpose of the use of each type of emergency vehicle at each ambulance station*'. The ambulance vehicle was the sole emergency vehicle for transferring casualties to hospitals [62, 64-66, 72, 73, 75]. Further, the purpose of using other types of emergency vehicles, including HART ambulances and MERIT ambulances in the work of Wilson et al. [65], was to transfer the associated emergency responders. Consequently, all identified models fully satisfy RME13.

RME14 is '*define the capacity of each type of emergency vehicle at each ambulance station*'. The capacity of emergency vehicles is ignored in all the identified models. Hence, none of the identified models satisfies RME14.

RME15 is ‘*define the number of each type of emergency vehicle at each ambulance station*’. In the work of Hawe et al. [66], 2-4 ambulance vehicles initially located at nine ambulance stations were considered. In the work of Repoussis et al. [64], 50 ambulance vehicles were assumed to be available at the incident site when the MCI occurred. However, in [62, 65, 72, 73, 75], the number of each type of emergency vehicle was unspecified. Hence, only one model [66] fully satisfies RME15, and one model [64] can be viewed as partially satisfying RME15. In contrast, the models presented in [62, 65, 72, 73, 75] did not satisfy such a requirement.

RME16 is ‘*define the number and specify the locations of fire and rescue stations in the MCI-affected geographical area*’. In the work of Hawe et al. [66], nine fire and rescue stations in Newcastle-upon-Tyne were considered: Newcastle North, Newcastle South, Newcastle East, Gateshead North, Gateshead East, South Tyneside West, South Tyneside East, North Tyneside East, and North Tyneside South. However, modelling fire and rescue stations was not considered in [62, 64, 65, 72, 73, 75]. Thus, only [66] fully satisfies RME16, whereas the models presented in [62, 64, 65, 72, 73, 75] did not.

RME17 is ‘*specify the type of emergency responders at each fire and rescue station’*. In [66], firefighters were initially located at fire and rescue stations. Since there was no consideration of modelling fire and rescue stations in the previously published models [62, 64, 65, 72, 73, 75], there was no consideration of modelling emergency responders at fire and rescue stations, except for the work of Wilson et al. [65], SAR responders were considered, but their initial locations were not specified. Accordingly, only one model [66] fully satisfies RME17, and one model can be viewed as partially satisfying RME17. However, the presented models in [62, 64, 72, 73, 75] did not satisfy this requirement.

RME18 is ‘*define the number of each type of emergency responders at each fire and rescue station*’. As with RME 10, the number of each type of emergency responders located at each fire and rescue station must be determined to accurately and efficiently allocate the available emergency responders at these stations to incident sites. However, no knowledge is provided regarding the number of emergency responders at each fire and rescue station in all seven identified models. Consequently, none of the identified models satisfies RME18.

RME19 is ‘*define the degree of expertise of each type of emergency responder at fire and rescue stations*’. As with RME 11, each type of emergency responder, initially located at fire and rescue stations, has a significant role in an MCI with regard to casualties, a point which should not be ignored. However, the degree of expertise of emergency responders is neglected in all seven identified models. Emergency responders of each type are considered identical, and no meaningful difference between emergency responders’ expertise is observed. Consequently, none of the identified models satisfies RME19.

RME20 is ‘*specify the type of emergency vehicle at each fire and rescue station*’. In [66], fire engines initially located at nine fire and rescue stations were considered. Since there was no consideration of modelling fire and rescue stations in the previously published models [62, 64, 65, 72, 73, 75], there was no consideration of modelling emergency vehicles at these stations. Thus, only [66] fully satisfies RME20, whereas the models presented in [62, 64, 65, 72, 73, 75] did not.

RME21 is ‘*define the purpose of the use of each type of emergency vehicle at each fire and rescue station*’. In the work of Hawe et al. [66], the purpose of using fire engines was to transfer firefighters to the incident sites. Since there was no consideration of modelling fire and rescue stations in [62, 64, 65, 72, 73, 75], there was no consideration of modelling emergency vehicles at these stations. Consequently, only one model [66] fully satisfies RME21, whereas the models presented in [62, 64, 65, 72, 73, 75] did not.

RME22 is ‘*define the capacity of each type of emergency vehicle at each fire and rescue station*’. The capacity of emergency vehicles at each fire and rescue station is ignored in all seven identified models. Accordingly, none of these models satisfies RME22.

RME23 is ‘*define the number of each type of emergency vehicle at each fire and rescue station*’. In the work of Hawe et al. [66], the number of fire engines at each station (nine stations were defined) was 2-3. However, the number of each type of emergency vehicle at each fire and rescue station was not defined in the previously published models [62, 64, 65, 72, 73, 75] since modelling emergency vehicles at fire and rescue stations was not considered (see RME16). Thus, only the work of Hawe et al. [66] fully satisfies RME23, whereas the models presented in [62, 64, 65, 72, 73, 75] did not.

5.3.4 Modelling hospitals

RME24 is ‘*define the number and specify the locations of hospitals located in the MCI-affected geographical area*’. In the work of Hawe et al. [66], four hospitals were considered in Newcastle-upon-Tyne: Royal Victoria Infirmary, Queen Elizabeth Hospital, South Tyneside Hospital, and North Tyneside Hospital. In the work of Repoussis et al. [64], ten hospitals were considered in lower Manhattan: New York Downtown Hospital, Bellevue Hospital Center, Beth Israel Medical Center, NY Eye and Ear, Hospital For Joint Diseases, NY University Medical Center, New York Hospital-New York, St. Vincents Hospital, St. Lukes Roosevelt/Roosevelt, and Lenox Hill Hospital. Thus, the models presented in [64, 66] fully satisfy RME24. In the work of Wilson et al. [65], three hospitals in central London were considered, but their locations were unspecified. In the work of Amram et al. [62], two major hospitals in Vancouver: Vancouver General Hospital and Royal Columbian Hospital, and five small hospitals were considered, but the locations of the small hospitals were unspecified. In the work of Wang et al. [72], 15 hospitals were considered; however, the locations of these hospitals were not specified. In the work of Bae et al. [73], five major hospitals in Gangnam District (four local emergency medical centres and one local emergency medical institution) were considered. However, the locations of these hospitals were not specified. In contrast, in the work of Rauner et al. [75], multiple hospitals were considered; however, the number and locations of these hospitals were not specified. Accordingly, the models presented in [62, 65, 72, 73] can be viewed as partially satisfying RME24; however, the work of Rauner et al. [75] can be viewed as not satisfying the requirement.

RME25 is ‘*define the casualty capacity level of each hospital*’. In the work of Amram et al. [62], the capacity of the two major hospitals was ten casualties per hospital, whereas the capacity of the five small hospitals was one casualty per hospital. In the work of Bae et al. [73], the capacity of the five major hospitals was between five and ten beds for each treatment service, including X-ray, admissions, and emergency department. In previously published models [64, 65, 72], the capacity of hospitals was not specified; however, it was assumed to be enough to receive all casualties from all incident sites. However, in two models [66, 75], no attention was given to the capacity of hospitals. Accordingly, the models presented in [62, 73] fully satisfy RME25, whereas the models presented in [64, 65, 72] can be viewed as partially satisfying RME25. However, two models [66, 75] did not satisfy RME25.

5.3.5 Modelling casualties

RM26 is '*model a realistic and comprehensive health profile for each casualty*'. In [73], casualty health profiles were modelled to take account of the injury or injuries that casualties may suffer, which include asphyxia, haemorrhage shock, or traumatic brain injury. However, such profiles were not comprehensive due to the missing realistic information, such as the vital signs needed to be measured for each casualty to determine his/her health classification. Thus, this model can be viewed as partially satisfying RME26. In previously published models [62, 64-66, 72, 75], casualties are distinguished by their health classification; immediate or urgent in [62, 64, 66], immediate, urgent or delayed in [65, 72], and severely or slightly injured in [75]. However, designing a health profile for each casualty is neglected in these models. Accordingly, none of these models satisfies RME26.

In relation to RME27 '*dynamic simulation of the health status of casualties*', three approaches to simulating casualties' health are mainly considered in the identified models: a classification-based approach as in [65, 72], a time-based approach as in [73, 75], and a static-based approach as in [62, 64, 66]. In two models [65, 72], the transition from one health classification to another was considered during the response using the Markov chain as in [65] and the Delphi technique as in [72]. In the work of Wilson et al. [65], only a negative health transition was allowed, in which the transition probabilities of the Markov chain were pre-defined. However, no information was given regarding the basis for defining such transition probabilities. In the work of Wang et al. [72], the Delphi technique was employed to estimate the deterioration in the RPM scores of casualties at fixed intervals (30 minutes); a low RPM score causes fast deterioration over the interval time. The RPM scores represent twelve values. Casualties scoring below three are classified as 'dead', casualties scoring between three and nine require immediate medical intervention and are thus classified as 'immediate', casualties scoring 10/11 are classified as 'urgent', and casualties scoring 12 are classified as 'delayed'. Accordingly, two previously published models [65, 72] can be viewed as fully satisfying RME27. In the work of Bae et al. [73], a mathematical formulation was developed to define the individualised survival probability according to the cause of death, including asphyxia and haemorrhage shock. In particular, casualties suffering from haemorrhage shock without treatment die within hours (exactly how long is unspecified), whereas casualties suffering from asphyxia without receiving treatment die within an hour or less (exactly how long is unspecified). In the work of Rauner et al. [75], each casualty at an incident site was assigned a random score ranging from 1-100, in line with [82, 83]. A score of 0, 1–40, 41–99, and 100 represent ‘dead’, ‘severely injured’, ‘slightly injured’, and ‘uninjured’ casualties, respectively. The health of severely injured casualties was assumed to deteriorate while waiting for treatment. That is, the worse their health score, the sooner they die. In the work of Rauner et al. [75], the deterioration in casualties’ health was based on the waiting time for treatment and the current health score of casualties. Accordingly, two previously published models [73, 75] can be viewed as fully satisfying RME27. A static-based approach implies that no changes in casualties’ health classifications are considered as in [62, 64, 66]; hence, they are assumed to remain constant until the response to the MCI is declared complete. Accordingly, these models did not satisfy RME27.

RME28 is ‘*define the tasks associated with casualties and the sequence of performing them by emergency responders during the response*’. The common task associated with casualties considered in all identified models is transporting all casualties from the incident site or sites to the assigned hospitals as in [62, 64-66, 72, 73, 75]. In such models, no emergency responders were assigned to accompany the casualties to hospitals and no treatment was provided to those casualties during the transfer to the assigned hospitals. Four additional tasks were considered: the searching for casualties task [65], the releasing task [65], the on-site triage task [66, 75], and the on-site treatment task [64-66, 75]. In [65], some casualties were assumed to be trapped in the incident sites, requiring release before being treated. The on-site treatment task was considered to be undertaken by a particular type of emergency responder for all casualties [66, 75] or trapped casualties only [65], although the fact that any casualty in any health classification, trapped or not trapped, may require on-site treatment at any time during the response. In previously published models [62, 64, 65, 72, 73, 75], the full triage operation was assumed complete, and the health classification of casualties was assumed to be known beforehand; thus, in these models, the on-site triage task was not considered. An attempt to perform triage on-site was made in the work of Hawe et al. [66], whereby an agent was designated to triage casualties at incident sites. However, no knowledge is provided on how the casualties were classified since no health profile, consisting of the essential information to determine the health classification for each casualty, was considered. One [65], one [66, 75], and four [62, 72, 73] identified models considered four, three, and one tasks, respectively. Further, none of the identified models considered all five tasks —accordingly, all the identified models can be viewed as partially satisfying RME28.

RME29 is '*define the duration of each task associated with a casualty*'. The duration of tasks, excluding transportation tasks (see RME3), was assumed to be fixed [64, 72], in pre-defined ranges [75], or estimated with a degree of error [65]. Consequently, these models can be viewed as partially satisfying RME29. However, in the model presented in [66], no knowledge was provided regarding the duration of on-site triage and on-site treatment tasks. Further, transporting casualties to the assigned hospitals was the only task considered [62, 73]. Thus, these models did not satisfy RME29. Defining the duration of tasks associated with casualties is essential, but the time taken to perform each task may vary depending on the following:

1) the level of expertise of the responders assigned to undertake the tasks;
2) the severity of injuries that casualties may suffer at incident sites.

However, in the seven models discussed above, the severity of casualties and the responders' expertise were not considered when defining the task duration. Therefore, an approach is required to vary the duration of tasks based on these two factors.

5.3.6 Coordination decisions

Following the critical review of the seven identified models against the requirements of modelling an MCI environment, this section reviews those models against the requirements of the coordination decisions (RCD1-RCD3). The requirements of the coordination decisions are related to the pre-hospital response consisting of the PDA and post-PDA responses.

RCD1 is '*determine the best allocation and scheduling of emergency responders to undertake tasks associated with casualties located at incident sites for the PDA response plan*. Hawe et al. [66] emphasised the importance of considering the PDA response despite the scarce available resources when an MCI occurs. Further, at the beginning of a simulation of a response, the user of the model is allowed to design the PDA response plan by allocating emergency vehicles, including fire engines and ambulances, to each incident site (two incident sites were considered). However, the number of emergency vehicles to be allocated by the user to each incident site is not specified. Accordingly, the model presented in [66] can be viewed as partially satisfying RCD1; however, information related to the PDA response plan was not provided. For six of the seven identified models [62, 64, 65, 72, 73, 75], the PDA response was not considered, and all the information related to the MCIs was assumed to be known beforehand. However, in reality, complete and accurate information related to MCIs is not available at the outset. Consequently, these six models do not meet RCD1.

RCD2 is '*determine the best allocation and scheduling of tasks associated with casualties for the initial post-PDA response plan*'. In the work of Wilson et al. [65], an MCI response plan is constructed incrementally by adding one task at a time from a set of tasks, each of which is associated with a casualty. Each task added to the plan was assigned to the emergency responder, who was due to complete all their assigned tasks first. Furthermore, the selection of a task to be allocated to a designated emergency responder, and thus the plan, was chosen based on the health classification of the associated casualty and the time at which the task under consideration for selection could begin. The process of assigning tasks to emergency responders was repeated until all outstanding tasks were allocated. Consequently, a complete emergency response plan was generated. However, in this plan, casualties were not allocated to hospitals; rather, this was done dynamically during the execution of the emergency response plan (see RCD3). In the work of Hawe et al. [66], the number of emergency vehicles carrying emergency responders to each incident site was determined using nine strategies. Three allocation strategies for fire engines and three allocation strategies for ambulance vehicles (i.e., 3 x 3). A separate Finite State Machine was designed for each type of emergency responder, representing the states each type of emergency responder should follow to perform a task. The state of an emergency responder transits from one to another until the task under consideration is fully completed. The tasks were allocated to emergency responders in two ways: when emergency responders were nearby casualties who needed lifesaving interventions and when emergency responders saw casualties who needed lifesaving interventions. The allocation of casualties to hospitals was pre-defined. Casualties with the same health classification (immediate or urgent) were sent to a particular hospital (two hospitals were considered). Further, the allocation of casualties to ambulance vehicles was not defined. The model presented in [64, 73] focused on transporting casualties to the assigned hospitals, and thus, the allocation of tasks to emergency responders was not considered. In the work of Repoussis et al. [64], casualties were assigned to hospitals based on: the number of available beds, the treatment capacity, and the health classification of casualties (i.e., immediate casualties were sent to specialist hospitals, and urgent casualties were sent to non-specialist hospitals). Further, casualties were assigned to ambulance vehicles based on a fixed priority ordering scheme (i.e., immediate casualties were sent to the assigned hospitals first). Further, in the work of Bae et al. [73], casualties were assigned to hospitals based on: the number of available beds, the number of X-ray rooms, and the medical staff available at each hospital (priority was given to immediate casualties). However, the allocation of casualties to ambulance vehicles was not defined. In the models presented in [62, 72, 75], no initial post-PDA response plan, or equivalent, was created; instead, an optimised post-PDA response plan, or equivalent, was generated in real-time (see RCD3). With respect to RCD2, four of the models discussed [64-66, 73] can be viewed as partially satisfying RCD2 because the generated initial post-PDA response plans, or equivalent, were not complete in the sense that if implemented, 'as they were', they would not result in transferring emergency responders to the allocated incident sites, performing the allocated tasks, and transferring all casualties to the assigned hospitals. In contrast, three models, including [62, 72, 75], do satisfy RCD2.

RCD3 is '*Dynamically schedule and allocate (if required) all tasks yet to be started to reflect the evolving MCI for the optimised post-PDA response plan, considering the aim to achieve a seamless transition from one optimised post-PDA response plan to another with minimal transition time*'. In the work of Wilson et al. [65], partial new information regarding MCIs was gradually introduced during the execution of the MCI plan (equivalent to the optimised post-PDA response plan). Thus, the local search algorithm was employed in real-time to find the best allocation of tasks (yet to be started) to emergency responders at each incident site. In addition, it was employed to allocate casualties to hospitals based on the real-time hospital capacity information, considering those who self-transferred to hospitals. However, no information is given regarding the allocation of casualties to ambulance vehicles. In the work of Amram et al. [62], real-time ambulance vehicles allocation to transport casualties to hospitals was considered based on the pre-defined travelling times between the incident sites and the assigned hospitals, along with the real-time hospital capacity information. Ambulance vehicles were assumed to be available at two incident sites when the MCIs occurred. The information regarding hospitals' casualty capacity was updated every 10 seconds. In the work of Wang et al. [72], ambulance vehicles (i.e., agents) transporting emergency responders (initial locations were unspecified) were requested to travel to a single incident site. Thus, no coordination decision was required. When ambulance vehicles arrived at the incident site, emergency responders loaded casualties into ambulance vehicles. However, no information is given regarding the basis for allocating such emergency responders and ambulance vehicles to casualties. Real-time casualty to hospital allocation was considered based on the health classification of casualties and the chosen policy. The policies defined in [72] were stated in Chapter 3, Section 3.2.3. In the work of Rauner et al. [75], real-time emergency responders and vehicles (the type was unspecified) allocation was considered to treat and transport casualties to hospitals, respectively. However, the allocation of emergency responders to casualties was made based on the health scores of casualties (assumed to be known beforehand). Furthermore, the allocation of casualties to hospitals was made based on the availability of emergency vehicles and the health classification of casualties (priority was given to severely injured casualties). The models presented in [62, 65, 72, 75] did not pay attention to the seamless transition between one optimised plan to another with less interruption. The time required to dynamically update the optimised post-PDA response plan, or equivalent, and meet the needs of casualties is critical in an MCI. Long processing times result in plans that may not reflect the evolving MCIs, as new information may become available at any time as the response unfolds. Further, the real-time allocation based on the available MCIs information may lead to a sub-optimal post-PDA response plan or equivalent. Accordingly, the models presented in [62, 65, 72, 75] can be viewed as partially satisfying RCD3. The models presented in [64, 66, 73] ignored the dynamic nature of MCIs and the complexity associated with dynamic scheduling due to the dependencies between tasks. In these models, the information related to MCIs was assumed to be known beforehand. No further changes were considered in such information. Thus, the generated post-PDA response plan (see RCD2), or equivalent, was considered the final and complete optimised post-PDA response plan since no updating in the generated plan was required. Therefore, these three models did not meet RCD3.

5.4 The scope for original and significant contributions of knowledge

In order to clearly define the scope for an original and significant contribution of knowledge to the academic literature in this research, Table 5.2 summarises the investigation in terms of a critical review and discussion of the seven identified models that are most closely related to the key elements of (a) an MCI environment and (b) the coordination decisions [62, 64-66, 72, 73, 75] (Table 5.1). However, a full review of all 14 models is provided in Appendix A.

Table 5.2: A summary of the critical review of seven identified models against the requirements defined in Chapter 4.

Key elements of		Req.	[62]	[64]	[65]	[66]	[72]	[73]	[75]
Modelling an MCI environment	RN	RME1	F	P	F	F	P	F	N
		RME2	F	N	F	F	N	F	N
		RME3	F	N	N	N	N	F	N
	IS	RME4	F	F	P	F	F	F	P
		RME5	N	F	N	N	F	F	F
		RME6	N	P	P	N	N	N	N
		RME7	N	N	F	N	N	N	N
	ESR	RME8	N	N	N	F	P	N	N
		RME9	N	N	P	F	P	N	P
		RME10	N	N	N	N	N	N	N
		RME11	N	N	N	N	N	N	N
		RME12	P	P	P	F	N	F	N
		RME13	F	F	F	F	F	F	F
		RME14	N	N	N	N	N	N	N
		RME15	N	P	N	F	N	N	N
		RME16	N	N	N	F	N	N	N
		RME17	N	N	P	F	N	N	N
		RME18	N	N	N	N	N	N	N
		RME19	N	N	N	N	N	N	N
		RME20	N	N	N	F	N	N	N
		RME21	N	N	N	F	N	N	N
		RME22	N	N	N	N	N	N	N
		RME23	N	N	N	F	N	N	N
	H	RME24	P	F	P	F	P	P	N
		RME25	F	P	P	N	P	F	N
	C	RME26	N	N	N	N	N	P	N
		RME27	N	N	F	N	F	F	F
		RME28	P	P	P	P	P	P	P
		RME29	N	P	P	N	P	N	P
Coordination decisions		RCD1	N	N	N	N	P	N	N
		RCD2	N	N	P	P	P	N	P
		RCD3	P	P	N	P	N	P	N

MCI, mass casualty incident; RME, requirements of modelling MCI environment; RCD, requirement of coordination decisions; RN, road network in the MCI-affected geographical; IS, incident sites; ESR, emergency services' resources; H, hospitals; C, casualties; F, fully satisfy a particular requirement; P, can be viewed as partially satisfy a particular requirement; N, did not satisfy a particular requirement.

In terms of the requirements of modelling an MCI environment, Table 5.2 shows that the seven identified models fully consider or can be viewed as partially considering RME13 or RME28, respectively. However, none of the reviewed models considers RME10, RME11, RME14, RME18, RME19, and RME22. In addition, Table 5.2 shows that:

- 4, 2, and 1 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME1, respectively;
- 4, 0, and 3 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME2, RME5 and RME27, respectively;
- 2, 0, and 5 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME3, respectively;
- 5, 2, and 0 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME4, respectively;
- 0, 2, and 5 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME6, respectively;
- 1, 0, and 6 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME7, RME16, RME20, RME21 and REM23, respectively;
- 1, 1, and 5 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME8, RME15 and RME17, respectively;
- 1, 3, and 3 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME9, respectively;
- 2, 3, and 2 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME12 and RME25, respectively;
- 2, 4, and 1 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME24, respectively;
- 0, 1, and 6 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME26, respectively;
- 0, 7, and 0 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME28, respectively;
- 0, 4, and 3 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME29, respectively.

With respect to the identified models, none of them fully considers or can be viewed as partially considering all 29 requirements of modelling an MCI environment (Table 5.2), whereas one [75], two [64, 72], one [65], one [62], one [73], and one [66] of the identified models fully consider 3, 4, 5, 6, 9, and 14 of the requirements, respectively. Further, one [66], two [62, 73], one [75], two [64, 72], and one [65] of the identified models can be viewed as partially satisfying 1, 3, 4, 7, and 9 of the requirements, respectively. For the requirements of coordination decisions, Table 5.2 shows that none of the requirements is fully satisfied by any of the seven identified models. Further, it shows that one identified model can be viewed as partially satisfying RCD1, whereas four of the identified models can be viewed as partially satisfying RCD2 and RCD3. In terms of identified models, none of the identified models fully includes consideration of any requirement. Further, none of them can be viewed as partially considering all requirements (Table 5.2). However, the models previously published [65, 66] and [62, 64, 72, 73, 75] consider two and one of the requirements, respectively.

Table 5.2 shows ample scope for a decision support model to coordinate the emergency response to MCIs. This leaves room for an original and significant contribution to knowledge by developing a model that satisfies all the requirements defined in Chapter 4, considering the limitation in the identified models discussed and reviewed in this chapter.

5.5 Summary

This chapter completed the definition and explanation for **RQ2** and **RQ3**. It presented an initial evaluation of models reviewed in Section 3.2 against the key elements defined in Chapter 3, Section 3.3 regarding a) an MCI environment and b) coordination decisions, leading to identifying a subset of the most closely related models to the key elements. Subsequently, the identified models were critically reviewed against the requirements defined in Chapter 4 for a decision support model to coordinate the emergency response to MCIs. Accordingly, the scope for an original and significant contribution to knowledge in the identified models was defined (Table 5.2). In Table 5.2, it is obvious that none of the identified models satisfied all the requirements. Thus, this chapter revealed ample room for a decision support model to coordinate the emergency response to MCIs, which satisfies all the requirements defined in Chapter 4 and considers the limitation in the identified models. The decision support model to coordinate the emergency response to MCIs will be presented in the following three chapters: Chapter 6 will discuss the three main components of the model, Chapter 7 will design the MCI environment based on RME1-RME29, whereas Chapter 8 will present the algorithms and an approach used in the pre-hospital response framework.

Chapter 6. A decision support model to coordinate the emergency services' response to MCIs

6.1 Introduction

The aim of this chapter is to present a decision support model to coordinate the emergency services' response to Mass Casualty Incidents (MCIs). The decision support model in this thesis consists of three interrelated components, namely the MCI environment, the coordination and management interface (CMI), and the pre-hospital response framework (PHRF). The MCI environment is covered in Chapter 7, and a discussion of the algorithms and an approach used in PRHF is presented in Chapter 8. In this chapter, a particular focus is placed on the initial information used to initiate the response to MCIs and new information that becomes available during the response to MCIs. The flow and the nature of this information, in reality, are used to discuss the three interrelated components. This chapter aims to discuss **RQ2**, which was initially introduced in Chapter 1 and is restated below.

To what extent can existing decision support models for this response be improved with dynamic optimisation-based modelling?

In Section 6.2, an overview is provided of the three main components of the presented decision support model to coordinate the emergency services' response to MCIs Further, the initial information related to an MCI needed to initiate the Pre-determined attendance (PDA) response is presented in Section 6.3, followed by the new information related to an MCI that becomes available during the response, requiring the generation of a new optimised post-PDA response plan is discussed in Section 6.4.

6.2 A decision support model to coordinate the emergency services' response to MCIs

The presented decision support model consists of three interrelated components: the MCI environment, the CMI, and the PHRF (Figure 6.1). The MCI environment refers to the MCI-affected geographical area in which a number of incidents have occurred, at which a PDA response plan and an optimised post-PDA response plan are executed. The CMI represents an information hub where the information related to an MCI is received from the MCI environment. Then, coordination decisions based on the available information are directed from the PHRF via the CMI to be executed in the MCI environment. The PHRF consists of optimisation-based algorithms, namely a greedy heuristic algorithm (GHA), a genetic algorithm (GA), a neighbourhood search algorithm (NSA), and an approach to reducing the transition times between successive optimised post-PDA response plans. Further discussion on these algorithms and the approach is provided in Chapter 8 (Sections 8.2 and 8.4, respectively). In Figure 6.1, the term *t* indicates the emergency response time measured in minutes. Note that the numbering of steps presented in Figure 6.1 does not refer to the sequential order of their execution; rather, it is used to aid the explanation. The dashed arrow in Figure 6.1 indicates that particular steps are executed only once during the response to MCIs. The decision support model is discussed as if an MCI is occurring in reality rather than discussing each component individually due to the interrelated nature of the components. The initial information related to an MCI used to initiate the response to MCIs is discussed first. Then, the new information that becomes available as the response unfolds and the effect of such information on the response to an MCI are discussed.

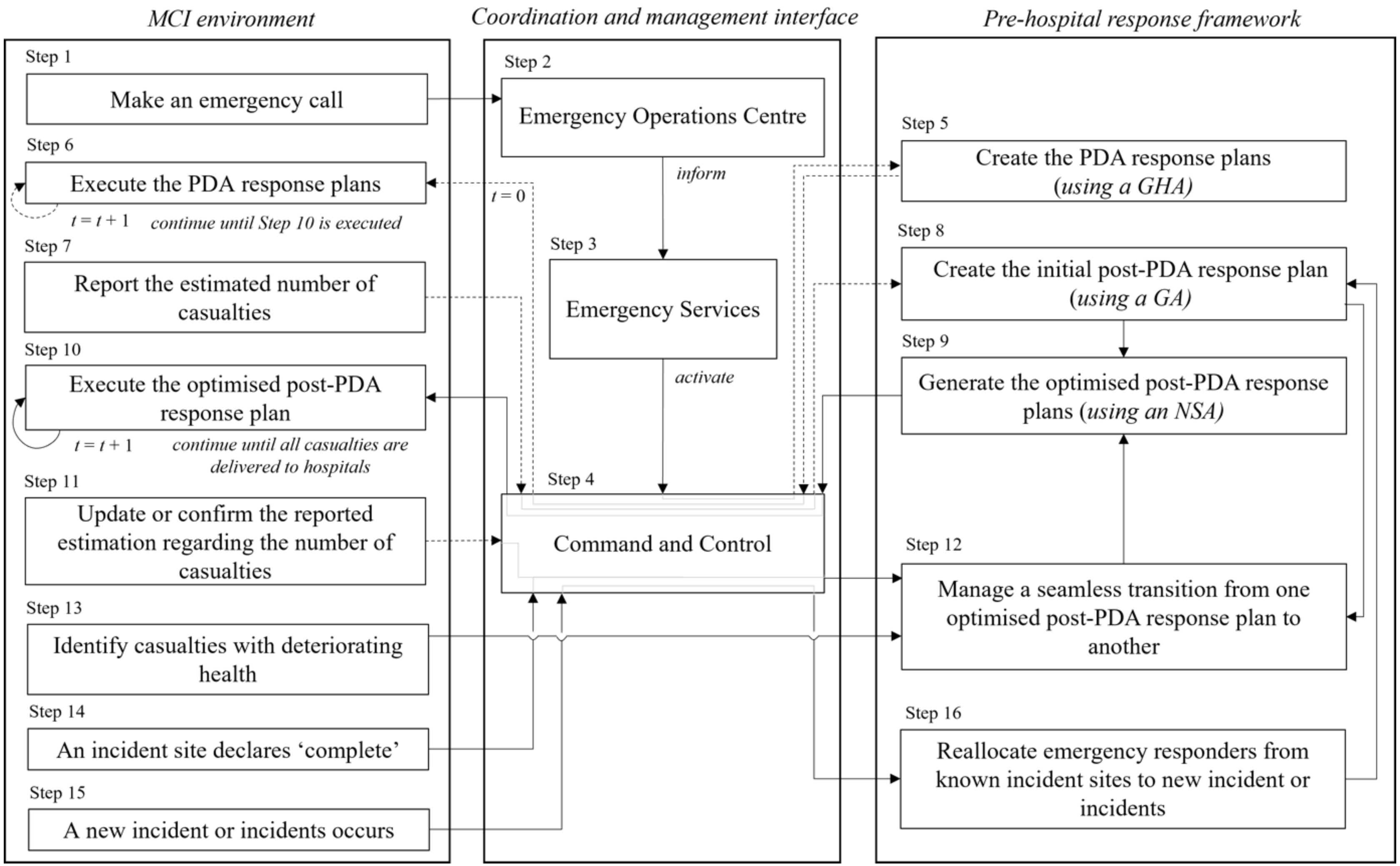


Figure 6.1: Three interrelated components of a decision support model.

6.3 Initial information related to an MCI

An emergency call is made by the public (Step 1, Figure 6.1) to the Emergency Operational Centre (EOC) (Step 2), reporting the location of an incident or a number of incidents. Subsequently, the EOC informs the Emergency Services (ES) about the location of the reported incident site or sites (Step 3) to activate command and control (CC) (Step 4). Based on the reported information related to the location of the incident site or sites, the GHA is requested by CC to create the PDA response plan involving the reported incident or incidents in the PHRF (Step 5). Since the number of emergency responders considered in the PDA response depends on a number of factors, such as the type and severity of the incident [47], one emergency vehicle of each type (Table 6.1) is assumed to be dispatched to each incident site transferring up to four emergency responders of the same type, in accordance with previously published research [84, 85]. This is to ensure that the emergency responders allocated to each incident site are able to undertake any tasks associated with casualties until more emergency responders are dispatched. Note that Hazardous Area Response Team (HART) and Medical Emergency Response Incident Team (MERIT) ambulances modelled in this research have been assumed smaller than normal ambulances, thus unsuitable for transporting casualties to the assigned hospitals.

Table 6.1: Purpose of using emergency vehicles.

Vehicles	Usage
HART ambulances	Transport HART responders to incident sites.
MERIT ambulances	Transport MERIT responders to the incident sites.
Normal ambulances	Transport paramedics responders to incident sites, as well as casualties to hospitals.
Fire engines	Transport Fire and Rescue (FAR) responders to incident sites.
Incident Support Vehicles	Transport Search and Rescue (SAR) responders to incident sites.

HART, Hazardous Area Response Team; MERIT, Mobile Emergency Response Incident Team.

Once the PDA response plan has been created involving all the reported incident sites, CC instructs emergency responders originally located at ambulance stations and fire and rescue stations in the MCI-affected area to execute the created plan in the MCI environment (Step 6). The first emergency responders of the PDA response who arrive at each incident site inform CC of the estimated number of casualties at that incident site (Step 7), which necessitates more emergency vehicles and responders to be sent to the incident site or sites as a part of the post-PDA response. Based on the information related to the estimated number of casualties, CC requests that GA create an initial post-PDA response plan in the PHRF (Step 8). The initial post-PDA response plan consists of the initial schedules of those emergency responders not involved in the PDA response. Furthermore, the schedules of the emergency responders involved in the PDA response are updated by assigning more tasks. In the initial post-PDA response plan, each emergency responder's schedule may consist of the following tasks.

- A task to travel from an ambulance station and fire and rescue station at which an emergency responder was originally located to an incident site to which that emergency responder has been allocated using an emergency vehicle.
- Tasks to be carried out at the allocated incident site to which an emergency responder has been allocated.
- Tasks to travel from an incident site where a particular emergency responder was originally located to the hospital where a casualty has been allocated using a normal ambulance and return to an incident site to collect another casualty.

Once the initial post-PDA response plan has been created involving all the reported incident sites and emergency responders and vehicles available at all ambulance stations and fire and rescue stations, CC requests the NSA to optimise the initial post-PDA response plan in the PHRF (Step 9). As a result of Step 9, the optimised post-PDA response plan will be generated, consisting of the schedules of all emergency responders, including those involved in the PDA response. Accordingly, CC instructs the emergency responders to execute that plan in the MCI environment (Step 10). Figure 6.2 shows an example of the application of the three-step approach to coordinating the response of the emergency services' resources to MCIs for two emergency responders, emergency responder 1 er_1 and emergency responder 2 er_2, in which er_1 is involved in the PDA response and er_2 is not involved.

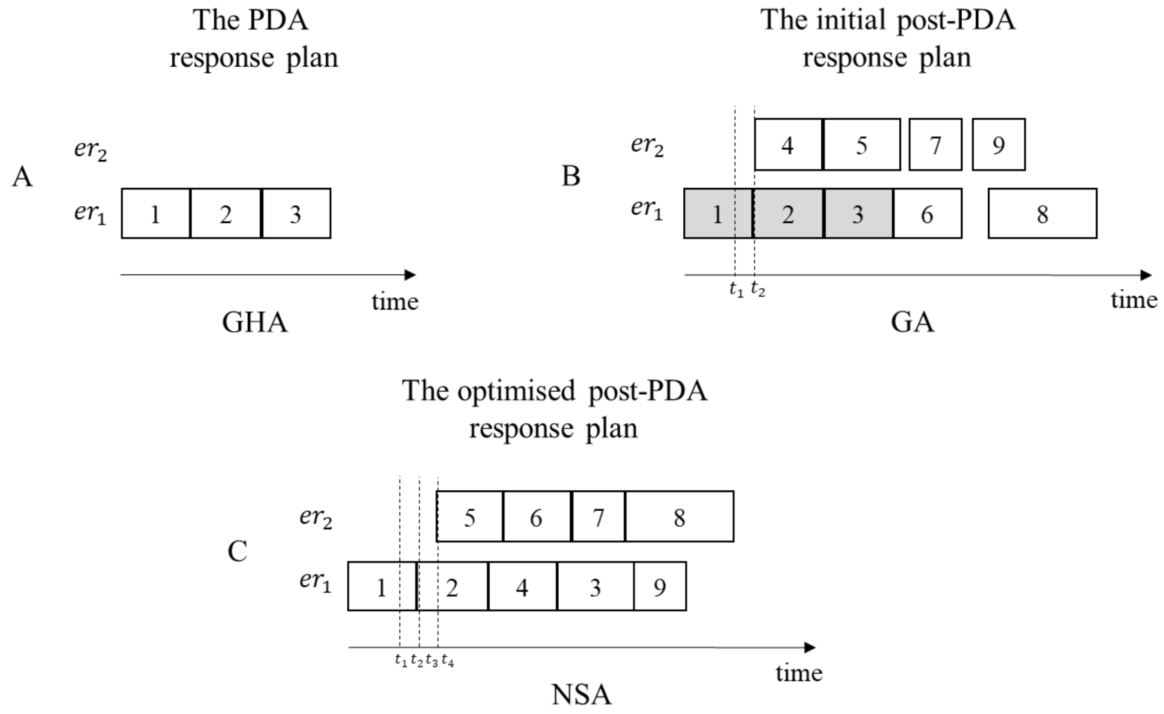


Figure 6.2: Three-step approach to generating a PDA response plan and the initial and optimised post-PDA response plans based on the initial information related to an MCI.

In Step 1, the GHA is used to create the PDA response plan, which consists of Tasks 1 to 3 allocated to er_1 (Figure 6.2 A). As the response unfolds, for illustrative purposes, six tasks (Tasks 4 to 9) are introduced. In Step 2, the GA is used to create the initial post-PDA response plan in which the original schedule of er_1 involved in the PDA response plan is preserved (i.e., shaded boxes for er_1 in Figure 6.2 B). Additionally, more tasks associated with casualties at the same incident site, where emergency responders er_1 has been allocated, are allocated to er_1. Further, the initial schedule of er_2 who is not involved in the PDA response, is created (Figure 6.2 B). In Figure 6.2 B, the vertical line at time t_1 indicates the time at which the initial estimation of the number of casualties from the MCI environment is received, thus necessitating the creation of the initial post-PDA response plan. The period from t_1 to t_2 represents the time needed for the GA to create the initial post-PDA response plan. In Step 3, the NSA is executed at time t_3, which starts immediately after time t_2, to generate the optimised post-PDA response plan (Figure 6.2 C). The period of time from t_3 to t_4 represents the time needed for the NSA to generate the optimised post-PDA response plan. As a result of Step 3, Tasks 8 and 6, which were originally allocated to er_1 in the initial post-PDA response plan, have been reallocated to er_2 (Figure 6.2 B) and Tasks 4 and 9 originally allocated to er_2 in the initial post-PDA response plan (Figure 6.2 B), have been reallocated to er_1. Furthermore, tasks being processed by an emergency responder but are yet to be completed are not interrupted, for example, Task 2 (Figure 6.2 B).

6.4 New information related to an MCI

During the execution of the optimised post-PDA response plan generated using the NSA (Step 10), new information related to an MCI that may become available as the response unfolds will be sent from the MCI environment to the CC. Such information may include the following.

- Updating or confirming the reported estimation of the number of casualties at an incident site by the same emergency responders that reported the original estimate to CC (Step 11), which requires the execution of the NSA to generate a new optimised post-PDA response plan (Step 12) to reflect the evolving MCI. Further detail of this is provided in Section 6.4.1.
- Identification of casualties with deteriorating health, requiring immediate lifesaving interventions by emergency responders (Step 13), which requires the execution of the NSA to generate a new optimised post-PDA response plan (Step 12) to reflect the evolving MCI. Further detail of this is provided in Section 6.4.2.
- Completion of the response at an incident site or sites reported to the CC by a pair of paramedics who collect the final casualty from the ALP at that incident site (Step 14), resulting in a number of emergency responders becoming available to be deployed to another incident site or sites. These emergency responders will have to be reallocated to other incident sites with tasks yet to be started using the NSA (Step 9). Further detail of this is provided in Section 6.4.3.
- Occurrence of a new incident or incidents reported as the response unfolds (Step 15), resulting in additional casualties requiring lifesaving and/or medical interventions. Particular emergency responders will have to be reallocated from their original incident site to respond to the new incident site using a reallocation approach (Step 16). Further detail of this is provided in Section 6.4.4.

Prior to the execution of the NSA to generate a new optimised post-PDA response plan based on the aforementioned information related to an MCI, a developed approach to reducing the transition time between successive optimised post-PDA response plans should be executed (Step 12). As indicated in Chapter 1 (Section 1.3), the term ‘transition time’ refers to the time when emergency responders may have no scheduled tasks to undertake due to the reallocation and rescheduling processes. When the NSA generates the new optimised post-PDA response plan to reflect the evolving MCI, the CC instructs the emergency responders at all incident sites to execute the generated plan in the MCI environment (Step 6).

6.4.1 Updating the estimated number of casualties at an incident site

The information reported in Step 7 (Figure 6.1) regarding the estimated number of casualties can never be guaranteed to be accurate; for example, the number of casualties may be over or under-estimated [6]. When all emergency responders, who are part of the PDA response (Step 6), have arrived at the allocated incident site, the number of casualties at that incident site will become known. Thus, at this point in time, the PDA emergency responder that has reported the initial estimate at the early stage of the PDA response will confirm or update the information regarding the number of casualties (Step 11). If the estimate is confirmed as correct, the emergency responders who have been allocated to the incident sites will carry out their tasks as scheduled in Step 10. In contrast, if the estimate is updated, a number of tasks will be assigned to emergency responders to be carried out during the process of generating the new optimised post-PDA response plan (Step 12), taking into account the dependencies between tasks (further discussion is provided when discussing the MCI environment in Chapter 7). Then, the current optimised post-PDA response plan will be interrupted, and a new optimised post-PDA response plan will be generated (Step 9), taking into account the new information related to the number of casualties at that incident site. Interrupting the current optimised post-PDA response plan may threaten casualties’ lives. However, the execution of the approach in Step 12 will minimise the effect of such a threat, as casualties will continue receiving essential lifesaving and/or medical interventions. At the same time, the new optimised post-PDA response plan is generated.

6.4.2 Identifying casualties with deteriorating health

During the response to MCIs, the health of casualties with head and/or burn injuries who are yet to be delivered to hospitals may deteriorate due to the progression of these injuries accompanied by bleeding or, alternatively, improve because of on-site lifesaving interventions provided by MERIT, HART, or paramedic responders. When a casualty loses more than 15% of the body’s blood (equivalence to 0.75 litres given that the average volume of blood in the human body is 5 litres) due to waiting for lifesaving interventions, he/she enters the hypovolemic shock preventing the heart from pumping enough blood to the body. In such a case, the health classification of that casualty is assumed to be immediate, in accordance with the previously published studies [86, 87]. Hypovolemic shock is a life-threatening condition resulting when a casualty loses more than 15% of the body's blood and causes death when a casualty loses more than 40% of the total volume of blood [86, 87]. Emergency responders can immediately identify casualties with deteriorating health at any incident site when the number of emergency responders is equal to or more than the number of the remaining casualties at that incident site (Step 13) and reports the information to the PHRF (Step 12) and then waits for further instructions (Figure 6.1). As a result of implementing the approach in Step 12, a number of tasks will be assigned to emergency responders to be carried out during the execution of the NSA, taking into account the nature of performing tasks. Then, the current optimised post-PDA response plan will be interrupted, and a new optimised post-PDA response plan will be generated (Step 9) and executed (Step 10), taking into account the new information related to the identified casualty's health. Again, interrupting the current optimised post-PDA response plan may threaten casualties' lives. However, the execution of the approach in Step 12 will minimise the effect of such a threat as casualties will continue receiving the essential lifesaving interventions while the NSA is generating the new optimised post-PDA response plan. However, it takes more time to identify these casualties at any incident site when the number of emergency responders is less than the number of remaining casualties at that incident site. In such cases, the ratio of casualties to emergency responders at an incident site is calculated to define the time needed for emergency responders to identify these casualties, indicating that emergency responders cannot quickly identify these casualties due to the high number of casualties at an incident site. For example, consider the number of casualties at an incident site at time t to be 40 and the number of emergency responders of all types allocated at that incident site to be 15. In this scenario, the time taken for an emergency responder to identify a casualty who requires immediate lifesaving intervention is $\frac{40}{15} = 2.66$ minutes.

It is possible that while a response plan is being developed using the NSA, another emergency responder reports that another casualty is in need of immediate lifesaving intervention. In such a case, the current execution of the NSA will be allowed to be completed, leading to the optimised post-PDA response plan being generated (Step 9) and executed (Step 10) rather than being terminated. Then, the NSA will be executed again, considering the new information related to a recent casualty or casualties with deteriorating health reported by an emergency responder or responders. This is because no information is available regarding when another casualty with deteriorating health will be identified, so action must be taken. Further, this avoids prolonged times that expose casualties to the risk of loss of life. Since the execution of the NSA takes approximately 15 seconds or less, it is possible for it to be executed again to include new information reported by any emergency responders regarding casualties at risk of losing lives.

Simulating the deterioration in casualties' health

In the decision support model presented in this thesis, the amount of bleeding is affected by the current health profile of casualties; the more severe the head and/or burn injuries, the greater the blood loss [88]. The litres of blood that each casualty with head and/or burn injuries loses in the next minute, $c_{q,t+1}^{BL}$, if no lifesaving interventions are provided when casualty c_q needs it is estimated using Eq. 6.1.

$$c_{q,t+1}^{BL} = c_{q,t}^{BL} + \left(\frac{c_q^t + c_q^{hc} + c_q^{hi} + c_q^{bi}}{100}\right) \qquad \text{Eq. 6.1}$$

The term $c_{q,t}^{BL}$ indicates the litres of blood that casualty c_q lost at time t. The term c_q^t signifies whether casualty c_q is trapped at an incident site, c_q^t= 1, or not trapped at an incident site, c_q^t= 0. The terms $c_q^{hc} \in \{0,1,2,3\}$ represents the health classification of casualty c_q with a value of 0 indicating that the casualty is yet to be classified, whereas 1, 2 and 3 indicate that casualty c_q is initially classified as delayed, urgent or immediate, respectively. A full definition of casualties' health classifications was presented in Chapter 2 (Section 2.3.3). The terms $c_q^{hi} \in \{0,1,2,3\}$ and $c_q^{bi} \in \{0,1,2,3\}$ represent the severity of a casualty's head injury and burn injury, respectively, with a value of 0 signifying that casualty c_q has no injury, whereas 1, 2, and 3 indicate that casualty c_q has mild, moderate, and severe head and burn injuries, respectively. The utilisation of Eq. 6.1 enables the dynamic deterioration of casualties' health to be simulated every minute if no lifesaving interventions are provided. For example, the blood loss of a trapped casualty yet to be classified, with both a moderate head and burn injury and having already lost 0.75 litres of his/her total blood, if no lifesaving interventions are provided in the next minute when such a casualty needs it, is computed as,

$$c_{q,t+1}^{BL} = 0.75 + \left(\frac{1+0+2+2}{100}\right) = 0.80 \text{ litres.}$$

This indicates that casualty c_q will lose 0.05 litres in the next minute, a total of 0.80 litres of blood, equivalent to 16% of his/her total blood, if no lifesaving intervention is provided. Thus, the current health classification of casualty c_q will be immediate, indicating that that casualty requires immediate lifesaving intervention [86].

Simulating the improvement in casualties' health

The health of casualties with head and/or burn injuries may improve after being treated. However, not all casualties respond in the same way to the treatment provided. Due to the lack of historical information regarding casualties' health in MCI events, in this research, a probability in a range of [0.1-0.2] is assumed for a casualty's health to improve after being treated. Furthermore, the improvement in casualties' health is modelled by reducing the severity of head and/or burn injuries. The probability has been set to differentiate the response of casualties to the treatment provided. Furthermore, it has been set to be low as the casualties' health, in reality, does not always improve after being treated. For example, after receiving treatment, a casualty with a moderate head injury may improve, such that the severity of his/her injury improves (becomes a mild head injury). Consequently, the vital signs, including blood pressure, pulse rate, and respiratory rate, and the level of consciousness of that casualty will be updated to be in proper ranges. Further discussion regarding the vital signs and the level of consciousness of a casualty will be provided in Chapter 7.

6.4.3 Completion of the response at an incident site or sites

The response at an incident site or sites can be completed at any time while the response to other incidents is still ongoing, resulting in emergency responders becoming available, indicating that these responders have no scheduled tasks associated with casualties to undertake at an incident site. The available emergency responders should be reallocated to the response at other incident sites with tasks yet to be completed. This will increase the chance of saving lives and reducing suffering, if possible, and make better use of the resources that are already available to respond to MCIs.

The response at an incident site is declared 'complete' to CC (Step 4, Figure 6.1) by a pair of paramedics who collect the final casualty from the ALP at that incident site (Step 14), necessitating the reallocation of the available emergency responders from that incident site. At this point in time, the current optimised post-PDA response plan will be interrupted, and the available emergency responders at that incident site will be reallocated to other incident sites with tasks yet to be completed using the NSA. Prior to interrupting the current optimised post-PDA response plan, a number of tasks will be assigned to emergency responders to be carried out (Step 12) while the NSA generates a new optimised post-PDA response plan (Step 9). Again, interrupting the current optimised post-PDA response plan may threaten casualties' lives. However, the execution of the approach in Step 12 will minimise the effect of such a threat as casualties will continue receiving the essential lifesaving interventions while the NSA generates the new optimised post-PDA response plan. As a result of implementing Step 9, a new optimised post-PDA response plan will be generated and executed (Step 10), consisting of the schedules of all emergency responders, including those from the recently declared 'complete' incident site or sites.

6.4.4 Occurrence of a new incident or incidents

As the response to MCIs unfolds (Step 10, Figure 6.1), the PHRF may be informed by CC that one or a number of new incidents have occurred (Step 15), in which case casualties in need of lifesaving interventions may be introduced. In this instance, an emergency responder who has originally been allocated to an incident site can be reallocated to a new incident site (Step 16) based on the following.

- The availability of emergency responders of all types, namely SAR, FAR, HART, paramedic, and MERIT, at the time a new incident site or sites is declared.
- Determination of the types of emergency responder required at a new incident site.
- The remaining number of casualties at other incident site or sites.

The availability of emergency responders refers to those who have already been allocated to an incident site and have completed their latest scheduled task and/or are waiting to begin their next task. Any remaining task or tasks of an emergency responder in a particular zone at an incident site, who is selected to be reallocated, will be reassigned to an emergency responder or responders with the same specialism who remain in that zone at the incident site and are able to perform them. Note that the emergency responders remaining in a particular zone at an incident site will always be able to perform the remaining task or tasks. Following the implementation of Step 16, the initial post-PDA response plan of the new incident site or sites is created (Step 8). Subsequently, the NSA will be executed to generate a new optimised post-PDA response plan involving the tasks associated with the new incident site or sites (Step 9).

In the presented decision support model, the following three scenarios for reallocating emergency responders to a new incident site or sites are considered.

- When a new incident occurs sequentially; for example, an incident occurs at 10:30:00 am, followed by another incident at 11:00:00 am.
- When multiple new incidents occur at exactly the same time; for example, two incidents occur at 10:30:00 am.
- When multiple new incidents occur in close succession; for example, an incident occurs at 10:30:00 am, followed by another incident at 10:30:30 am.

A new incident occurs sequentially.

In the scenario when a single new incident occurs sequentially, the number of emergency responders of each particular type, per, who will be considered for reallocation to a new incident site, $n_{er,is,t}^{per}$, (Step 14) is computed using Eq. 6.2,

$$\left|n_{er,is,t}^{per}\right| = \frac{n_{c,is,t}}{n_{c,is,t} + \sum_{w=0}^{w=l} rc_{is_w,t}} \times n_{er,t}^{per} \qquad \text{Eq. 6.2}$$

where $n_{c,is,t}$ indicates the number of casualties at the new incident site, is, that occurred at time t. Furthermore, the term $\sum_{w=0}^{w=l} rc_{is_w,t}$ refers to the total number of remaining casualties at another incident site or sites with tasks yet to be completed at time t, where l is the number of other incident sites. Also, $n_{er,t}^{per}$ represents the number of emergency responders of type per who are available at time t across all incident sites with tasks yet to be completed. Using Eq. 6.2, $n_{er,is,t}^{per}$ may be calculated to be less than one emergency responder, which indicates that an emergency responder of a particular type, per, cannot be reallocated to the new incident site is. Furthermore, $n_{er,t}^{per}$ could be equal to zero, which indicates that no emergency responder of type per is available at time t to be reallocated. However, in such cases, the first emergency responder of a particular type, per, that becomes available at any incident site at which the response is still ongoing will be reallocated to the new incident site.

Multiple new incidents occur at exactly the same time.

In the unlikely scenario where multiple incidents occurred at exactly the same time, t, Eq. 6.3 would be used to compute the number of emergency responders of each particular type per to be reallocated to each new incident site, is_v.

$$\forall v \left| n_{er,is_v,t}^{per} \right| = \frac{n_{c,is_v,t}}{\sum_{w=0}^{w=l} rc_{is_w,t} + \sum_{v=0}^{v=z} n_{c,is_v,t}} \times n_{er,t}^{per} \qquad \text{Eq. 6.3}$$

where v represents the index of the new incident sites and $n_{c,is_v,t}$ indicates the number of casualties located at the new incident site is_v that occurred at time *t*. The term $\sum_{w=0}^{w=l} rc_{is_w,t}$ is as defined in Eq. 6.2. Further, the term $\sum_{v=0}^{v=z} n_{c,is_v,t}$ indicates the total number of casualties at all new incident sites that occurred at time t, where z is the number of new incident sites that occurred at time t. In Eq. 6.3, $n_{er,is_v,t}^{per}$ may be calculated to be zero or less than one for one or more new incident sites. If $n_{er,is_v,t}^{per}$ is calculated to be zero or less than one for *one* new incident site is_v, the first emergency responder of type per that becomes available at any incident site at which the response is still ongoing would be reallocated to that new incident site. However, if $n_{er,is_v,t}^{per}$ is calculated to be zero or less than one for one or multiple new incident sites, any emergency responder of type per that becomes available at any incident site at which the response is still ongoing would be reallocated to the closest new incident site that has no emergency responder of a particular type per. This procedure will be repeated until at least one emergency responder of a particular type per has been reallocated to all new incident sites.

Multiple new incidents occur in close succession

In this scenario, the current process of reallocating emergency responders due to the occurrence of a new incident occurring at t_1 is interrupted and re-started to include information associated with a new, more recent incident occurring at t_2. The number of emergency responders of each particular type per to be reallocated to each new incident site, is_v, at time t_2, where t_2 is the time at which the most recent new incident occurred, is recomputed using Eq. 6.4.

$$\forall v \left| n_{er,is_v,t_2}^{per} \right| = \frac{n_{c,is_v,t_2}}{\sum_{w=0}^{w=l} rc_{is_w,t_2} + \sum_{v=0}^{v=z} n_{c,is_v,t_2}} \times n_{er,t_2}^{per} \qquad \text{Eq. 6.4}$$

where v represents the index of new incident sites under consideration. The term n_{c,is_v,t_2} indicates the number of casualties at the new incident site is_v at time t_2. The term $\sum_{w=0}^{w=l} rc_{is_w,t_2}$ refers to the total number of remaining casualties at other incident sites at which the response is still ongoing at time t_2, and l is the number of other known incident sites. Further, the term $\sum_{v=0}^{v=z} n_{c,is_v,t_2}$ indicates the total number of casualties at new incident sites at time t_2 yet to be allocated to emergency responders, and z is the number of the most recent new incidents that have occurred. Also, n_{er,t_2}^{per} represents the number of emergency responders of particular type per, who are available at time t_2, across all other incident sites with tasks yet to be completed. Furthermore, as explained in relation to Eq. 6.3, n_{er,is_v,t_2}^{per} in Eq. 6.4 may be calculated to be zero or less than one for one or multiple new incident sites being considered. In such cases, the first emergency responder of a particular type per that becomes available is reallocated, as indicated in the scenario when multiple new incidents occur at exactly the same time.

6.5 Summary

In this chapter, the three interrelated components of a decision support model to coordinate the emergency services' response to MCIs, namely the MCI environment, the CMI, and the PHRF, have been presented. Furthermore, the initial MCI information needed to initiate the PDA response plan and any new information that may become available during the response to MCIs, requiring the generation of a new optimised post-PDA response plan, have been discussed. Therefore, this chapter partially addressed RQ2. In the following chapter, the MCI environment of a decision support model to coordinate the emergency services' response in MCIs will be presented.

Chapter 7. A decision support model to coordinate the emergency services' response to MCIs: the MCI environment

7.1 Introduction

This chapter provides a continuation of the exploration of RQ2, which was introduced in Chapter 6. The aim of this chapter is to present the Mass Casualty Incident (MCI) environment of the decision support model to coordinate the emergency services' response in MCIs discussed in Chapter 6. The MCI environment must satisfy the requirements of modelling an MCI environment (RME1-REM29) defined in Chapter 4 and overcome the limitations in the identified models critically reviewed in Chapter 5. In Section 7.2, the definition of the MCI-affected geographical area where multiple incidents may occur is discussed. In Section 7.3, the modelling of the road network of an MCI-geographical affected area is presented. In Section 7.4, the modelling of incident sites is discussed. In Sections 7.5 and 7.6, the modelling of emergency services' resources and hospitals are presented, respectively. In Section 7.7, the modelling of casualties is presented.

7.2 Defining an MCI-affected geographical area

The topography layer of any MCI-affected geographical area in the UK where a single incident or multiple incidents may occur is provided by DigiMap [89]. DigiMap is a digital mapping resource that offers free access to the Ordnance Survey (OS) of Great Britain to students and staff at high education institutions. The OS is one of the available frameworks for mapping data in the UK [90], containing multiple and detailed layers, such as a topography layer and an integrated transport network layer. The topography layer represents a detailed and accurate map view, including roads, buildings, trees, and water. The integrated transport network layer is the GIS dataset of Great Britain's transport network, including the road network. The road network consists of a number of nodes and links that are fully topologically structured to represent all driveable roads. The maximum size of map data that can be requested from DigiMap is limited to 100 km^2 (per request). Thus, in the presented decision support model, an MCI-affected geographical area has been defined in a position that covered the locations of all hypothetical incident sites and maximised the number of ambulance stations, fire and rescue stations, and hospitals located in the defined area. However, ambulance stations, fire and rescue stations, or hospitals located outside the defined MCI-affected area have not been considered in response to MCIs. All hospitals considered in the defined area must have an Emergency and Accident department and are considered Major Trauma Centres in which acute, surgical, and rehabilitative services are available for casualties in all health classifications in accordance with the previously published report [91].

7.3 Road network of an MCI-affected geographical area

The road network of an MCI-affected geographical area has been modelled as an undirected graph. The undirected graph consists of a set of nodes representing road junctions and a number of key (actual) locations in the affected geographical area in which incidents occurred. The key locations include incident sites, ambulance stations, fire and rescue stations, and hospitals. In this research, the easting and northing coordinates of each location have been defined, and subsequently, the nearest node in the road network from such coordinates has been selected to represent the desired location. Furthermore, it consists of arcs joining the nodes to represent road links, each with a length given in kilometres. For illustrative purposes, Figure 7.1 is an example of the road network of an area in Glasgow, showing the dense and detailed data used to model the road network of any selected area in which multiple incidents may occur. The top right and bottom left easting and northing coordinates are (263534.5, 669366) and (252059, 660641), respectively.

Figure 7.1: Road network graph of an area of Glasgow.

Distance between key locations and emergency vehicles' speed.

The level of detail considered when modelling the road network of an MCI-affected area accurately identifies the actual distances between any two key locations in the affected geographical area. Furthermore, it enables determining the travel times between any key locations and thus simulates the movement of emergency vehicles in the road network credibly. Two factors should be considered when calculating the travelling times of emergency vehicles:

1) the actual distance between two key locations obtained from a realistic and accurate road network of the affected geographical area in which multiple incidents have occurred;
2) the speed of emergency vehicles in emergency events in the UK.

Due to the absence of historical data on the speed of emergency vehicles in emergency events in the UK, the average speed of ambulance vehicles reported in a previous study by McCormack et al. [81] has been used to determine the speed of all emergency vehicles considered in the model. In [81], the speed of ambulance vehicles was determined based on accurate data from the London Ambulance Service. It is also important to consider road traffic when calculating the actual travelling time between any two key locations in the affected geographical area. Therefore, in this thesis, the speed of all emergency vehicles reported in [81] has varied based on the time of the day and the day of the week of an incident. Figure 7.2 shows the average speeds of London Ambulance Service ambulance vehicles according to the time of the day and the day of the week.

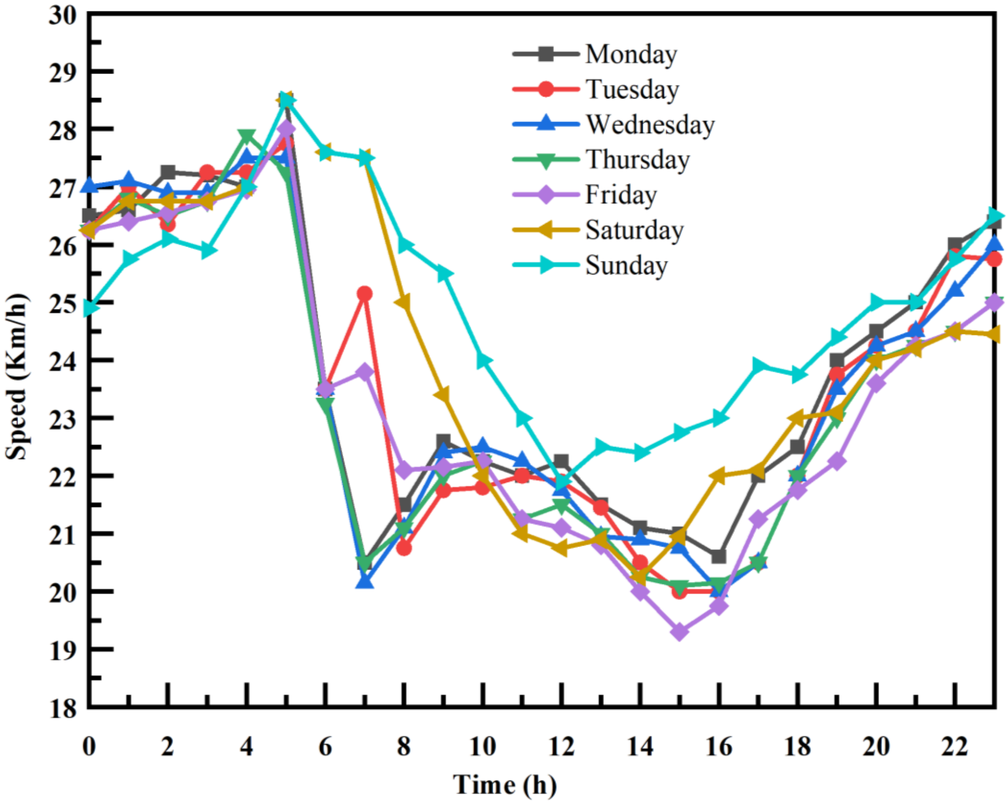


Figure 7.2: Average speeds of ambulance vehicles of the London Ambulance Service [81].

The x-axis and y-axis in Figure 7.2 represent the time of the day according to a 24-hour clock and the average speeds of ambulance vehicles in km/h, respectively. That is, in this research, the speed of the emergency vehicles is specified based on the time and the day of receiving the emergency call reporting the MCI event. Note that the speed of emergency vehicles will be updated every hour as the MCI response unfolds to simulate the road traffic.

7.4 Incident sites

In this context, the incident site refers to where an MCI has occurred, resulting in a number of casualties with different severity levels of injuries. A set of incident sites is denoted as IS, in which a single incident site is denoted as $is_i \in IS, 1 \leq i \leq n_{is}$, where i is the index of that incident site and n_{is} indicates the total number of incidents located in the affected geographical area. Furthermore, the location of incident site is_i and the occurrence day and time are denoted as l_{is_i}, d_{is_i}, and t_{is_i}, respectively. Not that the set of incident sites may increase during the response (Chapter 6, Figure 6.1, Step 15), introducing a new set of casualties.

Zones in incident sites.

An incident is required to be set up into four zones (i.e., Hot Zone (HZ), Casualty Clearing Station (CCS), Place of Safety (POS), and Ambulance Loading Point (ALP)) in accordance with previously published reports [61, 64]. A full explanation of the four zones can be found in Chapter 4 (Section 4.2.2). These zones are often defined by police services [92]. However, police services have not been considered in the decision support model presented in this thesis because they are not directly related to casualties at incident sites or related to any of the requirements of modelling an MCI environment, as defined in Chapter 4, Section 4.2. Therefore, in this research, these locations were assumed to be established when the MCI event occurred. The actual locations of these zones are location dependent. The London Resilience Group states that the distance between an HZ and other zones at an incident site should be no less than 15 meters [93]. Thus, in the road network of the affected geographical area, the node representing the location of an incident site has been considered to be the node representing the location of the HZ associated with that incident site. Furthermore, the locations of the other three zones (i.e., CCS, POS, and ALP) have been represented as three nodes in the road network close to the HZ but no less than 15 meters away from the HZ. The closest two nodes to the HZ represent the location of the CCS and POS, whereas the furthest node from the HZ represents the location of the POS. As stated in Chapter 4 (Section 4.2.2), defining these zones allows:

1) the allocation of emergency responders to the appropriate zone that matches their specialities and degree of expertise (further discussion of which is provided in Section 7.5.2);
2) the simulation of the movement of emergency responders at an incident site to carry casualties to the proper zones at which adequate treatment can be provided.

7.5 Emergency services' resources

As indicated in Chapter 4 (Section 4.2.3), the term 'emergency services' resources' refers to emergency stations, responders, and vehicles. Modelling emergency stations, namely, ambulance stations and fire and rescue stations, is discussed in Section 7.5.1. Next, the modellings of emergency responders and vehicles are discussed in Section 7.5.2 and Section 7.5.3, respectively.

7.5.1 Emergency stations

A set of ambulance stations is denoted as AS, with a single ambulance station denoted as $as_j \in AS, 1 \leq j \leq n_{as}$, where j is the index of that ambulance station and n_{as} indicates the total number of ambulance stations in the affected geographical area. Furthermore, the location of ambulance station as_j is denoted as l_{as_j}. A set of fire and rescue stations is denoted as FS, with a single fire and rescue station denoted as $fs_k \in FS, 1 \leq k \leq n_{fs}$, where k is the index of that fire and rescue station and n_{fs} indicates the total number of fire and rescue stations in the affected geographical area. Further, the location of fire and rescue station fs_k is denoted as l_{fs_k}.

7.5.2 Emergency responders

At each ambulance station as_j, three types of emergency responder, namely Hazardous Area Response Team (HART), Medical Emergency Response Incident Team (MERIT), and paramedic responders, are initially located [13, 47, 91, 94]. HART responders are responsible for triaging and treating casualties in the HZ at an incident site [47] (Table 7.1). MERIT responders are comprised of specially trained personnel to triage and treat casualties in the CCS at an incident site (Table 7.1). Paramedic responders are able to triage and treat casualties in an HZ, CCS, or POS, load casualties into standard ambulances in an ALP, accompany casualties to hospital and provide treatment to casualties if they need it, and unload casualties at the assigned hospitals from standard ambulances [13] (Table 7.1).

At each fire and rescue station fs_k, two types of emergency responder, namely Fire and Rescue (FAR) and Search and Rescue (SAR) responders, are initially located [65, 67, 68, 95]. FAR responders are trained to deal with hazardous situations, such as fires, in an HZ, whereas SAR responders are specially trained people who combine fire and medical skills [96] (Table 7.1). FAR and SAR responders are able to locate casualties and release those trapped in the HZ at an incident site [15] (Table 7.1). Table 7.1 shows the association between different types of emergency responder and each zone at an incident based on the literature [13, 47, 97]. Table 7.1 indicates that paramedic responders are the only type of emergency responder who can be allocated to all the zones at an incident site, whereas other types of emergency responders can be only allocated to a particular zone at an incident site.

Table 7.1: Zones at an incident associated with each type of emergency responder.

Zone at an incident site	Types of emergency responder				
	HART	MERIT	PA	SAR	FAR
HZ	✓	✗	✓	✓	✓
CCS	✗	✓	✓	✗	✗
POS	✗	✗	✓	✗	✗
ALP	✗	✗	✓	✗	✗

HZ, hot zone; CCS, casualty clearing station; POS, place of safety; ALP, and ambulance loading point; HART, hazardous area response team; MERIT, medical emergency response incident team; PA, paramedics; SAR, Search and Rescue; FAR, fire and rescue.

Defining the number of emergency responders of each type.

The set of emergency responders of all types is denoted as ER, with a single emergency responder denoted as $er_n \in ER, 1 \leq n \leq n_{er}$, where n is the index of that emergency responder and n_{er} indicates the total number of emergency responders of all types initially located at all ambulance stations and fire and rescue stations. A set of emergency responders of a particular type per, where $per \in \{\text{HART}, \text{MERIT}, \text{PA}, \text{SAR}, \text{FAR}\}$, is denoted as $ER_{per} \subseteq ER$. The number of emergency responders of type per initially located at ambulance station j and fire and rescue station k is denoted as n_{er,as_j}^{per} and n_{er,fs_k}^{per}, respectively.

Defining emergency responders' speciality and degree of expertise.

In the decision support model presented in this thesis, the emergency responders of all types considered in response to MCIs are differentiated based on each emergency responder's speciality and degree of expertise in dealing with incident sites. The emergency responder's speciality refers to his/her ability to perform particular tasks associated with casualties in a particular zone at an incident site. The degree of expertise refers to the level of knowledge that an emergency responder has about undertaking particular tasks associated with casualties in a particular zone at an incident site. HART and MERIT emergency responders have an advanced degree of expertise in treating and triaging casualties at incident sites [65], whereas paramedic responders can undertake such tasks; however, tasks are expected to be performed with a standard degree of expertise [47, 97]. Further, SAR responders have an advanced degree of expertise in identifying casualties and releasing those trapped at an incident site. FAR responders can perform such tasks; however, as stated, it is expected that tasks are performed with a standard degree of expertise [47, 97]. Emergency responders with an advanced degree of expertise are able to complete tasks within the pre-defined durations compared to those with a standard degree of expertise. Further discussion of the tasks associated with casualties and their duration is provided in Section 7.7.2.

7.5.3 Emergency vehicles

A set of all emergency vehicles of all types is denoted as EV, with a single emergency vehicle denoted as $ev_p \in EV, 1 \leq p \leq n_{ev}$, where p is the index of that emergency vehicle and n_{ev} indicates the total number of emergency vehicles of all types initially located at all ambulance stations and fire and rescue stations. A set of emergency vehicles of a particular type pev, where $pev \in$ {HART ambulances, MERIT ambulances, standard ambulances, fire engines (FE), incident support vehicles (ISV)}, is denoted as EV_{pev}. The total number of emergency vehicles of a particular type pev initially located at ambulance station as_j and fire and rescue station fs_k are denoted as n_{ev,as_j}^{pev} and n_{ev,fs_k}^{pev}, respectively.

Three types of emergency vehicle have been initially located at ambulance stations, namely HART, MERIT, and standard ambulances. Two types of emergency vehicles have been initially located at fire and rescue stations, namely fire engines and incident support vehicles. The purpose of using the five emergency vehicle types initially located at ambulance stations and fire and rescue stations is as specified in Chapter 6 (Table 6.1). Each emergency vehicle, including standard ambulances, has been modelled to transport up to four emergency responders of the same type [72, 84, 85], whereas standard ambulances have been modelled to transport to the assigned hospitals one immediate casualty or pairs of urgent or pairs of delayed casualties based on the health classification of the first casualty loaded into a standard ambulance (as in the work of Bae et al. [73]).

7.6 Hospitals

A set of hospitals is denoted as H, with a single hospital denoted as $h_m \in H, 1 \leq m \leq n_h$, where m is the index of that hospital and n_h indicates the total number of hospitals in the MCI-affected area. The casualty capacity of a hospital is considered sufficient to receive casualties transferred from all incident sites in accordance with published studies [64, 65, 72].

An MCI event places an extreme burden on hospitals in dealing with casualties with different levels of injury severity [93]. As indicated in the Department of Health and Social Care [98], medical staff at hospitals must be sufficient at hospitals for the clinical response or post-hospital response to provide immediate care to casualties when they are received from incident sites. Thus, no emergency responders or vehicles initially located at hospitals were considered to respond to MCIs. Instead, they were assumed to be available at hospitals to receive casualties and provide on-hospital lifesaving and/or medical interventions to those who needed them. However, as this research focuses on the pre-hospital response, on-hospital lifesaving and/or medical interventions were not considered as they relate to the post-hospital response. In the decision support model presented in this thesis, hospitals were modelled as destinations for standard ambulances and paramedic responders transferring casualties from incident sites to receive on-hospital lifesaving and/or medical interventions.

7.7 Casualties

A set of casualties is denoted as C, with a single casualty denoted as $c_q \in C, 1 \leq q \leq n_c$, where q is the casualty index and n_c indicates the total number of casualties at all incident sites. The set of casualties may increase as the MCI response unfolds due to the occurrence of a new incident or incidents. Casualties are initially located at incident sites, $C_{is_i} \subseteq C$, where C_{is_i} indicates the set of casualties initially located at incident site i, is_i. The number of casualties at incident site is_i is denoted as n_{c,is_i}. Each casualty is associated with a particular incident site, representing his/her location in the MCI environment. Initially, casualties are located in the HZ at an incident site. As the response unfolds, casualties can be moved by emergency responders to another zone, including CCS, POS, or ALP, at an incident site based on the further lifesaving and/or medical interventions that casualties may need.

7.7.1 Health profiles of casualties

As mentioned in Chapter 4 (Section 4.2.5), the health profile of a casualty refers to the current health status of a casualty, including information related to his/her injuries, vital signs and degree of consciousness, triage decisions, and other important parameters. Knowledge of the health profile of a casualty is essential in order to classify a casualty into one of the four health classifications, namely immediate, urgent, delayed, and dead, using a triage method. Definitions of the four health classifications of casualties can be found in Chapter 2 (Section

2.3.3). Based on the knowledge of the health profile of a casualty, the appropriate lifesaving and/or medical intervention can be provided by a particular type of emergency responders, which can be releasing a trapped casualty, providing on-site treatment, and/or transporting his/her to hospitals. Further, modelling health profiles enables the status of casualties' health to be dynamically simulated during the response to MCIs.

The health profile of each casualty consists of 15 parameters. Six of these parameters represent a casualty's injuries, five represent the vital signs and degree of consciousness, two represent the health classification decisions based on primary and secondary triage, and two represent other important parameters.

Injuries.

The six parameters representing a casualty's injuries are head injury (c_q^{hi}), facial wounds (c_q^{fi}), chest injury (c_q^{ci}), soft tissue wounds (c_q^{si}), extremity injury (c_q^{ei}), and burns injury (c_q^{bi}), which is consistent with [99]. The head injury parameter $c_q^{hi} \in \{0,1,2,3\}$ with a value of 0 signifying that casualty c_q has no head injury, whereas 1, 2, and 3 signify that casualty c_q has a mild, moderate, or severe head injury, respectively, which are the terms used in [99]. A casualty with a mild injury requires medical interventions that can be delayed, whereas a casualty with a severe injury requires immediate lifesaving medical interventions. A moderate injury indicates physical trauma to the body that is more critical than a mild injury and less critical than a severe injury, which also requires lifesaving medical interventions. The facial wounds parameter $c_q^{fi} \in \{0,1\}$, where a value of 0 and 1 indicate that casualty c_q has not and has facial wounds, respectively. The chest injury parameter $c_q^{ci} \in \{0,1\}$, where a value of 0 and 1 signify that casualty c_q has not and has suffered a chest injury, respectively. The soft tissue wounds parameter $c_q^{si} \in \{0,1\}$, where a value of 0 and 1 signify that casualty c_q has not and has soft tissue wounds, respectively. The extremity injury parameter $c_q^{ei} \in \{0,1\}$, where a value of 0 and 1 indicate that casualty c_q has not and has suffered from an extremity injury, respectively. The burn injury parameter $c_q^{bi} \in \{0,1,2,3\}$, with a value of 0 signifying that casualty c_q has no burn injury, whereas 1, 2, and 3 signify that casualty c_q has a mild, moderate, or severe burn injury, respectively, which are the terms used in [100]. Head injury, facial wounds, soft tissue wounds, extremity, and burn injury may present with bleeding. However, head and burn injuries, in particular, are accompanied by bleeding that may cause death, as indicated in [86, 87, 101].

Vital signs and degree of consciousness.

The parameters representing a casualty's vital signs are respiratory rate (c_q^{RR}), pulse rate (c_q^{PR}), systolic blood pressure (c_q^{SBP}), and blood loss (c_q^{BL}). The parameters representing a casualty's degree of consciousness is denoted by c_q^{GCS}, which is established using the Glasgow Coma Scale, which is a method used to assess the level of consciousness of acute medical and trauma casualties, as indicated in [102].

Health classification decisions.

Triage is a health classification method that reflects the priority assigned to a casualty in requiring lifesaving and/or medical interventions [48]. In an MCI event in the UK, two triage methods are used: Triage Sieve and Triage Sort, which are the primary and secondary triage methods, respectively, based on the published reports [1, 13, 103]. The parameters $c_q^{phc} \in \{0,1,2,3\}$ and $c_q^{shc} \in \{0,1,2,3\}$ indicate the health classification of casualty c_q based on performing the Triage Sieve and Triage Sort methods, respectively. In both methods, a value of 0 indicates that casualty c_q is yet to be classified, whereas 1, 2 and 3 indicate that casualty c_q is classified as delayed, urgent, or immediate, respectively.

Other important parameters.

The parameter c_q^{w} indicates whether or not casualty c_q is able to walk, where $c_q^{w} \in \{0,1\}$, where a value of 0 and 1 indicate that casualty c_q is and is not able to walk, respectively. The parameter c_q^{t} indicates whether or not casualty c_q is trapped at an incident site, where $c_q^{t} \in \{0,1\}$, where a value of 0 and 1 indicate that casualty c_q is not and is trapped at an incident site, respectively.

Initialisation of parameters' values.

To initialise the values of parameters associated with a casualty's ability to walk and his/her vital signs and degree of consciousness, the relationships between casualty injuries and the aforementioned parameters should be defined based on the literature [13, 86, 87, 100, 101, 104, 105]. Table 7.2 shows that head injury affects a casualty's ability to walk, his/her vital sign, namely blood loss, and his/her degree of consciousness. Further, facial and soft tissue wounds do not affect a casualty's ability to walk, his/her vital signs, or his/her degree of consciousness. A chest injury affects a casualty’s ability to walk, and his/her vital signs, namely respiratory and pulse rate. An extremity injury only affects a casualty’s ability to walk. A burn injury affects a casualty’s ability to walk, his/her vital signs, namely respiratory and pulse rate, and blood loss. The symbol × indicates that no effect exists.

Table 7.2: Effect of type of injury on a casualty’s ability to walk, his/her vital signs, and degree of consciousness based on the literature.

Type of injury	c_q^W	Vital signs				Degree of consciousness
		c_q^{RR}	c_q^{PR}	c_q^{SBP}	c_q^{BL}	c_q^{GCS}
Head	[101]	×	×	×	[86, 87]	[101]
Facial wounds	×	×	×	×	×	×
Chest	[104]	[104]	[104]	×	×	×
Soft tissue wounds	×	×	×	×	×	×
Extremity	[105]	×	×	×	×	×
Burn	[100]	[100]	[100]	×	[86, 87]	×

c_q^W, whether or not casualty c_q is able to walk; c_q^{RR}, respiratory rate of casualty c_q; c_q^{PR}, pulse rate of casualty c_q; c_q^{SBP}, systolic blood pressure of casualty c_q; c_q^{BL}, blood loss of casualty c_q; c_q^{GCS}, degree of consciousness of casualty c_q; ×, no effect exists.

The ranges of the parameters representing a casualty’s vital signs and his/her degree of consciousness are shown in Table 7.3. An uninjured and non-trapped casualty, along with a casualty with only facial and/or soft-tissue wounds, are considered to be able to walk, c_q^W= 1, and his/her vital signs and degree of consciousness are initialised in the normal ranges. In contrast, a trapped or non-trapped casualty with head, chest, extremity, and/or burn injuries is considered to be unable to walk, c_q^W= 0 and three of his/her vital signs, namely c_q^{RR}, c_q^{PR}, and c_q^{SBP}, and his/her degree of consciousness c_q^{GCS}, are initialised in the abnormal ranges. The vital sign c_q^{BL} of a casualty with chest and/or extremity injuries is initialised in the normal range, whereas for a casualty with head and/or burn injuries, it is initialised in the abnormal range.

Table 7.3: Ranges of the parameters of vital signs and degree of consciousness.

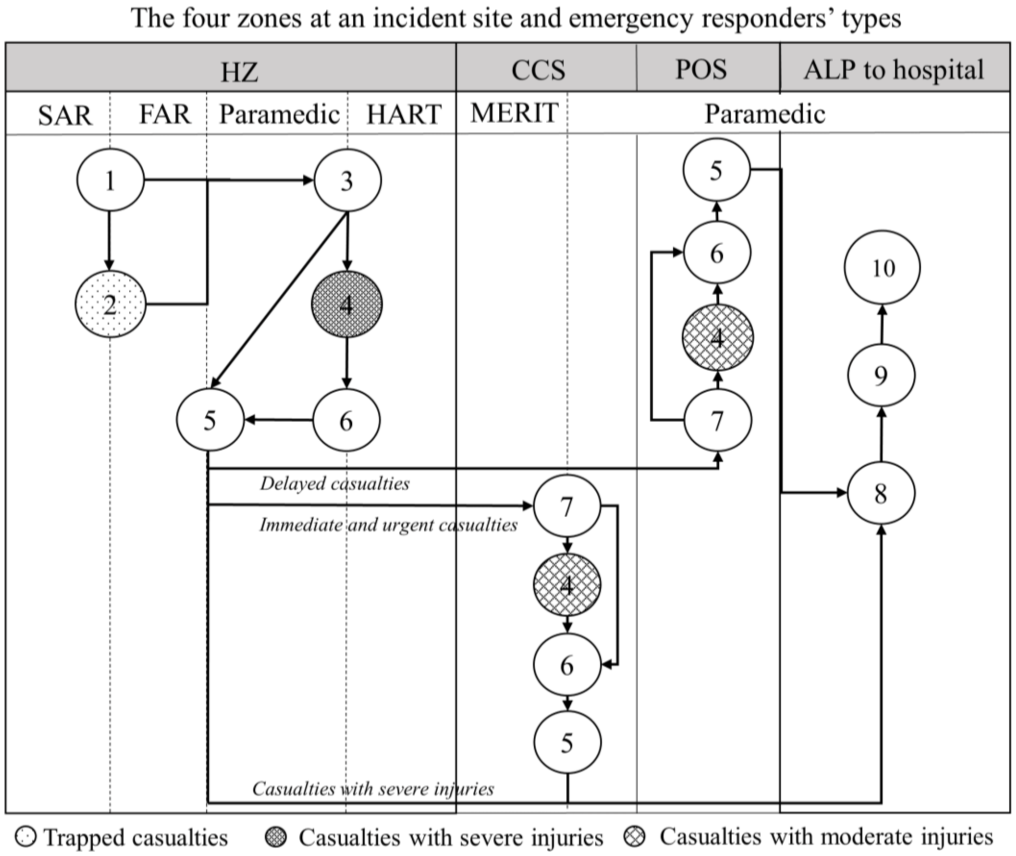
Parameter		Full range	Normal range	Abnormal range	Reference
Vital signs	c_q^{RR}	[1-35] breath/minutes	[12-20] breath/minutes	[1-11] or [21-35] breath/minutes	[106]
	c_q^{PR}	[1-140] beats/minutes	[60-100] beats/minutes	[1-59] or [101-140] beats/minutes	[107]
	c_q^{SBP}	[1-139] mmHg	[80-120] mmHg	[1-79] or [121-139] mmHg	[13]
	c_q^{BL}	[0-50] %	0%	[1-50] %	[86, 87]
Degree of consciousness	c_q^{GCS}	[2-15] scores	[2] scores	[3-15] scores	[13]

c_q^{RR}, respiratory rate of casualty c_q; c_q^{PR}, pulse rate of casualty c_q; c_q^{SBP}, systolic blood pressure of casualty c_q; c_q^{BL}, blood loss of casualty c_q; c_q^{GCS}, degree of consciousness of casualty c_q.

For example, the health profile of a non-trapped immediate casualty (based on the secondary triage method) with a severe head injury and moderate burn injury might be c_q^{hi}=3, c_q^{fi}= 0, c_q^{ci}= 0, c_q^{si}= 0, c_q^{bi}=2, c_q^{ei}= 0, c_q^{RR}= 16, c_q^{PR}= 50, c_q^{SBP}=120, c_q^{BL}=15, c_q^{GCS}=10, c_q^{phc}= 2, c_q^{shc}= 3, c_q^{w}= 0, and c_q^{t}= 0. The decisions of the primary and secondary triage methods may differ due to the deterioration in casualty's health during the response to MCI, as discussed in Chapter 6, Section 6.4.2. Another example of the health profile of a non-trapped casualty with facial wounds where that casualty is yet to be classified could be c_q^{hi}=0, c_q^{fi}= 1, c_q^{ci}= 0, c_q^{si}= 0, c_q^{bi}= 0, c_q^{ei}= 0, c_q^{RR}= 18, c_q^{PR}= 80, c_q^{SBP}= 100, c_q^{BL}= 0, c_q^{GCS}= 2, c_q^{phc}= 0, c_q^{shc}= 0, c_q^{w}= 1, and c_q^{t}= 0.

7.7.2 Tasks associated with casualties

A set of all tasks associated with all casualties at all incident sites is denoted as TC. An individual task associated with casualty c_q is denoted as $tc_{r,q}^{pr}$, in which $1 \leq r \leq n_{tc}$, where r is the index of that task, n_{tc} indicates the total number of tasks associated with all casualties at all incident sites, and pr refers to the index of the preceding task associated with casualty c_q that must be completed to allow a particular emergency responder to process task $tc_{r,q}^{pr}$. However, if task $tc_{r,q}^{pr}$ is the first task associated with casualty c_q, then pr=0, which indicates that no preceding task is associated with casualty c_q has to be completed in order to process task $tc_{r,q}^{pr}$. For example, there are three tasks associated with casualty c_1, namely 1, 2, and 3, and these tasks must be performed in the provided order. Tasks 1 and 2 have been allocated to two different emergency responders, namely emergency responder 1 and 2, respectively. Emergency responder 1 is yet to complete Task 1, and emergency responder 2, who has Task 2, is ready to perform this task. However, in the decision support model presented in this thesis, this is not allowed, and the nature of tasks should be maintained. Consequently, emergency responder 2 should wait until emergency responder 1 completes Task 1, and then, he/she can start the current task, Task 2. As the response unfolds, the set of tasks TC may increase due to the occurrence of a new incident or incidents, as indicated in Chapter 6 (Figure 6.1, Step 15), introducing a new set of casualties. Figure 7.3 shows ten tasks (Tasks 1-Task 10) that may be performed on a casualty by a number of emergency responders, taking into account their expertise at performing these tasks in a particular zone at an incident site. Figure 7.3 also shows the sequence of performing these tasks in each zone, namely HZ, CCS, POS, or ALP at an incident site.



Key table

No	Tasks
1	Locating a casualty at an incident site
2	Releasing a trapped casualty at an incident site
3	Performing primary triage for a casualty at an incident site
4	Administering on-site treatment for a casualty at an incident site
5	Moving a casualty to another zone at an incident site
6	Preparing a casualty for transportation to the assigned hospital at an incident site
7	Performing secondary triage for a casualty at an incident site
8	Loading a casualty into a normal ambulance in an ALP at an incident site
9	Accompanying a casualty in a normal ambulance when being transferred to the assigned hospital (during which treatment is provided if required)
10	Unloading a casualty from a normal ambulance once he/she has arrived at the assigned hospital

Figure 7.3: Association between the four zones at an incident site, types of emergency responder, and tasks associated with casualties.

When SAR and FAR responders arrive in the HZ at the allocated incident site, they will start searching for casualties until they are located (Task 1) (Figure 7.3). In the HZ, a number of casualties might be trapped; if the located casualty is trapped due to collapsed buildings or a fire, the casualty must be released by SAR or FAR responders (Task 2) [65]. Paramedics and HART responders are available in the HZ at the allocated incident site to perform a Triage Sieve (Task 3) for casualties being located or released (Figure 7.3). Triage Sieve is an algorithmic method for assessing and categorising casualties based on three parameters: c_q^w, c_q^{RR}, and c_q^{PR} [1, 13, 91]. An initial look can assess if a casualty is breathing or not (c_q^{RR}= 0 breath/minute); subsequently, the casualty is considered *dead* [48]. However, if the casualty is breathing, then c_q^{RR} is examined to assess the adequacy of breathing. If c_q^{RR} is examined as low (between 1 and 11 breaths/minute, inclusively) or as high (between 21 and 35 breaths/minute, inclusively), then a breathing problem is identified [13]. In this case, the casualty is categorised as *immediate* because abnormal breathing conditions are considered life-threatening [108]. If c_q^{RR} is examined as normal (between 12 and 20 breaths/minute, inclusively [106]), then the circulation must be checked by measuring c_q^{PR}. If c_q^{RR} is examined as low (between 1 and 59 beats/minute, inclusively) or as high (between 120 and 140 beats/minute, inclusively), then a circulation problem is identified; therefore, the casualty is categorised as *immediate* [13]. However, if the pulse rate of a casualty, c_q^{PR}, is examined between 100 and 119 beats/minute inclusive, then the casualty is categorised as *urgent* [13]. Delayed casualties are expected to have no breathing and/or circulation problems; thus, their c_q^{RR} and c_q^{PR} are set within the normal range (between 12 and 20 breaths/minute, inclusively and between 60 and 100 beats/minute, inclusively, respectively). Casualties with severe injuries - such as severe head and/or severe burn injuries - require on-site treatment (Task 4) in the HZ at an incident site [100, 105], which is undertaken by paramedics and HART responders before being prepared for transportation to the assigned hospitals (Task 6) [13] (Figure 7.3). A pair of emergency responders are required to move such casualties to the ALP (Task 5), so they can be loaded into standard ambulances (Task 8). Casualties classified as *immediate* or *urgent* (as a result of Triage Sieve method (Task 3)) and not suffering from severe head and/or severe burn injuries will be moved by a pair of emergency responders to the CCS at an incident site. In contrast, delayed casualties (as a result of Triage Sieve method (Task 3)) will be moved to the POS at an incident site (Task 5) (Figure 7.3).

MERIT and paramedic responders located at the CCS at an incident site and paramedic responders located at the POS at an incident site will perform Triage Sort (Task 7) for casualties being moved to one of these zones [6, 13, 109] (Figure 7.3). Triage Sort is used to assess the casualties' health based on three parameters: c_q^{RR}, and c_q^{SBP} and c_q^{GCS} [1]. Then, the measurements of these three parameters are scored using Triage Revised Trauma Score (TRTS) (Table 7.4).

Table 7.4: Results of the TRTS process.

c_q^{GSC} (scores)	Score	c_q^{RR} (breaths/min)	Score	c_q^{SBP} (mmHg)	Score
[13–15]	4	[10–29]	4	[90-139]	4
[9–12]	3	[10-29]	3	[76–89]	3
[6–8]	2	[6–9]	2	[50–75]	2
[4–5]	1	[1–5]	1	[1–49]	1
3	0	0	0	0	0

TRTS	Health classification of a casualty
12	Delayed
11	Urgent
[1-10]	Immediate
0	Dead

c_q^{GCS}, degree of consciousness of casualty c_q; c_q^{RR}, respiratory rate of casualty c_q; c_q^{SBP}, systolic blood pressure of casualty c_q; TRTS, triage revised trauma score.

The maximum score that can be given to casualties using the TRTS is 12, reflecting *delayed* casualties, whereas the minimum score is zero, reflecting *dead* casualties. Scores between 1 and 10, inclusively, reflect *immediate* casualties, whereas a score of 11 reflects *urgent* casualties [1]. On-site treatment (i.e., advanced treatment) is provided for *immediate* and *urgent* casualties with a chest injury or other injuries with moderate severity in the CCS at an incident site by MERIT or paramedic responders (Task 4) [100, 105] (Figure 7.3). In the POS at an incident site, on-site treatment (i.e., first aid) is provided for *delayed* casualties by paramedic responders (Task 4), which requires equipment similar to that used on a daily basis to alleviate life-threatening conditions affecting these casualties [13, 110]. Casualties from both zones (i.e., CCS or POS) will be prepared for transportation to the assigned hospitals (Task 6) and moved by a pair of emergency responders to the ALP at an incident site (Task 5) in order to be loaded into standard ambulances (Task 8). Casualties of all health classifications must be accompanied by a paramedic responder when being transferred to the assigned hospitals (Task 9). Casualties with severe injury or injuries and/or chest injury require further treatment in standard ambulances while being transferred to hospitals [100, 105]; this task is embedded with

Task 8. Once a casualty arrives at the assigned hospital, he/she will be unloaded from the standard ambulance (Task 10).

7.7.3 Duration of tasks associated with casualties

As indicated in Chapter 4 (Section 4.2.5), the duration of tasks associated with casualties may vary based on 1) the degree of expertise of an emergency responder to which a task has been allocated and 2) the health profile of the casualty associated with that task. Thus, Tasks 1-10 (defined in Section 7.7.2) have been classified into five categories according to their duration in Table 7.5. Table 7.5 shows the association between the types of emergency responder and the different tasks associated with casualties at an incident site. A tick signifies that an emergency responder can perform a task; however, the responder requires no particular expertise. In contrast, the symbols $\checkmark_{A}$ and $\checkmark_{S}$ signify that an emergency responder requires an advanced or a standard degree of expertise to perform a particular task, respectively. Further, a cross signifies that an emergency responder cannot perform a task due to a lack of expertise.

Table 7.5: Association between the types of responder and tasks associated with the casualties.

Category	Tasks associated with casualties	Types of emergency responder							Duration of tasks (minutes)	Reference
		SAR	FAR	HART	MERIT	PA				
						HZ	CCS	POS		
1	Locating a casualty at an incident site (Task 1)	✓	✓	✓	✖	✓	✖	✖	[0.1-10]	[65]
	Moving a casualty to another zone at an incident site (Task 5)	✖	✓	✖	✖	✓	✓	✓	[4-8]	Assumption
2	Loading a casualty into a standard ambulance in an ALP at an incident site (Task 8)	✖	✖	✖	✖	✓	✓	✓	5	Assumption
	Unloading a casualty from a standard ambulance once he/she has arrived at the assigned hospital (Task 10)	✖	✖	✖	✖	✓	✓	✓	10	[111]
3	Preparing a casualty for transportation to the assigned hospital at an incident site (Task 6)	✖	✖	✓	✓	✓	✓	✓	5	Assumption
4	Releasing a trapped casualty at an incident site (Task 2)	✓$_{A}$	✓$_{S}$	✖	✖	✖	✖	✖	5	Assumption
	Performing primary triage for a casualty at an incident site (Task 3)	✖	✖	✓$_{A}$	✖	✓$_{S}$	✖	✖	0.5	[112]
	Administering on-site treatment for a casualty at an incident site (Task 4)	✖	✖	✓$_{A}$	✓$_{A}$	✓$_{S}$	✓$_{S}$	✓$_{A}$	2 / injury	Assumption
	Performing secondary triage for a casualty at an incident site (Task 7)	✖	✖	✖	✓$_{A}$	✖	✓$_{S}$	✓$_{A}$	1	Assumption
5	Accompanying a casualty in a standard ambulance when being transferred to the assigned hospital (during which treatment is provided if required) (Task 9)	✖	✖	✖	✖	✓	✓	✓	Based on the actual distances between any two key locations and the varying speed of standard ambulances	[90]

SAR, search and rescue; FAR, fire and rescue; HART, hazardous area response team; MERIT, medical emergency response incident team; PA, paramedics; HZ, Hot Zone; CCS, Casualty Clearing Station; POS, Place of Safety; ALP, ✓, an emergency responder can perform a task; however, the responder requires no particular expertise; ✖, an emergency responder cannot perform a task due to a lack of expertise;✓$_{A}$ and ✓$_{S}$, an emergency responder requires an advanced or a standard degree of expertise to perform a particular task, respectively.

Duration of tasks associated with casualties in Category 1.

In Category 1 (Table 7.5), tasks 1 and 6 have a pre-defined duration range because these types of task cannot be carried out by particular types of emergency responder at a constant time. The pre-defined duration of Task 1 is 1-10 minutes [65]. However, no quantitative data exist related to the pre-defined duration range of Task 5. Indeed, it depends on a number of factors, such as the nature of the affected geographical area and the weather, which prevent establishing the exact or approximate time needed for this task. Therefore, the pre-defined duration range is assumed to be 4-8 minutes. The time needed for an emergency responder to walk to the allocated location to undertake other tasks associated with other casualties is assumed to be in the same range for the same factors mentioned.

Duration of tasks associated with casualties in Category 2.

In Category 2 (Table 7.5), tasks 8 and 10 have a pre-defined duration that is constant because they can be carried out in the same amount of time by particular types of emergency responder. The pre-defined duration for Task 8 is assumed to be 5 minutes, which is half the time needed to complete Task 10 (i.e., 10 minutes in accordance with the report of the Association of Ambulance Chief Executives [111]), because emergency responders are required to prepare casualties for transportation to hospitals (Task 6) before loading them into standard ambulances.

Duration of tasks associated with casualties in Category 3.

In Category 3 (Table 7.5), task 6 has a pre-defined duration that can vary depending on the health profile of the casualty associated with the task. Due to the absence of information related to the pre-defined duration of Task 6, it is assumed to be 5 minutes, equal to the time taken to complete Task 8. The total duration of Task 8 and Task 6 is 10 minutes, equal to the duration defined to complete Task 10. Thus, the duration of task s associated with casualty q, $d_{s,q}$, can be determined using Eq. 7.1,

$$d_{s,q} = pd_{s,q} + pd_{s,q}\left(\frac{c_q^{hc} + c_q^{hi} + c_q^{bi} + c_q^{ci} + c_q^{hs}}{100}\right) \qquad \text{Eq. 7.1}$$

where $pd_{s,q}$ is the pre-defined duration of task s associated with casualty q, as indicated in Table 7.5. The term c_q^{hs} represents the hypovolemic shock stage of casualty c_q, which is set in the range [0-4], with a value of 0 indicating that casualty c_q is not bleeding (i.e., $c_q^{BL}= 0$), whereas 1, 2, 3, and 4 indicate that casualty c_q has lost up to 15%, 15% to 30%, 31% to 40%, and more than 40% of his/her total volume of blood, respectively [86, 87]. For example, consider an emergency responder assigned to prepare a casualty for transportation to the assigned hospital at an incident site (Task 6), which has a pre-defined duration of 5 minutes. The casualty has been classified as urgent, suffers from mild head and chest injuries, and has lost 5% of his/her total blood volume. Using Eq. 7.1, the emergency responder will complete the task in,

$$d_{s,q} = 5 + 5\left(\frac{2+1+0+1+1}{100}\right) = 5.25 \text{ minutes.}$$

This indicates that the emergency responder will take 0.25 minutes more than the pre-defined duration due to the health profile of that casualty.

Duration of tasks associated with casualties in Category 4.

In Category 4 (Table 7.5), tasks 2-4 and 7 have a pre-defined duration that varies depending on the degree of expertise of the responder undertaking the task and the health profile of the casualty associated with the task. No quantitative data exist related to the pre-defined duration of Task 2; however, it is assumed to take 5 minutes (equal to the duration of Task 6) because casualties are not trapped underneath a heavy weight that requires time to be removed. Performing primary triage (Task 3) is relatively quick and takes 0.5 minutes [112]. No quantitative data exist relating to the pre-defined duration of Task 4. However, the pre-duration of treating each injury that a casualty may suffer is assumed to take 2 minutes. The pre-defined duration of performing secondary triage (Task 7) is assumed to take 1 minute. Task 7 requires slightly more time than Task 3 because vital signs and the degree of consciousness must be measured. Thus, the duration of task s associated with casualty q, $d_{s,q}$, can be determined using Eq. 7.2,

$$d_{s,q} = pd_{s,q} + er_{n,e}\left(pd_{s,q}\left(\frac{c_q^{hc} + c_q^{hi} + c_q^{bi} + c_q^{ci} + c_q^{hs}}{100}\right)\right) \qquad \text{Eq. 7.2}$$

where the term $er_{n,e}$ signifies the degree of expertise of emergency responder n; values of 0 and 1 signify an advanced and a standard degree of expertise, respectively. However, the other terms are as defined in Eq. 7.1. For example, consider a SAR responder has been assigned to release a trapped casualty (Task 2), which has a pre-defined duration of 5 minutes. The casualty has yet to be classified, suffers from a severe head injury and a mild burn injury, and has lost 26% of his or her total blood volume. Using Eq. 7.2, the SAR responder will complete the task in,

$$d_{s,q} = 5 + 0\left(5\left(\frac{0+3+1+0+2}{100}\right)\right) = 5 \text{ minutes,}$$

which is the pre-defined duration for that task due to the SAR responder's advanced degree of expertise in relation to this task. However, if the same task is assigned to a FAR responder with a standard degree of expertise, $pd_{s,q}$=1, the time taken to complete such a task by the FAR responder would be $5 + 0.25 = 5.25$ minutes.

Duration of tasks associated with casualties in Category 5.

In Category 5 (Table 7.5), task 9 has a built-in variability for a duration that depends on the speed that can be obtained from Figure 7.2 by determining the time of the day, the day of the week, and the actual distance between any two key locations obtained from the road network

7.8 Summary

This chapter has presented the MCI environment of the decision support model discussed in Chapter 6, taking into account satisfying the requirements of modelling the MCI environment (RME1-RME29) defined in Chapter 4 and overcoming the limitations in the identified models critically reviewed in Chapter 5. Therefore, this chapter partially addressed RQ2. The next chapter will present the developed optimisation-based algorithms based on RCD1-RCD3 as a part of the pre-hospital response framework.

Chapter 8. A decision support model the response of emergency services' resources to MCIs: the pre-hospital response framework

8.1 Introduction

This chapter provides a continuation of the exploration of RQ2, which was introduced in Chapters 6 and 7. The aim of this chapter is to present the three-step algorithm-based approach within the PHRF of the decision support model (Chapter 6, Figure 6.1). The approach within the PHRF has been designed to generate a pre-determined attendance (PDA) response plan, an initial post-PDA response plan, and optimised post-PDA response plans based on initial or newly available information as a Mass Casualty Incident (MCI) response unfolds. In addition, this chapter presents the approach to reducing the transition times between successive optimised post-PDA response plans. Collectively, the aforementioned plans provide a continuous coordinated emergency response by the emergency services to be implemented in the MCI environment, as defined in Chapter 7. The PHRF aims to satisfy the requirements of coordination decisions RCD1-RCD3, as defined in Chapter 4, and overcome the limitations highlighted in the models critically reviewed in Chapter 5.

In Section 8.2, the three-step algorithm-based approach – including a greedy heuristic algorithm (GHA), a genetic algorithm (GA), and a neighbourhood search algorithm (NSA) – is presented. In Section 8.3, the objective functions used by the GA and NSA are defined for the evaluation of the initial and optimised post-PDA response plans, respectively. In Section 8.4, the approach to reducing the transition times between successive optimised post-PDA response plans is discussed.

8.2 Three-step algorithm-based approach to generate a PDA and post-PDA response plans

The three-step algorithm-based approach has been designed to generate a PDA response plan, an initial post-PDA response plan, and optimised post-PDA response plans based on initial or newly available information as an MCI unfolds.

- In Step 1, a GHA establishes a PDA response plan involving all incident sites (Chapter 6, Figure 6.1, Step 5). As a result of the activation of this plan, information regarding the estimated number of casualties at the incident sites is gathered and reported, which may necessitate further emergency vehicles and responders to be sent to the incident sites as part of the post-PDA response.

- In Step 2, a GA creates a feasible initial post-PDA response plan involving all incident sites considered in the PDA response plan (Chapter 6, Figure 6.1, Step 8). The initial post-PDA response plan has been created based on the information reported following the execution of the PDA response plan, which has been created as a starting point for the NSA.
- In Step 3, an NSA optimises the initial post-PDA response plan created by the GA to generate an optimised post-PDA response plan (Chapter 6, Figure 6.1, Step 9). It is subsequently used to generate new optimised post-PDA response plans that reflect the status of the MCI as it evolves in response to new information becoming available.

8.2.1 Greedy heuristic algorithm

The GHA has been designed to establish a PDA response plan involving all incident sites that occurred in the MCI-affected area. In the PDA response plan, emergency responders have been deployed to the incident sites nearest to their initial locations. The schedules of each emergency responder involved in the PDA response plan have been initialised by allocating a number of tasks associated with casualties at each incident site, taking into account their specialisms in performing tasks. Accordingly, the PDA response plan which has been created must be executed in an MCI environment. The flowchart of the GHA is shown in Figure 8.1.

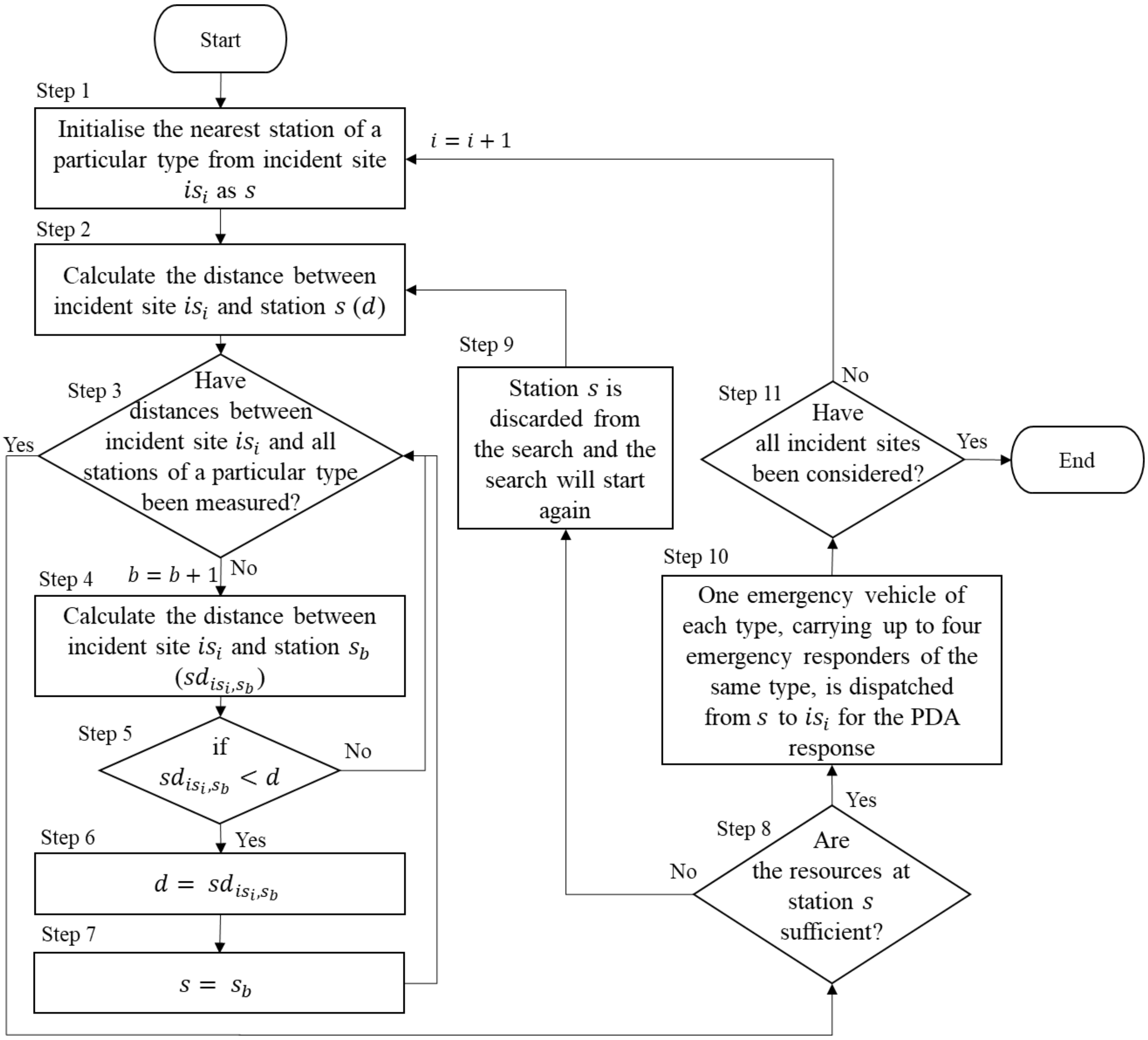


Figure 8.1: Flowchart of the GHA.

In Step 1, the nearest station of a particular type from incident site is_i is initialised as s. The term 'station of a particular type' in this context indicates that the type of station can be an ambulance or a fire and rescue station. In Step 2, the distance, d, between station s and incident site is_i is calculated, where i is the index of an incident site, where 1≤ $i \leq n_{is}$, and n_{is} is the number of incident sites. Step 3 ensures that the distances between all stations of a particular type and incident site is_i are measured. If these distances are not measured, then in Step 4 the distance between another station s of a particular type and incident site is_i, sd_{is_i, s_b}, is calculated, where b is the index of a station of a particular type, where 1≤ $b \leq n_s$, and n_s is the number of stations of a particular type. Step 5 compares the distances d and sd_{is_i, s_b}. If the distance sd_{is_i, s_b} is longer than d, then station s_b will be ignored and Step 3 will be implemented. However, if the distance sd_{is_i, s_b} is shorter than d, then d = sd_{is_i, s_b}, and s = s_b

(Steps 6 and 7, respectively). In that case, the algorithm will continue to measure the distances between other stations of a particular type and incident site is_i (Step 3). However, if the distances between all stations of a particular type and incident site is_i have been measured (Step 3), then the emergency vehicles and responders initially located at station s are checked (Step 8); if the emergency vehicles and responders at station s are insufficient, station s will be ignored and the search will start again (Step 9, then Step 2). However, if the resources initially located at station s are sufficient (Step 8), then one emergency vehicle of each type is dispatched from station s to incident site is_i for the PDA response transporting up to four emergency responders of the same type (Step 10). Five types of emergency vehicles are considered in the PDA response: Hazardous Area Response Team (HART), Medical Emergency Response Incident Team (MERIT), and standard ambulances initially located at ambulance stations; and fire engines (FEs) and incident support vehicles (ISVs) initially located at fire and rescue stations, as indicated in Chapter 6 (Table 6.2). Step 11 ensures that the PDA response plan is established for all incident sites in order to terminate the GHA; as a result, the PDA response plan is established, and if not, Step 1 will be implemented.

8.2.2 Genetic algorithm

In the PHRF, the GA has been designed to create a feasible initial post-PDA response plan for use as a starting point in the application of the NSA, as discussed further in this chapter (Section 8.2.3). The GA has been chosen from among four approaches for the creation of an initial post-PDA response plan to find the optimal initial post-PDA response plan to be used as a starting point for the NSA. These four approaches were:

1) a fully random assignment of tasks associated with casualties to emergency responders;
2) the same as (1) but with at least one task associated with a casualty assigned to each emergency responder;
3) the same as (1) but with equal numbers of tasks associated with casualties assigned to all emergency responders, if possible;
4) the GA as discussed in this section.

The GA has yielded a better initial post-PDA response plan in terms of the emergency response time $f_4(\mathrm{x})$, and a better execution time for the NSA to generate the optimised post-PDA response plan. Further discussion of the objective function $f_4(\mathrm{x})$ and other objective functions are provided in this chapter (Section 8.3), and the results of the implementation of these approaches to create an initial post-PDA response plan have been published in [113]. The flowchart for the GA is given in Figure 8.2.

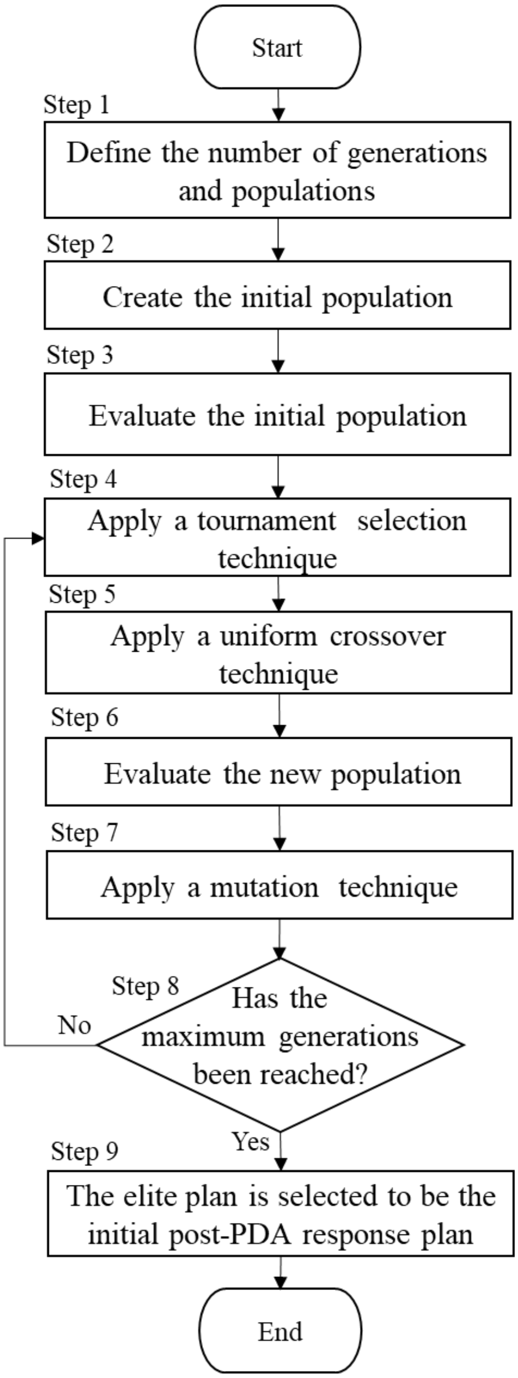


Figure 8.2: Flowchart of the GA.

In Step 1, the number of generations and the population size of each generation are defined. The term 'population' refers to a subset of post-PDA response plans of a specific generation. Grefenstette [114] stated that a population size of 60-110 is ideal for the convergence of GA-based systems in order to find an optimal solution. Thus, in the GA developed in this thesis, a population size of 60 initial post-PDA response plans and ten generations have been chosen, given that the aim of the use of the GA is merely to create a feasible initial post-PDA response plan as a starting point for the NSA. In Step 2, the initial population is created by allocating emergency responders to tasks associated with casualties at incident sites, taking into account their specialisms. Note that the schedules of emergency responders involved in the PDA response plan are maintained, but additional tasks may be allocated to these schedules. In Step 3, the initial population is evaluated in terms of the calculation of the emergency response time, $f_4(\mathrm{x})$ of each initial post-PDA response plan. In Step 4, the tournament selection technique is applied, in which three initial post-PDA response plans are selected to represent a mating pool. The size of the mating pool has been set at three in order to reduce the number of selecting the fittest solution, as indicated in a previously published study [115]. Then, the fittest initial post-PDA response plan from that meeting pool is selected as a parent. Step 4 is repeated until the new population is reached (with a size of 60, as indicated in Step 1). In Step 5, a uniform crossover technique is applied, in which two parent initial post-PDA response plans from those selected in Step 4 are mated and recombined to create two new initial post-PDA response plans for the next generation. That is, the hospital assigned to each casualty from the first initial post-PDA response plan is swapped with the hospital assigned to the corresponding casualty of the second initial post-PDA response plan. As a result, two new initial post-PDA response plans are created. Step 5 is repeated until the population size of the next generation is reached. In Step 6, the new population is evaluated, which involves the calculation of the emergency response time, $f_4(\mathrm{x})$, for each initial post-PDA response plan. In Step 7, a mutation technique is applied, in which a random change is applied with 0.01 probability in each initial post-PDA response plan in order to introduce and maintain diversity in a generation in accordance with previous research [116, 117]. The mutation technique is usually recommended at a low probability, 0.01 [118, 119], which implies that only a few initial post-PDA response plans are subjected to mutation. However, the initial post-PDA response plan with the shortest emergency response time, $f_4(\mathrm{x})$, from the new population (elite) is copied to the next generation without undergoing mutation. In Step 8, the number of generations is checked; if it has not been reached, then Step 4 is implemented. However, if the number of generations has been reached, then the initial post-PDA response plan with the shortest emergency response time, $f_4(\mathrm{x})$, is selected as a starting point for the NSA (Step 9), and the GA will be terminated.

8.2.3 Neighbourhood search algorithm

In the PHRF, the NSA has been designed to optimise the initial post-PDA response plan created using the GA. Each time the status of an MCI evolves and new information becomes available (Chapter 6, Section 6.3), the NSA is used to generate a new optimised post-PDA response plan that reflects the current situation, which is then executed in the MCI environment.

The NSA is an iterative algorithm that employs a number of neighbourhood structures, which are randomly selected, to explore solutions (in this case, post-PDA response plans) in the search space neighbouring the current solution [137]. In this context, the term ‘neighbourhood structure’ refers to an operation implemented to modify the current optimised post-PDA response plan in order to generate a new post-PDA response plan, which is potentially an improvement in relation to a number of objective functions (defined in Section 8.3). Each time the NSA is executed to generate an optimised post-PDA response plan, termination occurs when the algorithm has generated 50 feasible plans in succession and no improvement in these plans has been found. The term ‘feasible plans’ refers to new post-PDA response plans in which emergency responders have been assigned tasks in an order consistent with the dependency relationships between those tasks. The number of successive feasible plans, with no improvement, defined to terminate the NSA is problem-scale dependent. In this research, 50 non-improved feasible post-PDA response plans are chosen to terminate the NSA based on a number of experiments that have been applied to a large-scale problem (Appendix D).

Neighbourhood structures

The NSA consists of eight neighbourhood structures, NS1 to NS8. In each iteration of the NSA, a number of checks are required to be performed in order to establish which neighbourhood structures may be applied to the current optimised post-PDA response plan. For example, seven of the neighbourhood structures, NS1 to NS3 and NS5 to NS8, may be applied by the NSA when the problem under consideration consists of a single incident site only, whereas all eight structures may be applicable when the problem involves multiple incident sites. Other checks involve the number of emergency responders and the nature of the tasks assigned to them. These other checks are stated in the descriptions of each neighbourhood structure to follow.

Once all checks have been performed and the applicable neighbourhood structures have been identified, the one that is randomly selected to be applied to the current post-PDA response plan considers only tasks yet to be started. That is, all tasks that have already been initiated by the emergency responders, but are yet to be completed, are not considered. These 'started' tasks are not re-scheduled or interrupted in the MCI environment.

Four neighbourhood structures, NS1 to NS4, have been developed to allow modifications to the allocation of emergency responders to the tasks associated with casualties at an incident site or sites. One neighbourhood structure, NS5, has been designed to allow modification to the allocation of casualties to hospitals. Three neighbourhood structures, NS6 to NS8, have been developed to allow modifications to the allocation of casualties to standard ambulances used for transportation to hospitals.

Neighbourhood Structure 1 (NS1)

NS1 is only considered if more than one emergency responder with the same specialism is currently assigned to the same zone at the same incident site, and at least one of them has one or more outstanding tasks in his/her schedule. NS1 comprises four steps, as shown in Figure 8.3, for illustrative purposes.

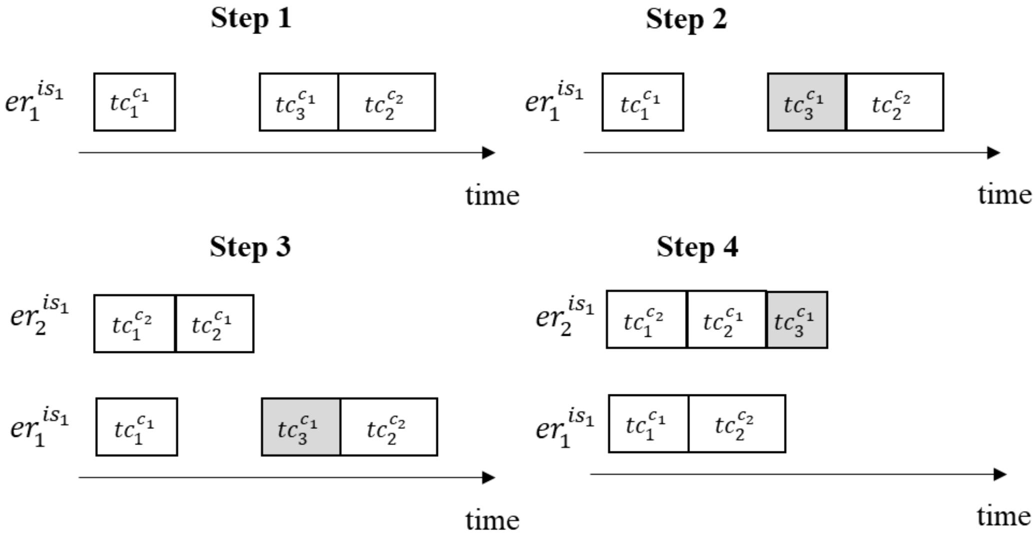


Figure 8.3: Example of the application of neighbourhood structure 1.

Step 1 involves selecting one emergency responder who has at least one outstanding task in his/her schedule and has been assigned to a zone at an incident site. As previously defined (Chapter 7, Section 7.4), zones can be a Hot Zone (HZ), Casualty Clearing Station (CCS) or Place of Safety (POS). In Figure 8.3 Step 1, emergency responder 1 located at incident site 1, $er_1^{is_1}$, is selected, who has three outstanding tasks in his/her schedule, namely $tc_1^{c_1}$, $tc_3^{c_1}$, and $tc_2^{c_2}$ associated with two casualties c_1 and c_2. Step 2 involves selecting randomly an outstanding task from the schedule of the emergency responder chosen in Step 1, as shown in Figure 8.3, $tc_3^{c_1}$ is selected from the schedule of er_{1,is_1}. Step 3 involves the selection of a different emergency responder assigned to the same zone and incident site and with the same specialism as the emergency responder chosen in Step 1. In Figure 8.3, Step 3, emergency responder 2 located at incident site 1, $er_2^{is_1}$, is selected, who has two outstanding tasks in his/her schedule, $tc_1^{c_2}$, and $tc_2^{c_1}$, associated with two casualties c_1 and c_2. In Step 4, the outstanding task chosen in Step 2 is removed from the schedule of the emergency responder selected in Step 1 and then assigned randomly to the schedule of the emergency responder named in Step 3. Assigning the selected outstanding task to the emergency responder chosen in Step 3 may lead to an infeasible post-PDA response plan, meaning this application of NS1 would be ignored. In this context, the term ‘infeasible plan’ refers to a plan in which tasks are scheduled in an order that contravenes the dependencies that exist between them. In addition, a consequence of applying Step 3 is that it may reduce, maintain, or increase the task’s duration, indicating that the emergency responder named in Step 3 has an advanced, the same, or a lesser degree of expertise than the emergency responder chosen in Step 1, respectively (as discussed previously in Chapter 6 Section 7.5.3). In Figure 8.3, Step 4 shows $tc_3^{c_1}$ of $er_1^{is_1}$ is assigned randomly to the schedule of $er_2^{is_1}$ in the position following $tc_2^{c_1}$. Note that this positioning of $tc_3^{c_1}$ in the schedule of $er_2^{is_1}$ results in a feasible post-PDA response plan. However, had this task been positioned between $tc_1^{c_2}$ and $tc_2^{c_1}$, or before $tc_1^{c_2}$, then the resulting schedule of $er_2^{is_1}$ would be infeasible, since $tc_3^{c_1}$ must be undertaken after the completion of $tc_2^{c_1}$. Also, note that a consequence of $tc_3^{c_1}$ being assigned to $er_2^{is_1}$, with an advanced degree of expertise compared to $er_1^{is_1}$, is that the duration of this task is reduced.

Neighbourhood Structure 2 (NS2)

NS2 is only considered if more than one emergency responder with the same specialism is currently assigned to the same zone at the same incident site, and at least two of them have one or more outstanding tasks in his/her schedule. NS2 comprises five steps, as shown in Figure 8.4, for illustrative purposes.

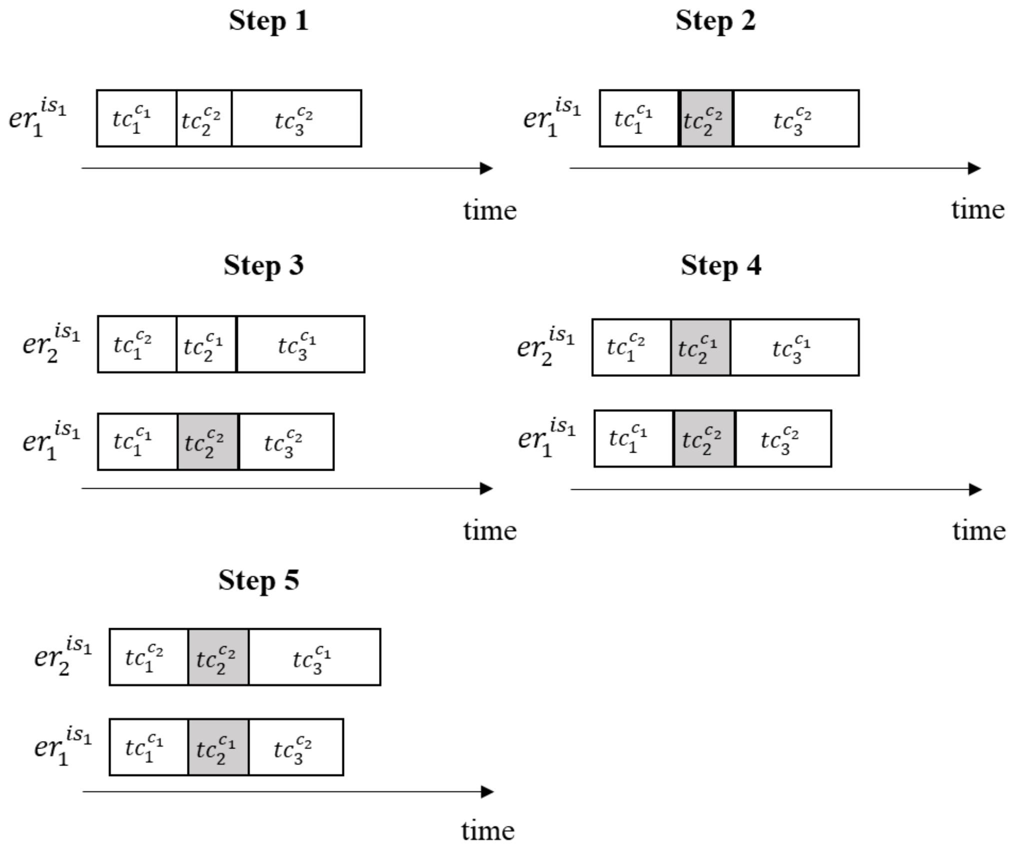


Figure 8.4: Example of the application of neighbourhood structure 2.

For NS2, the operation of Steps 1, 2, and 3 is the same as explained in relation to NS1. However, in Step 4, an outstanding task from the schedule of the emergency responder named in Step 3 is randomly selected, whereas in Step 5, the outstanding tasks selected in Step 2 and Step 4 from the schedule of the emergency responders named in Steps 1 and 3 are swapped. That is, the outstanding task selected from the schedule of the emergency responder named in Step 1 is assigned to the schedule of the emergency responder named in Step 3 in the position of the outstanding task selected in Step 4. Furthermore, the outstanding task selected from the schedule of the emergency responder named in Step 3 is assigned to the schedule of the emergency responder named in Step 1 in the position of the outstanding task selected in Step 2. Thus, in Figure 8.4, Step 1, emergency responder 1 located at incident site 1, $er_1^{is_1}$, is selected and has three outstanding tasks in his/her schedule, namely $tc_1^{c_1}$, $tc_2^{c_2}$, and $tc_3^{c_2}$ associated with two casualties c_1 and c_2. In Step 2, $tc_2^{c_2}$ is selected from the schedule of $er_1^{is_1}$. In Step 3, emergency responder 2 located at incident site 1, $er_2^{is_1}$, is selected and has three outstanding tasks in his/her schedule, namely $tc_1^{c_2}$, $tc_2^{c_1}$, and $tc_3^{c_1}$ associated with two casualties c_1 and c_2. In Step 4, $tc_2^{c_1}$ is selected from the schedule of $er_2^{is_1}$. In Step 5, $tc_2^{c_2}$ chosen in Step 2 is removed from the schedule of $er_1^{is_1}$ selected in Step 1 and then assigned to the schedule of $er_2^{is_1}$ named in Step 3 in the position of the outstanding task selected in Step 4. Furthermore, $tc_2^{c_1}$ chosen in Step 4 is removed from the schedule of $er_2^{is_1}$ selected in Step 3 and then assigned to the schedule of $er_1^{is_1}$ named in Step 1 in the position of the outstanding task selected in Step 2. Note that this positioning of $tc_2^{c_2}$ and $tc_2^{c_1}$ in the schedules of $er_2^{is_1}$ and $er_1^{is_1}$, respectively, results in a feasible post-PDA response plan. However, had $tc_1^{c_1}$ and $tc_3^{c_1}$ been selected and swapped, then the resulting schedule of $er_2^{is_1}$ would be infeasible, since $tc_3^{c_1}$ must be undertaken after the completion of $tc_2^{c_1}$. Note that the durations of $tc_2^{c_2}$ and $tc_2^{c_1}$ remained the same in Figure 8.4, indicating that $er_1^{is_1}$ and $er_2^{is_1}$ have the same degree of expertise.

Neighbourhood Structure 3 (NS3)

NS3 is only considered if more than one emergency responder with the same specialism is currently assigned to the same zone at the same incident site, and at least one of them has one or more outstanding tasks in his/her schedule. NS3 comprises four steps, as shown in Figure 8.5, for illustrative purposes.

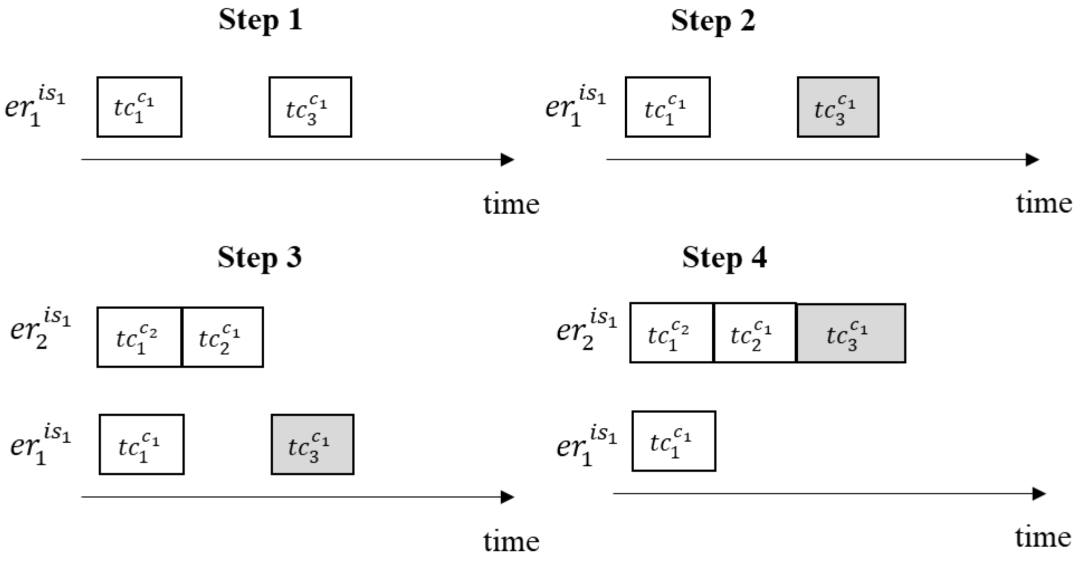


Figure 8.5: Example of the application of neighbourhood structure 3.

For NS3, the operation of Steps 1 and 3 is similar to those explained for NS1, whereas the operation of Steps 2 and 4 is the same. Step 1 involves selecting one emergency responder who has the highest workload in terms of the completion time of the outstanding tasks in his/her schedule and has been assigned to a zone at an incident site. Step 3 involves the selection of a different emergency responder who has the lowest workload in terms of the completion time of the outstanding tasks and is assigned to the same zone and incident site, and with the same specialism as the emergency responder chosen in Step 1. In Figure 8.5 in Step 1, emergency responder 1 located at incident site 1, $er_1^{is_1}$, is selected, who has two outstanding tasks in his/her schedule, namely $tc_1^{c_1}$ and $tc_3^{c_1}$ associated with casualty 1, c_1. In Step 2, $tc_3^{c_1}$ is selected from the schedule of $er_1^{is_1}$. In Step 3, emergency responder 2 located at incident site 1, $er_2^{is_1}$, is selected, who has two outstanding tasks in his/her schedule, $tc_1^{c_2}$, and $tc_2^{c_1}$, associated with two casualties c_1 and c_2. In Step 4, the outstanding task chosen in Step 2, $tc_3^{c_1}$, is removed from the schedule of $er_1^{is_1}$ and then assigned randomly to the schedule of $er_2^{is_1}$. Note that this positioning of $tc_3^{c_1}$ in the schedule of $er_2^{is_1}$ results in a feasible post-PDA response plan. However, had $tc_3^{c_1}$ been positioned between $tc_1^{c_2}$ and $tc_2^{c_1}$, or before $tc_1^{c_2}$, then the resulting schedule of $er_2^{is_1}$ would be infeasible, since $tc_3^{c_1}$ must be undertaken after the completion of $tc_2^{c_1}$. Note that a consequence of $tc_3^{c_1}$ being assigned to $er_2^{is_1}$, with a standard degree of expertise compared to $er_1^{is_1}$, is that the duration of this task is increased (Figure 8.5).

Neighbourhood Structure 4 (NS4)

NS4 is applied by the NSA when the problem under consideration consists of multiple incident sites only. Furthermore, NS4 is only considered if at least two emergency responders with the same specialism are currently assigned to the same type of zone but at different incident sites, and one of them has completed all assigned tasks such that there are no outstanding tasks in his/her schedule. NS4 consists of four steps, as illustrated in Figure 2.

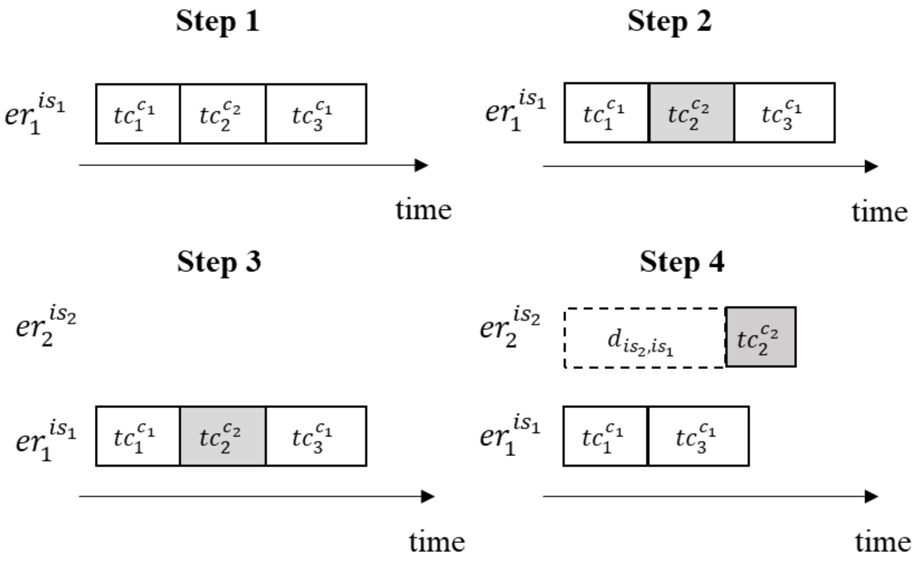


Figure 8.6: Example of the application of neighbourhood structure 4.

For NS4, the operation of Steps 1 and 2 is the same as explained in relation to NS1, whereas Step 4 is similar. However, in Step 3, the emergency responder selected should be located at a different incident site to the emergency responder selected in Step 1, but at the same type of zone and must have completed all assigned tasks, so he/she has no outstanding tasks in his/her schedule. Thus, In Figure 2 Step 1, emergency responder 1, currently located at incident site 1, $er_1^{is_1}$, is selected and has three outstanding tasks in his/her schedule, namely $tc_1^{c_1}$, $tc_2^{c_2}$, and $tc_3^{c_1}$ associated with two casualties c_1 and c_2. In Step 2, $tc_2^{c_2}$ has been selected from the schedule of $er_1^{is_1}$. In Step 3, emergency responder 2, currently located at incident site 2, $er_2^{is_2}$, who has no outstanding tasks in his/her schedule, is selected. In Step 4, $tc_2^{c_2}$ chosen in Step 2 is removed from the schedule of $er_1^{is_1}$ selected in Step 1 and then assigned to the schedule of $er_2^{is_2}$ named in Step 3. Furthermore, as part of Step 4, $er_2^{is_2}$ is required to travel from is_2 to is_1 where $tc_2^{c_2}$ can be performed. Hence, an additional task indicated with a dashed rectangle is assigned to the schedule of $er_2^{is_2}$, signifying the time needed for $er_2^{is_2}$ to travel to incident site 1 to perform $tc_2^{c_2}$. The arrival time of $er_2^{is_2}$ at the incident site at which he/she will carry out the newly assigned task is calculated by adding the time required to be collected by a particular type of emergency vehicle from is_2 at which he/she is currently located to the time required for him/her to travel to is_1 at which he/she will carry out the newly assigned task. The travel time between any two locations on the road network in the MCI-affected area is calculated based on the distance obtained from the GIS dataset of the MCI-affected area and the speed of emergency vehicles, accounting for the road traffic on the day and time of the MCI occurrence, as explained in Chapter 7 (Section 7.3). The type of emergency responder selected in Step 3 determines the type of emergency vehicle required to transport the responder to the incident site at which he/she will carry out the newly assigned task, as indicated in Chapter 6 (Table 6.1). An emergency vehicle of a particular type may be available at the incident site at which the emergency responder selected in Step 3 is currently located. If this is the case, that emergency vehicle is chosen to transport the selected emergency responder to the incident site at which he/she will carry out the newly assigned task. However, if there are no emergency vehicles of a particular type at the incident site where the selected emergency responder is currently located, the fastest-arriving vehicle of that type is chosen. In the event that all emergency vehicles of a particular type are in use, the time required for them to become available and collect the selected emergency responder is calculated and the vehicle that arrives at the incident site first is chosen. In the case that the selected emergency vehicle is a standard ambulance that has been assigned to transport a pair of urgent or a pair of delayed casualties to the allocated hospital, the priority of delivering to the assigned destination is given to the casualties and then to the emergency responder. In this instance, the time required to transport the casualties to the allocated hospital is also considered when calculating the arrival time of the selected emergency responder at the newly allocated incident site. It is likely that multiple emergency responders of the same type require to be transported from the same incident site to the same newly assigned incident site. If this is the case, one emergency vehicle of a particular type is selected based on its capacity, as explained in Chapter 7 (Section 7.5.3). Note that NS4 considers the availability of a particular type of emergency vehicle to collect the emergency responder selected in Step 4 to the newly assigned incident site, the dependency between tasks associated with casualties, and the arrival time of the selected emergency responder to the newly assigned incident site when allocating the outstanding task selected in Step 3 to the schedule of selected the emergency responder. In Figure 2, Step 4 shows $tc_2^{c_2}$ is assigned to the schedule of $er_2^{is_2}$ in a position which is immediately after his/her arrival at is_1 because no pre-dependent tasks are required to be completed in order to perform $tc_2^{c_2}$. However, had pre-dependent tasks to task $tc_2^{c_2}$ been yet to complete, then $tc_2^{c_2}$ would be assigned to the schedule of $er_2^{is_2}$ in a position which is immediately after the completion of the latest pre-dependent task because $er_2^{is_2}$ cannot start this task until all pre-dependent tasks associated to c_2 were completed. All new post-PDA response plans generated using NS4 are feasible in which emergency responders have been assigned tasks in an order consistent with the dependency relationships between them and can be executed in the MCI environment because the emergency responder selected in Step 3 has no outstanding tasks in his/her schedule. However, the new post-PDA response plan is only discarded when the outstanding task selected in Step 2 is associated with an immediate casualty and the actual starting time of that task is prior to the arrival time of the emergency responder selected in Step 3 to the incident site at which he/she will carry out the newly assigned task. This is because immediate casualties should receive lifesaving and/or medical interventions as quickly as possible, as opposed to urgent and delayed casualties, whose treatment can be safely delayed, in accordance with the previously published research [13]. Note that the durations of $tc_2^{c_2}$ reduced, indicating that $er_2^{is_1}$ has a higher degree of expertise than $er_1^{is_1}$.

Neighbourhood structure 5 (NS5)

NS5 is only considered if at least one casualty is located at an incident site and multiple hospitals are considered. NS5 consists of four steps, as shown in Figure 8.7, for illustrative purposes.

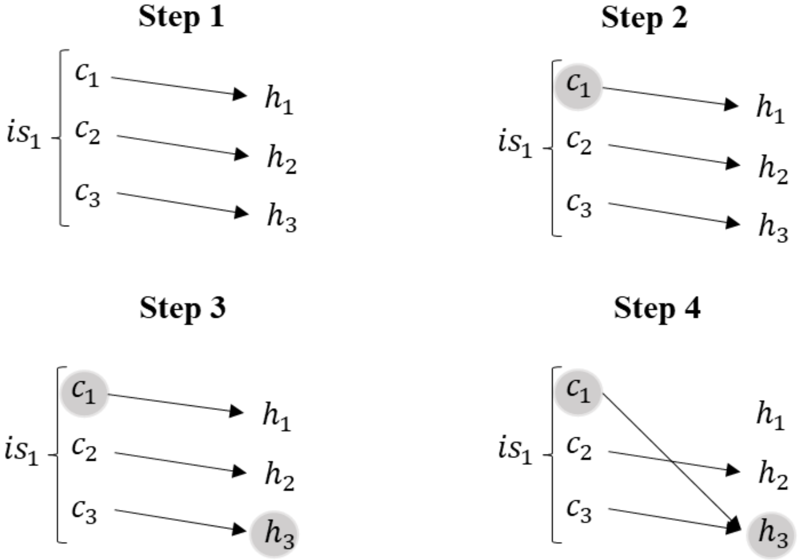


Figure 8.7: Example of the application of neighbourhood structure 5.

Step 1 involves selecting one incident site with at least one casualty yet to be loaded into a standard ambulance to be transported to the assigned hospital. In Figure 8.7, Step 1, incident site 1, is_1, with three casualties who are yet to be transported to the assigned hospitals, namely c_1, c_2 and c_3, is selected. Step 2 involves selecting one casualty who is yet to be transported to the assigned hospital and located at the incident site chosen in Step 1, as shown in Figure 8.7 Step 2, casualty 1, c_1, is chosen. Step 3 involves selecting a different hospital in the MCI-affected area to receive the casualty named in Step 2. In Figure 8.7, Step 3, hospital 3,

h_3, with one casualty allocated, c_3, is selected. In Step 4, the casualty selected in Step 2 is removed from the original hospital and assigned to the hospital selected in Step 3. In Figure 8.7, Step 4 shows c_1 who has been allocated to $h_1$is assigned to h_2. Assigning the selected casualty to the hospital selected in Step 3 may reduce or increase the transportation time of that casualty to the newly assigned hospital from the incident site selected in Step 1, dependent on how far the newly assigned hospital from the incident site at which the casualty selected in Step 2 is currently located. The application of NS5 always results in a feasible post-PDA response plan because NS5 only modifies the hospital that will receive the selected casualty.

Neighbourhood structure 6 (NS6)

NS6 is only considered if there are at least one standard ambulance has been allocated to transport at least one casualty to the assigned hospital. NS6 consists of four steps, as shown in Figure 8.8, for illustrative purposes.

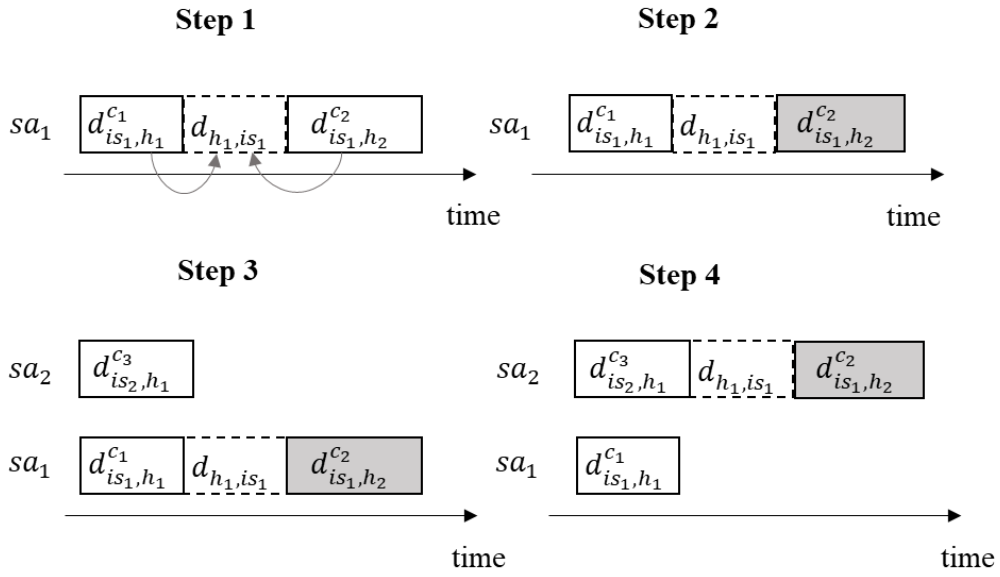


Figure 8.8: Example of the application of neighbourhood structure 6.

Step 1 involves selecting one standard ambulance that has been allocated to transport at least one casualty to the assigned hospital. In Figure 8.8, in Step 1, standard ambulance 1, sa_1, is selected that has been allocated to transport two casualties, casualty 1, c_1, and casualty 2, c_2, to their assigned hospitals, hospital 1, h_1, and hospital 2, h_2, respectively. The solid boxes indicate the duration of transporting a casualty from an incident site to the assigned hospital, whereas the dashed boxes indicate the time needed for a standard ambulance to arrive at the incident site to collect the next casualty. Step 2 involves selecting randomly a transportation task from those allocated to the standard ambulance chosen in Step 1; as shown in Figure 8.8, the transportation task associated with c_2 is selected. Step 3 involves the selection of a different standard ambulance. In Figure 8.8, Step 3, standard ambulance 2, sa_2, that has been assigned to transport one casualty, casualty 3, c_3, to h_1 is selected. In Step 4, the transportation task chosen in Step 2 is removed from those allocated to the standard ambulance selected in Step 1 and assigned randomly to the standard ambulance named in Step 3. Furthermore, as part of Step 4, sa_2 is required to travel from the hospital at which c_3 is assigned to the incident site at which the newly assigned casualty is currently located, as shown in Figure 8.8, Step 4, the time needed for sa_2 to collect c_2 from is_1 is built-in to the schedule of sa_2. In addition, a consequence of applying Step 4 is that the built-in travel time associated with c_2 is removed from the schedule of sa_1. The travel time is calculated based on the distance, speed, and road traffic as explained in relation to NS4. The application of NS6 always results in feasible post-PDA response plans because the reassignment of casualties to another standard ambulance does not affect the nature of the ordering of tasks assigned to emergency responders that may result in infeasible post-PDA response plans.

Neighbourhood structure 7 (NS7)

NS7 is only considered if there are at least two standard ambulances, each of which has been allocated to transport at least one casualty to the assigned hospital. NS7 consists of five steps, as shown in Figure 8.9, for illustrative purposes.

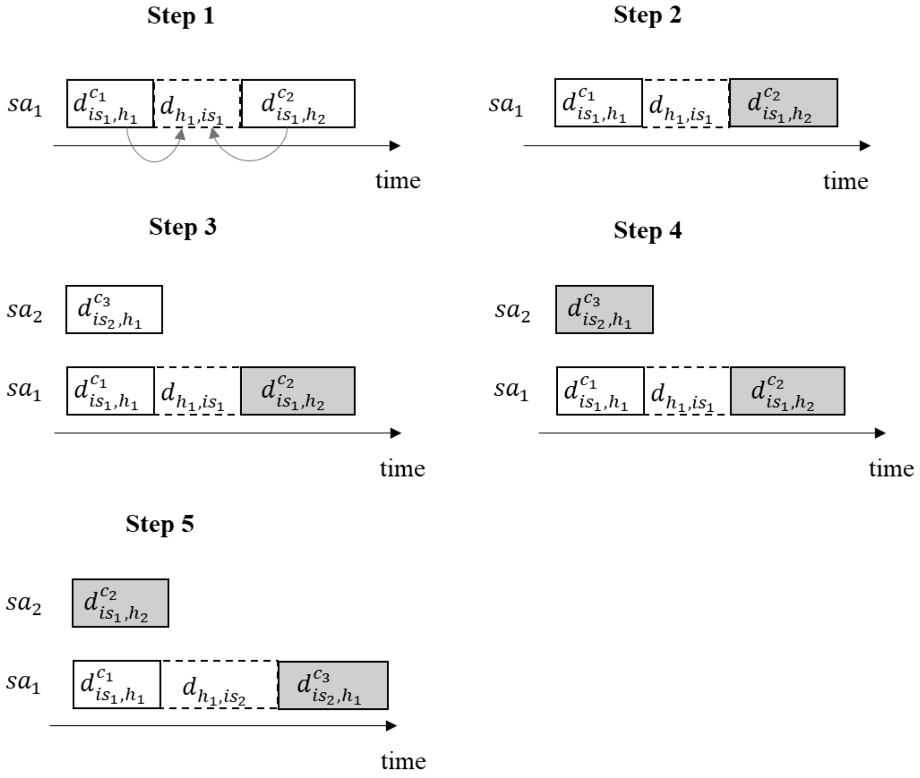


Figure 8.9: Example of the application of neighbourhood structure 7.

For NS7, the operation of Steps 1, 2, and 3 is the same as explained for NS6. However, Step 4 involves randomly selecting a transportation task from those allocated to the standard ambulance chosen in Step 3. In Step 5, the transportation tasks selected in Step 2 and Step 4 from those allocated to the standard ambulances named in Steps 1 and 3 are swapped. That is, the transportation task selected from the standard ambulance named in Step 1 is assigned to the standard ambulance named in Step 3 in the position of the transportation task selected in Step 4. Furthermore, the transportation task selected from the standard ambulance named in Step 3 is assigned to the standard ambulance named in Step 1 in the position of the transportation task selected in Step 2. Thus, in Figure 8.9, Step 1, standard ambulance 1, sa_1, is selected and has been allocated to transport two casualties, casualty 1, c_1, and casualty 2, c_2, to their assigned hospitals, hospital 1, h_1, and hospital 2, h_2, respectively. In Step 2, the transportation task associated with c_2 from those assigned to sa_1 is selected. In Step 3, standard ambulance 2, sa_2, is selected and has been assigned to transport one casualty, casualty 3, c_3, to h_1 is selected. In Step 4, the transportation task associated with c_3 is selected from those assigned to sa_2. In Step 5, the transportation task associated with c_2 chosen in Step 2 is removed from those assigned to sa_1 selected in Step 1 and then assigned to sa_2 named in Step 3 in the position of the transportation task selected in Step 4. Furthermore, the transportation task associated with c_3

chosen in Step 4 is removed from those assigned to sa_2 selected in Step 3 and then assigned to sa_1 named in Step 1 in the position of the transportation task selected in Step 2. Furthermore, as part of Step 5, sa_2 is required to travel from the hospital at which c_1 is assigned to the incident site at which the newly assigned casualty is currently located, as shown in Figure 8.9, Step 5, the time needed for sa_1 to collect c_3 from is_2 is built-in to the schedule of sa_1. The travel time is calculated based on the distance, speed, and road traffic as explained in relation to NS4. The application of NS7 always results in feasible post-PDA response plans because the reassignment of casualties to another standard ambulance does not affect the nature of the ordering of tasks assigned to emergency responders that may result in infeasible post-PDA response plans.

Neighbourhood structure 8 (NS8)

As with NS7, NS8 is only considered if there are at least two standard ambulances, each of which has been allocated to transport at least one casualty to the assigned hospital. NS8 consists of four steps, as shown in Figure 8.10, for illustrative purposes.

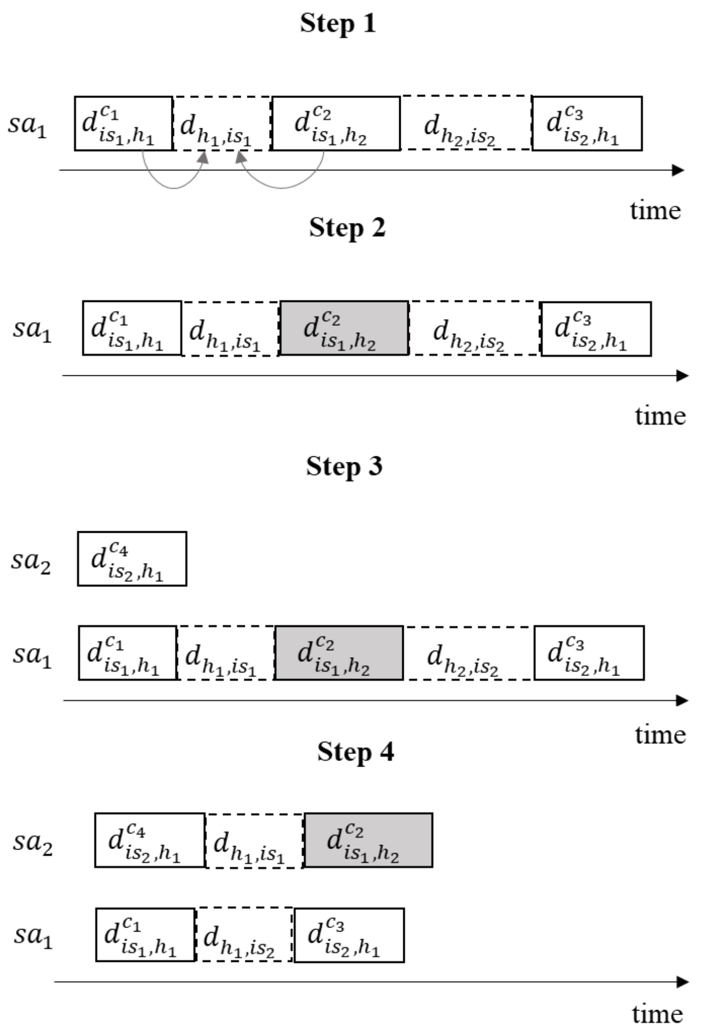


Figure 8.10: Example of the application of neighbourhood structure 8.

For NS8, the operation of Steps 1 and 3 is similar to those explained for NS6, whereas the operation of Steps 2 and 4 is the same. Step 1 involves selecting one standard ambulance that has the highest workload in terms of the completion time of transporting the assigned casualties to the assigned hospitals. Step 3 involves the selection of a different standard ambulance that has the lowest workload in terms of the completion time of transporting the assigned casualties to the assigned hospitals. In Figure 8.10, Step 1, standard ambulance 1, sa_1, is selected that has been allocated to transport three casualties, casualty 1, c_1, casualty 2, c_2, and casualty 3, c_3, to their assigned hospitals, hospital 1, h_1, hospital 2, h_2, and h_1, respectively. In Step 2, the transportation task associated with c_2 is selected. In Step 3, standard ambulance 2, sa_2, that has been assigned to transport one casualty, casualty 4, c_4, to h_1 is selected. In Step 4, the transportation task chosen in Step 2 is removed from those allocated to the standard ambulance selected in Step 1 and assigned randomly to the standard ambulance named in Step 3. Furthermore, as part of Step 4, sa_2 is required to travel from the hospital at which c_3 is assigned to the incident site at which the newly assigned casualty is currently located, as shown in Figure 8.10, Step 4, the time needed for sa_2 to arrive at is_1 at which c_2 is currently located from h_1 at which c_4 is transferred is built-in to the schedule of sa_2. In addition, a consequence of applying Step 4 is that the built-in travel time associated with c_2 is removed from the schedule of sa_1. The travel time is calculated based on the distance, speed, and road traffic as explained in relation to NS4. The application of NS8 always results in feasible post-PDA response plans because the reassignment of casualties to standard ambulances does not affect the nature of the ordering of tasks assigned to emergency responders that may result in infeasible post-PDA response plans.

The flowchart of the NSA

Figure 8.11 illustrates the flowchart of the NSA developed for this thesis.

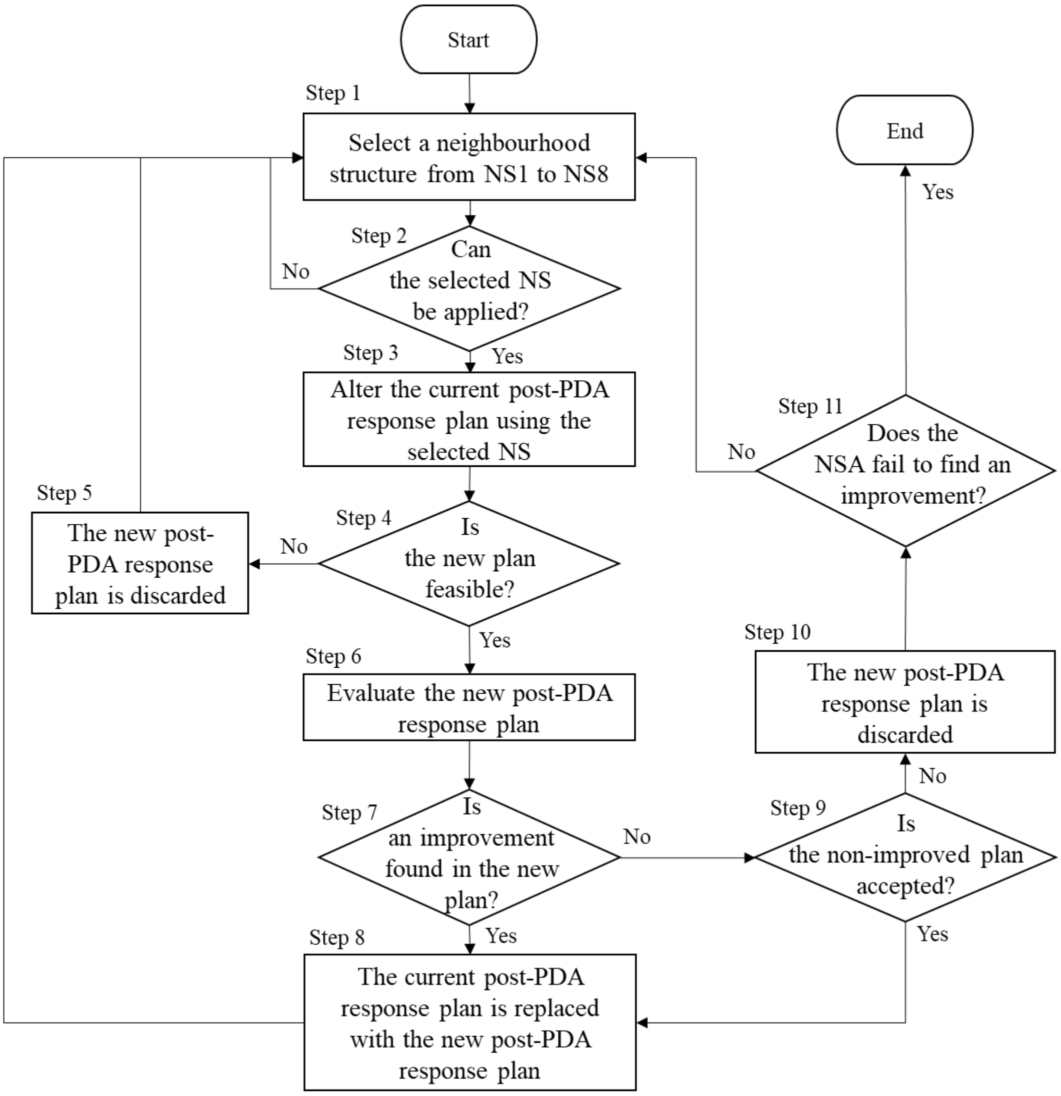


Figure 8.11: Flowchart of the developed neighbourhood search algorithm.

In Step 1, one neighbourhood structure from NS1 to NS8 is selected. In Step 2, a number of checks are applied to ensure that the selected NS can be applied. In Step 3, the selected NS in Step 2 is applied to the current post-PDA response plan in order to generate a new one. In Step 4, the new post-PDA response plan is checked; if it is an infeasible plan, then it will be discarded in Step 5, and Step 1 will be implemented. However, if the new plan is feasible, then the new post-PDA response plan is evaluated in Step 6 using the four objective functions, as discussed further in Section 8.3. If an improvement is found in the new post-PDA response plan in relation to the four objective functions in Step 7, then the current post-PDA response plan will be replaced with the new one (Step 8). Step 1 will then be implemented. However, if no improvement in the new post-PDA response plan is found in Step 7, then a low probability of 0.01 is set as a criterion for the acceptance of this plan in Step 9. The aim of accepting non-improved plans is to explore plans in the search space neighbouring the current solution and to circumvent the local-optimum problem similar to that encountered in simulated annealing [50]. If the probability of acceptance of a non-improving new optimised post-PDA response plan exceeds 0.01 (Step 9), the plan will be discarded (Step 10), or it will be accepted if the probability is equal to 0.01 (Step 8). Step 11 checks if the NSA has returned 50 successive non-improved feasible plans. If this is the case, the NSA will be terminated; otherwise, Step 1 will be implemented.

8.3 Objective functions to evaluate an optimised post-PDA response plan

Four objective functions have been defined to evaluate the post-PDA response plan generated using the NSA. All the objective functions' values are measured in minutes.

- Objective function $f_1(\mathrm{x})$ indicates the arrival time at the assigned hospital of the final immediate casualty across all incident sites.
- Objective function $f_2(\mathrm{x})$ indicates the arrival time at the assigned hospital of the final urgent casualties across all incident sites.
- Objective function $f_3(\mathrm{x})$ indicates the total processing time of all casualties. The processing time of each casualty begins when the first task (locating a casualty (Task 0)) associated with that casualty starts to be undertaken by the assigned emergency responder, and it ends when the final task (delivery to the assigned hospital (Task 8)) associated with that casualty is completed.
- Objective function $f_4(\mathrm{x})$ indicates the emergency response time, which is the time from when the PDA response plan is executed (Chapter 6, Figure 6.1, Step 6) to when the final

casualty of any health classification type across all incident sites is delivered to the assigned hospital (Chapter 6, Figure 6.1, Step 10)

Definitions of the terms ‘immediate’ and ‘urgent’ are provided in Chapter 2 (Section 2.3.3). These objective functions (i.e., $f_1(\mathrm{x})$, $f_2(\mathrm{x})$), in addition to the objective function $f_4(\mathrm{x})$, have been defined to ensure the delivery of casualties to the assigned hospitals in the shortest time possible based on their health classification priority, as delays can lead to death. Further, minimising these objective functions saves casualties’ lives and reduces suffering, as indicated in previously published research [120]. In addition, the objective function $f_3(\mathrm{x})$ aims to ensure the minimum waiting time possible for casualties of all health classifications for emergency responders to provide the appropriate lifesaving interventions.

From the initial post-PDA response plan generated using the GA, the initial arrival times at the assigned hospitals of the final immediate and final urgent casualties across all incident sites, objective functions $f_1(\mathrm{x})$ and $f_2(\mathrm{x})$, respectively, are computed using Eq. 8.1 and Eq. 8.2, respectively:

$$f_1(\mathrm{x}) = \max tc^{ct}_{s',c^{I}_{q}} \tag*{Eq. 8.1}$$

$$f_2(\mathrm{x}) = \max tc^{ct}_{s',c^{U}_{q}} \tag*{Eq. 8.2}$$

where $tc^{ct}_{s',c^{I}_{q}}$ and $tc^{ct}_{s',c^{U}_{q}}$ represent the completion time of the final task s' associated with the final casualty c_q classified as immediate and urgent, respectively, across all incident sites.

In order to compute the parameters needed to determine the value of the objective function $f_3(\mathrm{x})$, the initial processing time of each casualty, pt_{c_q}, should be computed from the initial post-PDA response plan generated using the GA and by using Eq. 8.3:

$$pt_{c_q} = \left| tc^{st}_{s,c_q} - tc^{ct}_{s',c_q} \right| \tag*{Eq. 8.3}$$

where tc^{st}_{s,c_q} refers to the starting time of the first task s (locating a casualty at an incident site (Task 1)) associated with casualty c_q, and tc^{ct}_{s',c_q} refers to the completion time of the final task s' (unloading a casualty from a standard ambulance once he/she has arrived at the assigned hospital (Task 10)) associated with casualty c_q. Tasks associated with casualties have been discussed in Chapter 6 (Section 6.5.2). Then, the initial total processing time of all casualties is computed using Eq. 8.4:

$$f_3(\mathrm{x}) = \sum_{b=1}^{b=n_c} \left|pt_{c_q}\right| \qquad \text{Eq. 8.4}$$

During the computation of the value of the objective function $f_3(\mathrm{x})$, the initial emergency response time $f_4(\mathrm{x})$ from the initial post-PDA response plan generated using the GA is recorded using Eq. 8.5:

$$f_4(\mathrm{x}) = \max tc^{ct}_{s',c_{q'}} \qquad \text{Eq. 8.5}$$

where $tc^{ct}_{s',c_{q'}}$ represents the completion time of the final task s' associated with the final casualty $c_{q'}$ of any health classification across all incident sites.

As the response to MCIs unfolds, the arrival time at the assigned hospital of the final immediate casualty across all incident sites, tc^{ct}_{s',c_q^I}, the arrival time at the assigned hospital of the final urgent casualty across all incident sites, tc^{ct}_{s',c_q^U}, the processing time of each casualty, pt_{c_q}, yet to be delivered to the assigned hospitals, and the arrival time at the assigned hospital of the final casualty of any health classification across all incident sites, $tc^{ct}_{s',c_{q'}}$, will be updated every time the NSA generates a new optimised post-PDA response plan, leading to the values of objective functions $f_1(\mathrm{x})$, $f_2(\mathrm{x})$, $f_3(\mathrm{x})$, and $f_4(\mathrm{x})$ being updated.

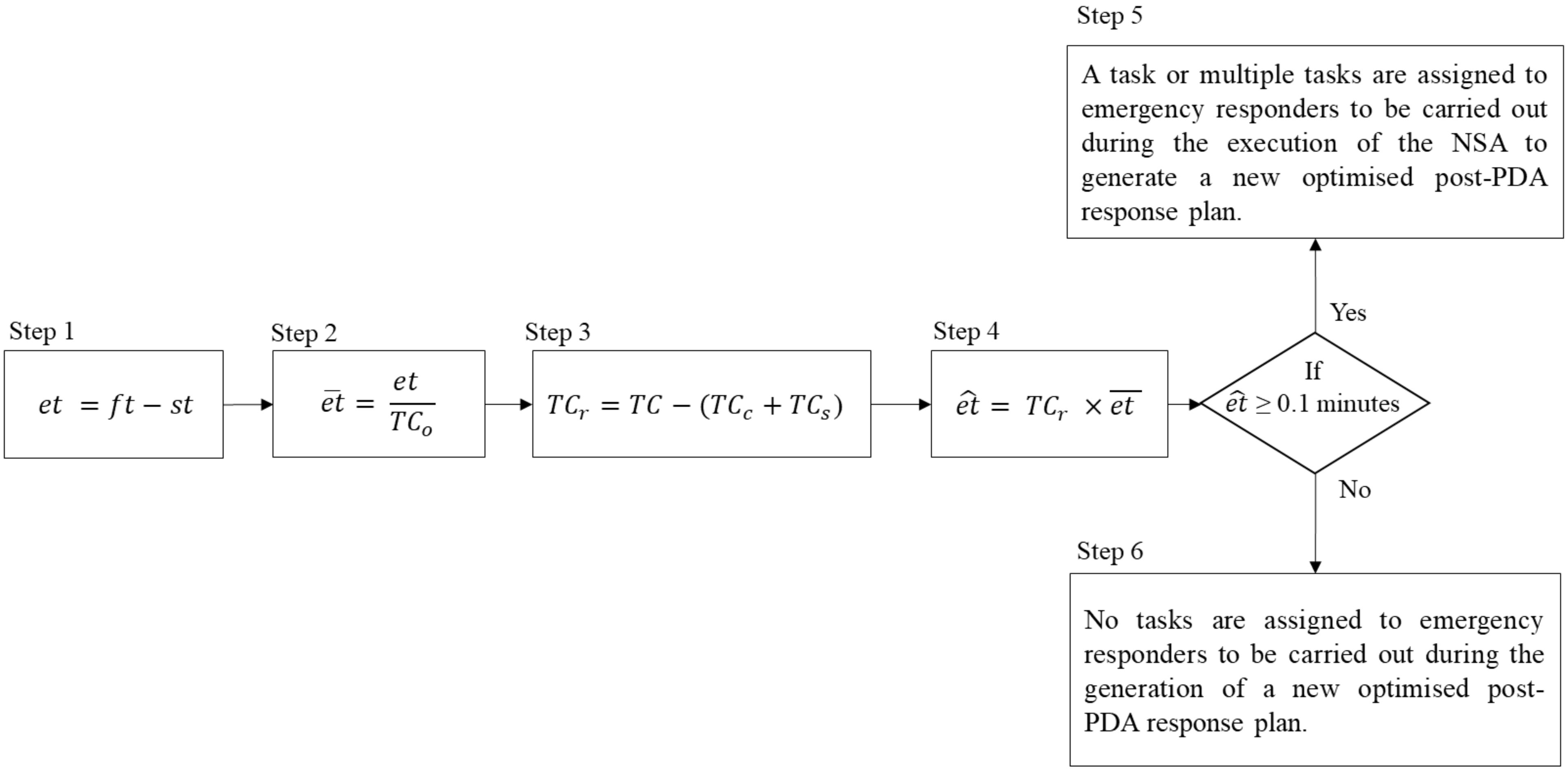
Defining the priority level of the objective functions

The lexicographic approach has been chosen to define the priority level of the aforementioned objective functions. The approach refers to the preferences imposed to order the defined objective functions according to their respective significance [117]. Accordingly, in this research, objective function $f_1(\mathrm{x})$ is ordered first because it is associated with the most critical casualties (i.e., immediate casualties), who are at highest risk of losing their lives. Next, objective function $f_2(\mathrm{x})$ is ordered second as it is associated with urgent casualties, who are not as critical as those defined as immediate but more critical than those who are delayed. Minimising the waiting time of all casualties for emergency responders to perform the tasks associated with them that have yet to be started, namely objective function $f_3(\mathrm{x})$, is considered more important than minimising the emergency response time, namely objective function $f_4(\mathrm{x})$. Thus, objective functions $f_3(\mathrm{x})$ and $f_4(\mathrm{x})$ are ordered third and fourth, respectively.

In terms of evaluating a new optimised post-PDA response plan generated using the NSA, the plan would only be accepted when an improvement is found in one objective function compared to the same objective function of the current optimised post-PDA response plan in the defined order. If no improvement has been found in any objective function of the new optimised post-PDA response plan in terms of minimising any objective functions in the defined order, a low probability of 0.01 has been set to accept the non-improving new optimised post-PDA response plans, as discussed in Section 8.2.3.

8.4 Reduce transition times between successive optimised post-PDA response plans

During the execution of an optimised post-PDA response plan, new information related to MCI may become available as the MCI response unfolds, requiring the generation of a new optimised post-PDA response plan that reflects the evolving situation on the ground. Subsequently, the execution of the current optimised post-PDA response plan will be terminated. However, tasks that have been started by emergency responders but are yet to be completed are not re-scheduled or interrupted. In such a scenario, emergency responders may have no scheduled tasks to undertake due to the time taken by the NSA to generate a new optimised post-PDA response plan. Thus, an approach has been developed to reduce the transition times between successive optimised post-PDA response plans. This approach aims to estimate the execution time of the NSA to generate a new optimised post-PDA response plan and then assign a task or a number of tasks that are yet to be started with a duration less than or equal to the execution time of the NSA to emergency responders to be carried out during the execution of the NSA, considering the sequence of performing tasks. Note that this approach will not be implemented if the NSA has not been previously executed because information regarding the latest execution time of the NSA to generate the current optimised post-PDA response plan is required. The application of the developed approach is illustrated in Figure 8.12.



A task or multiple tasks are assigned to emergency responders to be carried out during the execution of the NSA to generate a new optimised post-PDA response plan.

No tasks are assigned to emergency responders to be carried out during the generation of a new optimised post-PDA response plan.

Figure 8.12: Reducing the transition times between successive optimised post-PDA response plans.

When new information becomes available, the execution time of the NSA to generate the current optimised post-PDA response plan, *et*, is measured retrospectively (Figure 8.12, Step 1). In Step 1, the parameters st and ft refer to the actual time of starting and completing the latest execution of the NSA to generate the current optimised post-PDA response plan, respectively, consisting of TC_o optimised tasks, where $TC_o \subset TC$. The parameters st and ft are computed during the latest execution of the NSA to be used later when this approach is required. The number of optimised tasks, TC_o, is updated each time a current optimised post-PDA response plan is generated. In Step 2, the average execution time of optimising a single task using the NSA when generating the current optimised post-PDA response plan, $\overline{et}$, is estimated. Following Step 2, the execution of the current optimised post-PDA response plan is terminated. However, all tasks that have been started by emergency responders but are yet to be completed are not re-scheduled nor interrupted in the MCI environment. In Step 3, the number of remaining tasks, TC_r, that are yet to be started are calculated each time the execution of the current optimised post-PDA response plan is terminated because emergency responders may complete or start performing some tasks during the execution of the latest optimised post-PDA response plan, TC_c and TC_s, respectively. Then, based on the results obtained from Step 2 and Step 3, the execution time of the NSA, $\widehat{et}$, to generate a new optimised post-PDA response plan consisting of TC_r tasks is estimated (Step 4). In step 5, the first task that is yet to be started in each emergency responder's schedule from the current optimised post-PDA response plan will be assigned to each emergency responder to be carried out during the execution of the NSA in which:

- the estimated execution time of the NSA to generate the new optimised post-PDA response plan, $\widehat{et}$, is greater than or equal to 0.1 minute, which is the lower bound duration required to complete Task 1 (locate a casualty) among TC. The duration of tasks associated with casualties was discussed in Chapter 7 (Section 7.7.3);
- the preceding task or tasks related to that task to be assigned to emergency responders has/have been completed.

When the estimated execution time of the NSA, $\widehat{et}$, is greater than 0.1 minutes, it is possible that an emergency responder will carry out more than one task during the execution of the NSA in which the total duration of these tasks is less than or equal to the estimated execution time of the NSA, $\widehat{et}$, and the preceding task or tasks related to these tasks has/have been completed. In the event that the estimated execution time of the NSA, $\widehat{et}$, is less than 0.1 minutes, no task will be carried out during the execution of the NSA by any emergency responders, which is considered a 'transition time' (Step 6). Figure 8.13 presents an example of the application of the approach to reducing the transition times between successive optimised post-PDA response plans. Three emergency responders, emergency responder 1 er_1, emergency responder 2 er_2 and emergency responder 3 er_3, are considered in Figure 8.13 for illustrative purposes. The shaded boxes indicate the tasks that have been completed or started by emergency responders but are yet to be completed, whereas the unshaded boxes indicate the tasks that are yet to be started.

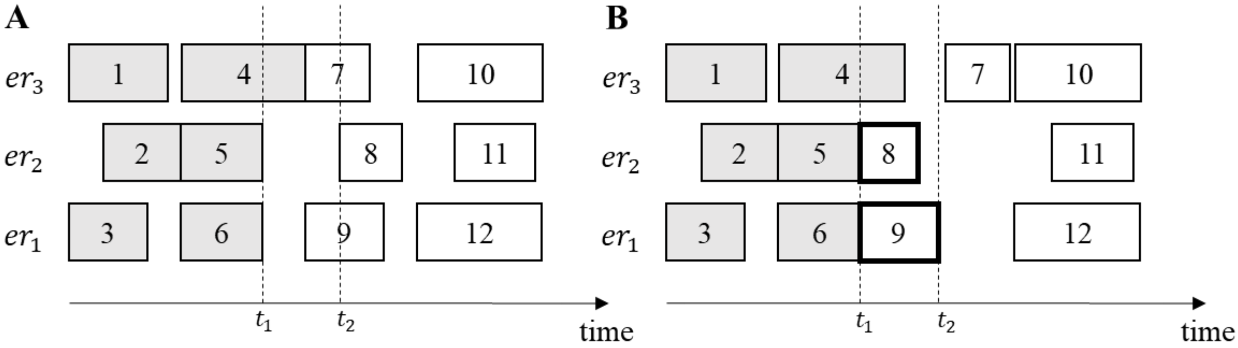


Figure 8.13: Example of the application of the approach to reducing the transition times between successive optimised post-PDA response plans.

Consider the latest execution of the NSA to generate the current optimised post-PDA response plan started after 10 minutes and finished after 10 minutes and 15 seconds from the initiated time of the MCI response. Accordingly, the latest execution of the NSA can be computed as 10.15 - 10.00 = 0.15 seconds, which indicates that the NSA generated the current optimised post-PDA response plan within 15 seconds, which consists of TC_o=12 tasks. The average execution time of optimising a single task, $\overline{et}$, is $\frac{15}{12} = 1.25$ seconds. New information related to an MCI becomes available at time t_1 (Figure 8.13 A), necessitating the generation of a new optimised post-PDA response plan that reflects the evolving MCI using the NSA. Subsequently, the current optimised post-PDA response plan is terminated and the number of tasks that are yet to be started, TC_r, is updated to 6 tasks (see unshaded boxes in Figure 8.13 A). Note that Task 4 has been started but is yet to be completed; thus, it will not be re-scheduled nor interrupted in the MCI environment. The period of time from t_1 to t_2 represents the estimated execution time of the NSA to generate the new optimised post-PDA response plan, $\widehat{et} = 6 \times 1.25 = 7.5$ seconds. Task 9 and Task 8 (boxes with a thick border in Figure 8.13 B) will be carried out by er_1 and er_2, respectively, during the execution of the NSA as their durations are less than or equal to 7.5 seconds, taking into account that the preceding task or tasks related to Task 8 and Task 9 have been completed. As a result, a seamless transition between the latest and the new optimised post-PDA response plans is achieved by reducing the transition time between the current and new post-PDA response plans (Figure 8.13 B).

8.5 Summary

This chapter has discussed the algorithms and the approach to reducing the transition times between successive optimised post-PDA response plans used in the PHRF of the decision support model, based on the requirements of the coordination decisions defined in Chapter 4, with the aim to overcome the limitations highlighted in the models critically reviewed in Chapter 5. The establishment of a PDA response plan for all incident sites using the GHA has been then explained. The creation of a feasible initial post-PDA response plan to be used as a starting point for the NSA has been subsequently discussed, followed by a description of the execution of the NSA to optimise the initial post-PDA response. As a result of this process, an optimised post-PDA response plan has been generated. As new information associated with an MCI becomes available, the use of the NSA to generate new optimised post-PDA response plans that reflect the evolving MCI has been illustrated. In addition, the four objective functions defined to evaluate the optimised post-PDA response plan have been discussed. Finally, the approach to reducing the transition times between successive optimised post-PDA response plans has been presented and discussed. Therefore, this chapter partially addressed RQ2. In the next chapter, the developed decision support model will be validated.

Chapter 9. Validation of the decision support model

9.1 Introduction

Computational models are mathematical representations of complex real-world systems or phenomena, which are often difficult to study using experiments and observations alone. Although mass casualty incidents (MCI) are not a common occurrence, they are often associated with a significant number of casualties with various levels of injury severity and economic burden. Training, preparation, and optimising the response to MCIs are, therefore, pivotal to minimising morbidity and mortality. Using computational models enable scientists to understand the model's behaviour and gain insights to assist in making decisions about the problem under consideration. It is essential to ensure computational models are validated, ensuring that they accurately reflect the behaviour of real-world systems, especially considering that modelling often requires assumptions to be made. The validation of a computational model requires a comparison of the model's findings with existing experimental and/or observational data to determine its accuracy and reliability. Validated models are able to provide inter-reliability, which facilitates informed decision-making. Prior to any computational modelling approaches being implemented in reality, they must first undergo a rigorous assessment and validation process, as any failure or shortcomings of computational modelling could be expensive and impact casualties [121].

This chapter provides a continuation of the exploration of RQ2, which was introduced in Chapters 6, 7 and 8. The purpose of this chapter is to assess the validity of the developed decision support model to coordinate the response of emergency service resources to MCIs, discussed in Chapters 6 to 8, using two validation techniques, namely grounding and calibration [12, 122]. Consequently, this chapter answers two questions: 1) is the decision support model reliable and appropriately constructed? and 2) are the results generated from the decision support model valid?.

9.2 Validation techniques

According to the Department of Defence 'Online M&S Glossary', validation can be defined as a process of proving the validity and adequacy of computational models in matching real-world data [123]. In this thesis, particularly Chapter 3, a number of decision support models have been reviewed, including models concerning the coordinated response to man-made incidents [62, 64-66], natural incidents [61, 67-70], and unspecified MCIs [71-75]. However, to date, these models have not undergone any stringent validation assessment. The only exception to this is the work of Su et al. [69], who asserted that applying the same experimental conditions repeatedly (50 replications) to a model is sufficient to validate the results generated from that model. This approach of repeating the simulations has been identified as a suitable approach for reducing potential errors, maintaining data integrity, and accounting for the dynamicity and uncertainty in computational models. Although promising, the approach of Su et al. [69] is insufficient for assessing the reliability of the results generated from developed models and could be seen as unfounded and unreliable [124, 125].

The two main validation techniques that have been extensively used in the literature to validate computational models are grounding and calibration [12, 122]. The grounding technique is an approach used to determine if a computational model being studied is able to generate similar findings to those previously reported using existing models developed to solve similar problems [122]. The calibration technique is a process where a specific model that is being developed, such as the decision support model in this thesis, can be modified in an attempt to replicate the experiments and outcomes of published models [122, 126]. In the event that the results generated by the developed model do not align with previously published models, the current model may require further modification to ensure the results are comparable with those previously published and therefore increase the confidence of the developed model, in this case, the developed decision support model.

9.2.1 Grounding technique

The grounding technique is processed using a three-step process. Step 1 identifies previously published models developed to solve a similar problem to that described in this thesis. In Chapter 3, there have been fourteen existing models published [61, 62, 64-75] identified and reviewed. Step 2 highlights the key findings from the models identified in Step 1. In Chapter 3, the findings of these models were identified, and the findings that can be generated using the developed model were re-stated:

1) Incident sites with a higher number of casualties were allocated a larger number of emergency responders [61] and vehicles [66].
2) Increased waiting times for casualties prior to treatment contributed to health deterioration [61].

3) An increase in the number of casualties leads to an increase in emergency response time [64, 66].
4) An increase in the number of normal ambulances improved the response time [127].
5) Hospitals closer to the incident sites received more casualties [62].
6) An increase in the number of hospitals reduced the arrival time of the last immediate casualty assigned to a hospital [127] and the response time [64].

Other findings demonstrated from the models identified in Step 1 have been excluded as they required modifications to the problem under consideration, which is not the purpose of the grounding technique. For example, altering the objective functions or adding new ones. In Step 3, the six key findings identified from the models identified in Step 1 are compared to those from the developed decision support model using three experiments defined in Appendix B (Table B.1). These experiments are restated in Table 9.1 for ease of access. Experiment 4 is newly added to the table in order to generate results that can be compared to the key finding four that has previously been reported [127]. Experiments 2 to 4 are the same as experiment 1; however, the distribution of casualties among incident sites $n_{c,is}$, total number of casualties, and number of standard ambulances $n_{ev,as}^{SA}$ in experiments 2, 3, and 4 are different. In experiment 2, unequal distribution of casualties was considered, which means that at each of the four incident sites, the distribution of casualties is as follows, 80, 60, 40, and 20, respectively. In experiment 3, the total number of casualties was increased from 200 to 240, with an equal allocation to each incident site of 60, previously 50. In experiment 4, the number of standard ambulances was increased from 50 to 63, an increase of one to two standard ambulances located at each ambulance station.

Table 9.1: Design of experiments.

E	Incident sites			Casualties					Ambulance stations								Fire and rescue stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is} and t_{is}	$n_{c,is}$	$n_{c_{is}^{t}}$ (%)	Health profile (%)			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$			$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
1	4	BM	Sun 15:00:00	50	50	25	25	50	7	BAS	6	7	2	1	2	1	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	1	2	1		EFS	6	3	4	2				GH
		EUS		50	50	25	25	50		LAS	6	7	2	1	2	1		FFS	6	2	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	2	4	1				SMH
		HP		50	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	2	4	1				RLH
										WAAS	5	7	2	1	2	1		PEFS	5	2	5	2				UCH
		OC		50	50	25	25	50		WEAS	5	8	3	1	3	1		SFS	5	2	5	2				
				200							**40**	**50**	**15**	**7**	**15**	**7**			**40**	**16**	**30**	**12**	**140**	**92**		
2	4	BM	Sun 15:00:00	80	50	25	25	50	7	BAS	6	7	2	1	2	1	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	1	2	1		EFS	6	3	4	2				GH
		EUS		60	50	25	25	50		LAS	6	7	2	1	2	1		FFS	6	2	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	2	4	1				SMH
		HP		40	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	2	4	1				RLH
										WAAS	5	7	2	1	2	1		PEFS	5	2	5	2				UCH
		OC		20	50	25	25	50		WEAS	5	8	3	1	3	1		SFS	5	2	5	2				
				200							**40**	**50**	**15**	**7**	**15**	**7**			**40**	**16**	**30**	**12**	**140**	**92**		

E, experiment; BM, British Museum; EUS, Embankment underground; HP, Hyde park; OC, Oxford Circus; BAS, Bloomsbury ambulance station; FAS, Fulham ambulance station; LAS, London ambulance station; OAS, Oval ambulance station; SJWAS, St John's Wood ambulance station; WAAS, Waterloo ambulance station; WEAS, Westminster ambulance station; DFS, Dowgate fire station; EFS, Euston fire station; FFS, Fulham fire station; OKRFS, Old Kent Road fire station; PAFS, Paddington fire station; PEFS, Peckham fire station; SFS, Soho fire station, CWH, Chelsea and Westminster Hospital; GH, Guy's Hospital; KCH, King's College Hospital, SMH, St Mary's Hospital; RLH, Royal London Hospital; UCH, University College Hospital;n_{is}, the number of incident sites; l_{is}, location of incident sites; d_{is} and t_{is}, day and time of the occurrence of incident sites, respectively; $n_{c,is}$, number of casualties at incident sites; $n_{c_{is}^{t}}$, number of trapped casualties at incident sites; n_{as}, number of ambulance stations; l_{as}, location of ambulance stations; $n_{er,as}^{pa}$ and $n_{ev,as}^{SA}$, number of paramedics and standard ambulances located at ambulance stations, respectively; $n_{er,as}^{HART}$ and $n_{ev,as}^{HART}$, number of HART responders and ambulances located at ambulance stations, respectively; $n_{er,as}^{MERIT}$ and $n_{ev,as}^{MERIT}$, number of HART responders and ambulances located at ambulance stations, respectively; n_{fs}, number of fire and rescue stations; l_{fs}, location of fire and rescue stations; $n_{er,fs}^{FAR}$ and $n_{ev,fs}^{FE}$, number of FAR and fire engines located at fire and rescue stations, respectively; $n_{er,fs}^{SAR}$ and $n_{ev,fs}^{ISV}$, number of SAR responders and incident support vehicles located at fire and rescue stations, respectively; n_{er} and n_{ev}, number of emergency responders and vehicles, respectively; n_h, number of hospitals; l_h, location of hospitals.

Table 9.1: Design of experiments (cont.).

E	Incident sites			Casualties					Ambulance stations								Fire and rescue stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is} and t_{is}	$n_{c,is}$	$n_{c_{is}^{t}}$ (%)	Health profile (%)			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$			$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
3	4	BM	Sun 15:00:00	60	50	25	25	50	7	BAS	6	7	2	1	2	1	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	1	2	1		EFS	6	3	4	2				GH
		EUS		60	50	25	25	50		LAS	6	7	2	1	2	1		FFS	6	2	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	2	4	1				SMH
		HP		60	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	2	4	1				RLH
										WAAS	5	7	2	1	2	1		PEFS	5	2	5	2				UCH
		OC		60	50	25	25	50		WEAS	5	8	3	1	3	1		SFS	5	2	5	2				
				240							**40**	**50**	**15**	**7**	**15**	**7**			**40**	**16**	**30**	**12**	**140**	**92**		
4	4	BM	Sun 15:00:00	50	50	25	25	50	7	BAS	6	9	2	1	2	1	7	DFS	6	3	4	2			6	CWH
										FAS	6	9	2	1	2	1		EFS	6	3	4	2				GH
		EUS		50	50	25	25	50		LAS	6	9	2	1	2	1		FFS	6	2	4	2				KCH
										OAS	6	9	2	1	2	1		OKRFS	6	2	4	1				SMH
		HP		50	50	25	25	50		SJWAS	6	9	2	1	2	1		PAFS	6	2	4	1				RLH
										WAAS	5	9	2	1	2	1		PEFS	5	2	5	2				UCH
		OC		50	50	25	25	50		WEAS	5	9	3	1	3	1		SFS	5	2	5	2				
				200							**40**	**63**	**15**	**7**	**15**	**7**			**40**	**16**	**30**	**12**	**140**	**106**		

The results from experiments 1 and 2 relate to the key finding number one, *'Incident sites with a higher number of casualties were allocated a larger number of emergency responders [61] and vehicles [66]'.* The findings from experiment 1 indicated that the number of emergency responders allocated to the British Museum (BM), Embankment underground station (EUS), Hyde Park (HP), and Oxford Circus (OC) were 34(±5), 37(±7), 36(±2), and 33(±4). In experiment 2, the mean number of emergency responders allocated to incident sites BM, EUS, HP, and OC were 45(±6), 37(±2), 33(±4), and 25(±4). The results of experiment 2 clearly demonstrate that a large number of emergency responders were allocated to the incident site with a higher number of casualties, aligning with key finding number one [61, 66].

In relation to the key finding number two, '*Increased waiting times for casualties prior to treatment contributed to health deterioration [61]*', Figure 9.1 shows the mean times in hours from the four objective functions previously defined in Chapter 8 (Section 8.5). Objective function $f_1(\mathrm{x})$ relates to the arrival time at the allocated hospital of the final immediate casualty across all four incident sites. Objective function $f_2(\mathrm{x})$ relates to the arrival time at the allocated hospital of the final urgent casualty across all four incident sites. Objective function $f_3(\mathrm{x})$ relates to the total processing times of all casualties allocated at all four incident sites. The processing time of each casualty begins when Task 1, locating a casualty, is undertaken by an assigned emergency responder and is complete when Task 10, delivering a casualty to their assigned hospital, has been completed. Objective function $f_4(\mathrm{x})$ relates to the emergency response time, which is defined as the time from when the pre-determined attendance (PDA) response plan is executed to when the final casualty of any health classification type across all four incident sites is delivered to their allocated hospital. The findings from experiments 1 and 2 highlighted that more than 50% of casualties arriving at their allocated hospitals had a mild health condition (delayed casualties) with no mortalities. The results of $f_3(\mathrm{x})$ from both experiments show that the average processing time for a casualty was approximately 1.10 hours, confirming that a short processing time of casualties could lead to better outcomes in terms of the casualties' health. In contrast, a longer processing time of casualties could affect the overall health of casualties and may increase mortality, aligning with key finding number two [61].

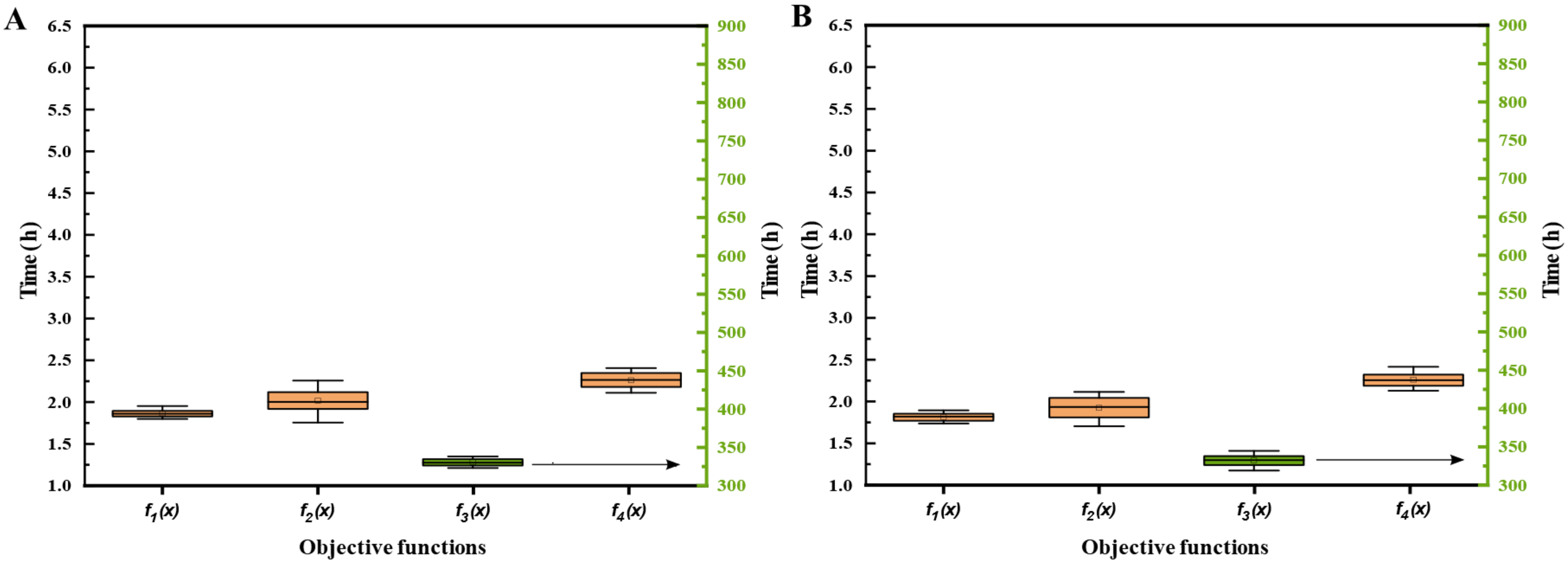


Figure 9.1: Boxplots presenting mean times in hours for the four objective functions from A) experiment 1 and B) experiment 2 (based on 50 runs).

A larger number of casualties at an incident site ultimately requires more emergency responders to treat casualties, or a decrease in response time can be observed, linking with key finding number three, '*an increased in the number of casualties leads to an increase in the response time*' *[64, 66]*. The data presented in Figure 9.2 is the mean time in hours from the four objective functions from experiment 3.

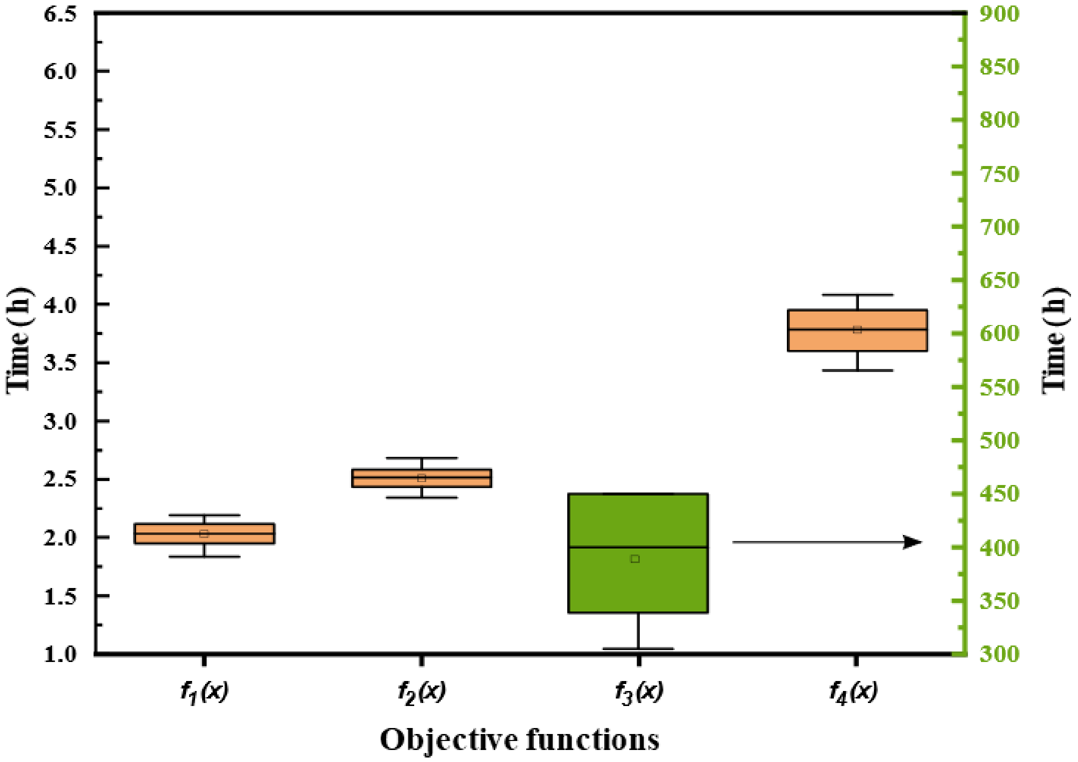


Figure 9.2: Boxplots presenting mean time in hours for the four objective functions from experiment 3 (based on 50 runs).

The mean emergency response time ($f_4(x)$) obtained from experiment 3 was 3.76 hours (Figure 9.2), an increase of 10.94% when compared with experiment 1, given that the number of casualties defined in experiment 3 is larger than those defined in experiment 1, 240 and 200 casualties, respectively. These findings from experiment 3 confirm the key finding number three that has previously been reported [64, 66].

In order to assess if '*An increase in the number of normal ambulances improved the response time'* [127], the results of experiment 4 will be compared to experiment 1. As indicated earlier, experiments 1 and 4 are the same; however, the number of normal ambulances is different. Figure 9.3 presents the mean time in hours from the four objective functions for experiment 4.

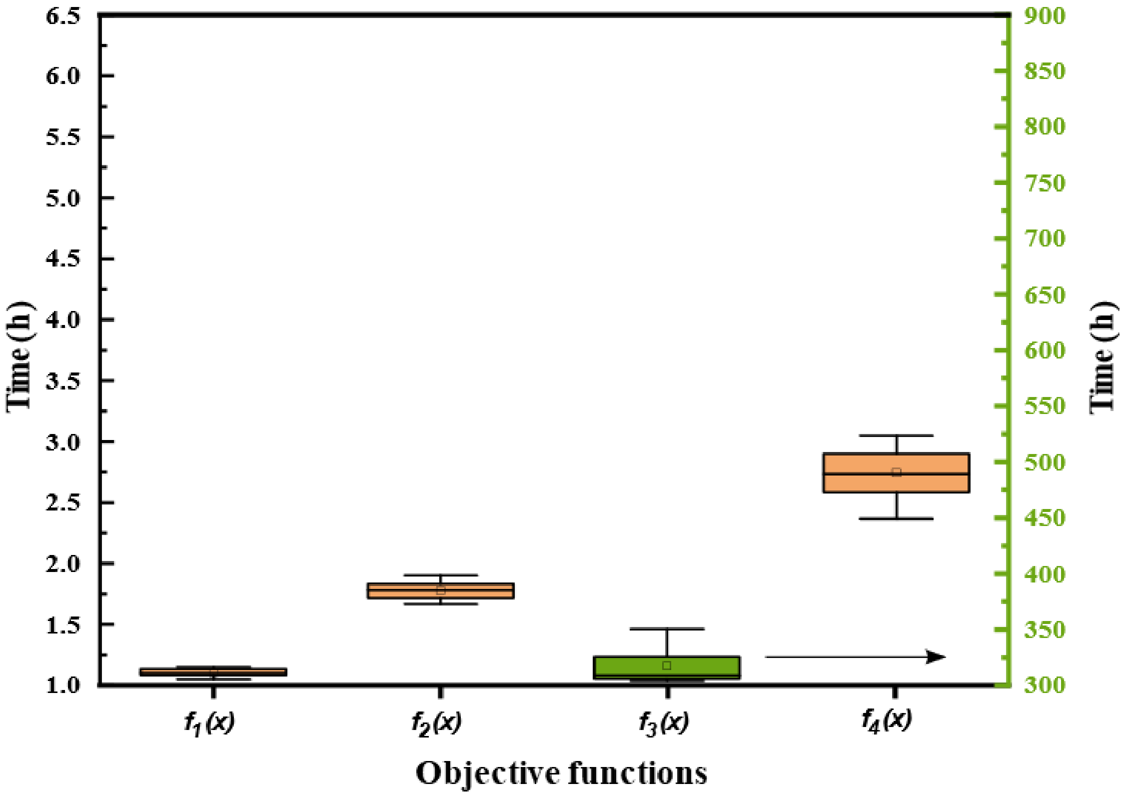


Figure 9.3: Boxplots presenting time in hours from the four objective functions for experiment 4 (based on 50 runs).

The mean emergency response time ($f_4(x)$) obtained from experiment 4 was 2.74 hours (Figure 9.3), 20.62% lower than experiment 1, given that the number of standard ambulances in experiment 4 was higher than those defined for experiment 1, 63 and 50 standard ambulances, respectively. These findings demonstrate a clear association between the number of standard ambulances and the response time, confirming that the developed decision support model in this thesis is able to generate the key finding number four [127].

In an attempt to reduce the treatment time required of casualties, it is rationale to allocate casualties to the hospital that is closest to the incident site, which is in alignment with previously observed findings *[62]*', where *'the hospitals closer to the incident sites received more casualties'*, key finding number five. The results of experiments 1 to 4 clearly demonstrate a positive association between hospital location and the number of casualties in relation to proximity to the incident site. For example, in experiments 1, the University College Hospital (UCH) was the closest to three of the four incident sites and was subsequently allocated the largest number of casualties, 66 out of 200, when compared to the other hospital sites, aligning with previously observed findings [62].

An increase in emergency resources, such as the number of hospitals, would be anticipated to reduce the time taken to travel to a hospital and reduce the response time, aligning with key finding number six and previous literature [64, 127], '*An increase in the number of hospitals reduced the arrival time of the last immediate casualty assigned to a hospital [127] and the response time [64]*'. In experiment 1, six hospitals were specified, but to allow the comparison between the results, three out of the six hospitals were selected randomly to receive casualties from incident sites, namely UCH, Guy's Hospital (GH), and King's College Hospital (KCH). The results indicated that the mean arrival time of the last immediate casualty to the assigned hospital ($f_1(x)$) was 2.93 hours when considering only three hospitals. In contrast, there was a decrease in the value of $f_1(x)$, 2.75 hours when considering all six hospitals (Figure 9.1). Consequently, the mean emergency response time ($f_4(x)$) increased from 3.30 to 3.78 hours when considering only three hospitals. These findings clearly demonstrate that increasing the number of hospitals is able to reduce the arrival times of casualties at the assigned hospitals and emergency response times, confirming previously reported findings [64, 127].

9.2.2 Calibration technique

The process of modifying a computational model being studied may necessitate setting and resetting certain parameters, objective functions, and/or methods. In this context, the term 'modifying' refers to a process of iteratively modifying a computational model until the results of the model being studied are comparable, within a reasonable margin of error, to the results of a specific existing model using the same experiments provides evidence demonstrating the validity of a model [122]. In the event that this is not the case, the parameters and/or methods must be modified. However, if necessary, additional parameters, methods, and/or approaches should be considered in the model being developed. The calibration technique in this chapter has been processed using a three-step process. Step 1 identifies experiments that have previously been published in models developed to solve a similar problem to that described in this thesis. Therefore, Table 9.2 provides a summary of existing experiments associated with seven of the 14 models reviewed previously [62, 64-66, 72, 73, 75] (Section 11.2.2, Step 1).

The seven models that were selected and included in Table 12.1 were identified as those that closely resembled the key elements defined in Chapter 3 (Section 3.3) regarding a) an MCI environment and b) coordination decisions. In Table 9.2, the symbol ‘-‘ denotes whether the value of a parameter was not provided or not considered. The term ‘modified model’ refers to the modified version of the developed decision support model in this thesis to coordinate the response of emergency service resources to MCIs discussed in chapters 6 to 8. The green cell denotes when a modified model results in an improvement in the values of the objective functions considered when compared to those of the original model. The letters ‘NC’ denotes experiments not considered due to missing information.

Table 9.2: Existing experiments applied in seven models critically reviewed in Chapter 5.

No	Ref	Incident sites			Ambulance stations							Fire stations						n_{er}	n_{ev}	Hospitals	Results	
		n_{is}	d_{is}, t_{is}	$n_{c,is}$	n_{as}	Emergency responders and vehicles						n_{fs}	Emergency responders and vehicles									
						$n^{pa}_{er,as}$	$n^{SA}_{ev,as}$	$n^{HART}_{er,as}$	$n^{HART}_{ev,as}$	$n^{MERIT}_{er,as}$	$n^{MERIT}_{ev,as}$		$n^{FAR}_{er,fs}$	$n^{FE}_{ev,fs}$	$n^{SAR}_{er,fs}$	$n^{ISV}_{ev,fs}$			n_h	Existing model	Modified model
1	[65]	3	-	210	-	-	-	-	-	-	-	-	-	-	-	-	36	-	3	61.31	60.45
2.1	[64]	1	-	10	-	-	4	-	-	-	-	-	-	-	-	-	-	4	4	99 mins	73.1 minutes
2.2		1	-	20	-	-	4	-	-	-	-	-	-	-	-	-	-	4	4	178 mins	139.6 minutes
3	[62]	2	-	21	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2	NC	NC
4	[66]	2	-	-	9	-	2-4	-	-	-	-	9	-	2-4	-	-	-	36-72	4	NC	NC
5	[72]	1	-	150	6	-	-	-	-	-	-	-	-	-	-	-	-	-	15	NC	NC
6	[73]	1	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5	NC	NC
7	[75]	1	-	120	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	NC	NC

n_{is}, the number of incident sites; d_{is} and t_{is}, day and time of the occurrence of incident sites, respectively; $n_{c,is}$, number of casualties at incident sites; n_{as}, number of ambulance stations; $n^{pa}_{er,as}$ and $n^{SA}_{ev,as}$, number of paramedics and standard ambulances located at ambulance stations, respectively; $n^{MERIT}_{er,as}$ and $n^{HART}_{ev,as}$, number of Medical Emergency Response Incident Team (MERIT) and Hazardous Area Response Team (HART) responders and ambulances located at ambulance stations, respectively; $n^{MERIT}_{er,as}$ and $n^{MERIT}_{ev,as}$, number of MERIT and HART responders and ambulances located at ambulance stations, respectively; n_{fs}, number of fire and rescue stations; $n^{FAR}_{er,fs}$ and $n^{FE}_{ev,fs}$, number of Fire and Rescue (FAR) responders and fire engines located at fire and rescue stations, respectively; $n^{SAR}_{er,fs}$ and $n^{ISV}_{ev,fs}$, number of Search and Rescue (SAR) responders and incident support vehicles located at fire and rescue stations, respectively; n_{er} and n_{ev}, number of emergency responders and vehicles, respectively; n_h, number of hospitals; -; the value of a parameter was not provided or was not considered; modified model, the modified version of the developed decision support model to coordinate the response of emergency service resources to MCIs; green cell, the developed decision support model results in an improved when compared to the original model. NC, the experiment has not been considered due to missing information.

Step 2 identifies the experiments that can be applied using the decision support model presented in this thesis. In order to simulate the response from the existing experiments presented in Table 9.2 using a modified version of the decision support model, the number of incident sites, casualties, and emergency vehicles and/or responders must be specified. These parameters are essential to generate and simulate an emergency response plan because the decision support model cannot be applied if any of these values are missing. Thus, in the validation process using the calibration technique, experiments 1, 2.1 and 2.2 in Table 9.2 relate specifically to two models, optimisation models for use in an MCI response [65] and the response model implemented following an MCI [64]. These two models were selected, and their associated experiments were applied using the developed decision support model in this thesis, as all the required information to execute the developed model was included in their existing experiments. However, the remaining experiments, 3 to 7 (Table 9.2), were excluded as they lacked essential values. For example, experiments 3, 5, and 7 did not include the number of emergency responders or vehicles, and in experiments 4 and 6, the number of casualties was not specified, limiting their application to the developed decision support model in this thesis. Step 3 generates, compares, and discusses results from the experiments determined in Step 2 using the developed decision support model presented in this thesis whilst considering if any subsequent modifications to the decision support model are required. In all experiments, the developed decision support model has been modified to be as functionally close as possible to the model in each experiment under consideration. A limitation of this approach is that any assumptions made regarding missing information may influence the overall results. All measures have been made to ensure that all assumptions align with the experiment under consideration.

In this section, each experiment is discussed individually, and a discussion is provided on the process of modifying the developed decision support model, including a rationale for all assumptions. Finally, a discussion is provided regarding the results obtained using the modified developed decision support model based on the replications of experiments (i.e., 50 replications) when compared to the findings generated by the original model associated with the experiment under consideration.

Experiment 1

Key information for experiment 1 is presented in Table 9.2 and is associated with the optimisation model for use in an MCI response presented by Wilson et al. [65]. In experiment 1, central London was considered as the MCI-affected area. In the MCI-affected area, three incident sites and hospitals were specified; however, no specific locations were described. A total of 36 emergency responders were included, specifically, Search and Rescue (SAR), Hazardous Area Response Team (HART), and Medical Emergency Response Incident Team (MERIT); however, site-specific locations for emergency responders were not included. Although specific numbers were not specified, standard ambulances were allocated at all three hospitals and designated to transport casualties to their allocated hospitals. At each incident site, 50% of the casualties allocated to the incident site were assumed to be trapped and required assistance to be rescued. In a similar manner to those previously described, the number of casualties located at each incident site was not specified.

The optimisation model applied to experiment 1 was aimed at simulating emergency responses to multiple man-made incident sites in an attempt to minimise the fatalities. In the optimisation model, casualties at risk of losing their lives were increased if they were trapped at the incident site; however, once freed, no further risk of losing their lives was included. These findings demonstrate the quick arrival of emergency responders at the incident site to free those casualties that are trapped is essential to minimising fatalities.

In this section, the process of modifying the developed decision support model presented in this thesis in order to be as functionally close as possible to the optimisation model presented by Wilson et al. [65] in experiment 1 is discussed. The assumptions for any missing parameters are highlighted, and the rationale behind each assumption is discussed. Finally, the results generated from experiment 1 using the modified model are presented and discussed in comparison with those of the original model (the optimisation model).

Modifying the developed decision support model to simulate the response to an MCI using experiment 1.

The primary aim of the model presented by Wilson et al. [65] was to minimise the number of fatalities in casualties trapped at the incident sites. Thus, the objective function defined by Wilson et al. [65], designed to incorporate the sum probabilities of fatalities prior to being released at the incident site, has been used in the modified version of the decision support model presented in this thesis to evaluate the optimised post-PDA response plan. The model developed by Wilson et al. [65] did not account for the creation of a PDA response plan. Therefore, the creation and implementation of a PDA response plan were ignored in the modified version of the decision support model presented in this thesis. The model developed by Wilson et al. [65] identified that the time spent travelling between any two locations was defined using a built-in function. This built-in function, which has been included in the modification of the decision support model developed in this thesis, is able to generate an estimated median travel time in minutes that is dependent on the distance between the two selected locations. The application of this function generated an unrealistic travel time. Furthermore, in contrast to the decision support model developed here, where standard ambulances were initially located at ambulance stations, Wilson et al. [65] identified that standard ambulances were initially located at hospitals.

In terms of modelling casualties, Wilson et al. [65] did not account for the severity of health conditions in their model. Therefore, to ensure a direct comparison in the decision support model developed in this thesis, the health profiles of casualties described in Chapter 7 (Section 7.7.1) were excluded. However, in accordance with Wilson et al. [65], two specific parameters reflecting a casualty's health classification and whether or not the casualty was trapped at the incident site were included. To account for the deterioration in casualties' health during the response to MCIs, Wilson et al. [65] implemented a Markov chain model to determine the probability of a trapped casualty dying prior to being released based on (1) the current health classification of that casualty and (2) the expected time the casualty would need to wait for before being released moved to the casualty clearing station (CCS) at an incident site. Note that in the work of Wilson et al. [65], the Markov chain model was only applied if at least one trapped casualty was yet to be released, and no deterioration in the casualty's health was considered following release. However, no improvement in the casualty's health was considered in the work of Wilson et al. [65]. Consequently, the dynamic approach in the developed decision support model in this thesis that simulated the changes in the health of casualties, discussed in Chapter 6 (Sections 6.4.2), was excluded. Instead, the Markov chain model was incorporated into the modified version of the developed decision support model in alignment with previous research [65].

In terms of tasks associated with casualties, three tasks were considered in the model presented by Wilson et al. [65], namely releasing a trapped casualty at an incident site, administering on-site treatment to casualties at incident sites, and transferring casualties to their allocated hospitals, which is in contrast to the ten tasks associated with casualties considered in the decision support model, discussed in Chapter 7 (Section 7.7.2). Therefore, to align with the optimisation model, the developed decision support model was modified to only include the three tasks described by Wilson et al. [65] when accounting for tasks associated with casualties. Finally, for the emergency responders in the model presented by Wilson et al. [65], all emergency responders were assumed to possess the same degree of expertise and were able to complete similar tasks, contrasting the approach used in the developed decision support model in this thesis. Therefore, the decision support model was modified to ensure emergency responders all had the same level of expertise. Consequently, the neighbourhood structures associated with the neighbourhood search algorithm discussed in Chapter 8 (Section 8.1.3) were modified to ensure that all emergency responders were able to perform any tasks associated required at incident sites.

Assumptions associated with the missing values.

In experiment 1, there was a variety of missing information. The specific locations of incident sites and hospitals in the MCI-affected area were not included in the study by Wilson et al. [65]. However, the authors do include a map of the road network of central London with these locations included. Therefore, the hospital locations were assumed as close to their markings on the road network in the modified version of the decision support model developed in this thesis. Furthermore, despite identifying that there were 210 casualties included in the simulations, there were no details relating to casualties' health classification or if casualties were allocated equally or unequally across the three sites [3]. Therefore, the number of casualties has been modified to 210, with 70 casualties initially located at each of the three incident sites, including 24 immediate casualties, 23 urgent casualties, and 23 delayed casualties in the modified version of the decision support model in this thesis.

Wilson et al. [65] did not identify any specifics relating to the skill set and knowledge of emergency responders, their distribution, or their initial locations. The decision support model developed in this thesis has subsequently been modified to distribute emergency responders equally across the three incident sites (4 SAR, 4 MERIT, and 4 HART), with all emergency responders available at incident sites when the MCI event occurred. In addition, Wilson et al. [3] did not specify the duration of tasks required. To ensure a direct comparison, the durations of the same tasks defined and discussed in Chapter 7 (Section 7.7.3) have been considered. Finally, the number of standard ambulances, which has been shown to be important in response time, was not included in the work of Wilson et al. [65]. However, the number of standard ambulances assumed would not affect the objective function, which is associated with the sum of probabilities of fatalities among trapped casualties. Therefore, the number of standard ambulances in the modified version of the decision support model has been assumed to be the same as the number of emergency responders defined in the work of Wilson et al. [3] (36 standard ambulances).

Results summary

When comparing the results in experiment 1 generated by the optimisation model presented in the work of Wilson et al. [65], the modified decision support model differed by only 1.41%: 61.3 and 60.5 minutes, respectively (Table 9.2, experiment 1). Interestingly, modifying the decision support model results in a decrease in the sum probabilities of fatalities among trapped casualties, which may in part be due to the assumptions made regarding the distribution of casualties, the initial location of emergency responders, duration of tasks associated with casualties, and the number of emergency responders of each type. However, the ability of the modified decision support model developed in this thesis to improve the sum probabilities of fatalities among trapped casualties provides evidence that the decisional support model is valid and robust when compared with the published optimisation model [65]. Furthermore, the optimisation-based algorithms presented in this thesis in allocating emergency responders to casualties as quickly as possible, giving priority to immediate casualties at risk of losing their lives, provides further validation of the decision support model.

Experiment 2

Experiments 2.1 and 2.2 relate to the work of Repoussis et al. [64], as specified in Table 9.2. The model developed by Repoussis et al. [64] in experiments 2.1 and 2.2 were defined to examine the effect that increasing the number of casualties has on the time from the onset of an incident to the time the final casualty arrives at their allocated hospital, defined as makespan [64].

Modifying the developed decision support model to simulate the response to an MCI using experiment 2.

The model presented by Repoussis et al. [64] is a static model, where all parameters defined at the onset of the incident and implementation of the model remained constant until the incident had been completed. This is in contrast to the dynamic design of the developed decision support model presented in this thesis, which replicates the complexities of an MCI as the events develop. Therefore, to directly compare the developed decision support model with the published model of Repoussis et al. [64], all aspects that contributed to the dynamic nature of the decision support model were excluded, including 1) the modifications to the number of casualties as a result of the PDA response, 2) the dynamic nature of casualties' health, 3) the occurrence of new incident sites, 4) completion of the response to an incident site while the response to other incident sites remains ongoing and requires the reallocation of emergency responders from the completed incident sites, and 5) the changes in the speed of the emergency vehicles based on the time of the day as the response unfolds (Chapter 6, Sections 6.4.1-6.4.4). Furthermore, the model developed by Repoussis et al. [65] did not account for the creation of a PDA response plan. Therefore, the creation and implementation of a PDA response plan were ignored in the modified version of the decision support model presented in this thesis.

In accordance with the work of Repoussis et al. [64], the road network in the modified decision support model and the use of only standard ambulances as the emergency vehicle type included has been tuned to account for predetermined travel times between the incident site and hospitals. The model defined by Repoussis et al. [64] only considered one task associated with casualties located at a single incident site, which is the transportation of casualties to hospitals. This is in contrast to the developed decision support model presented in this thesis, which considers ten tasks associated with casualties described in this thesis (Chapter 7, Section 7.7.2). In the modified decision support model, only one task, namely transporting casualties to the assigned hospitals, was considered.

In the developed decision support model described in this thesis, the severity of casualties was accounted for. This is in contrast to the work of Repoussis et al. [64], which assumed that all casualties had the same health classification, meaning this is unlikely to be the case in a real MCI. Nevertheless, the modelling of the health profiles of casualties addressed in Chapter 7 (Section 7.7.1) was excluded from the modified decision support model. In the model defined by Repoussis et al. [64], standard ambulances were designed to make just two trips each hour, and each hospital was modelled to receive and treat four casualties per hour. However, in the modified decision support model, hospital treatment was excluded because the model has been designed to coordinate the emergency service resources in the pre-hospital response to MCIs, whereas hospital treatment falls outside the model's scope. Thus, the makespan calculated by the tuned model did not account for the time required to treat casualties at the assigned hospitals. Finally, the objective function described by Repoussis et al. [64] and used to calculate the makespan has been incorporated into the modified decision support model in place of the objective functions presented in Chapter 8 (Section 8.3).

Assumptions made within the tuned model

Due to the lack of information regarding experiments 2.1 and 2.2 (Table 9.2), it was necessary to make a number of assumptions. In Repoussis et al. [64], ten hospitals were listed in the MCI-affected area; however, only four were considered to be able to receive casualties, with the remaining six hospitals assumed to be incapable due to a lack of capacity. However, there were no specific details in experiments 2.1 and 2.2 (Table 9.2) relating to which of the four hospitals were chosen. Therefore, the first four hospitals listed by Repoussis et al. [64] were included in the modified decision support model, namely New York (NY) Downtown Hospital, Bellevue Hospital Center, Beth Israel Medical Center, and NY Eye and Ear. Finally, Repoussis et al. [64] allocated four standard ambulances to transport casualties from each incident site to their allocated hospital in experiments 2.1 and 2.2 (Table 9.2); however, the initial location of the standard ambulances was not defined. Consequently, in the modified decision support model, all four standard ambulances have been assumed to be initially located at the incident site when the incident occurred.

Results summary

The ability to reduce the makespan, thus improving completion times of the MCI response, has the implication for improving casualties' health outcomes and reducing mortality. When comparing the modified decision support model with the model presented by Repoussis et al. [64], there was a difference of 30.10%: with a makespan time of 73 vs. 99 minutes, respectively (Table 9.2, experiment 2.1). In addition, when the number of casualties was doubled (Table 9.2, experiment 2.2), the makespan of the model reported by Repoussis et al. [64] differed by 24%, with times of 140 vs. 178 minutes, respectively. Furthermore, in experiment 2.2, where the number of casualties was doubled, the makespan presented using the model presented by Repoussis et al. [64] increased by 80%, but the modified decision support model increased by only 63%. The discrepancies between the model presented by Repoussis et al. [64] and the modified decision support model may be primarily due to the assumption of the hospitals included in the modified model. If the hospitals in the modified model were incorrect or closer to the incident site, then this may account for the shorter makespan. However, these findings do provide evidence that the decision support model utilised in this thesis is a valid approach, evident by the similarities in both experiments with respect to the increase in casualties.

9.2.3 Summary of validating the developed decision support model

In Sections 9.2.1 and 9.2.2, the findings generated by the decision support model to coordinate the response of emergency service resources to MCIs, discussed in Chapters 6 to 8, have been validated using grounding and calibration techniques. In section 9.2.1, the findings generated from the developed decision support model using four experiments have been assessed against the findings generated by previously published models (reviewed in Chapter 3) using the grounding technique. The results of the validation process using the grounding technique illustrated the ability of the developed model to generate comparable findings with those of published models. Furthermore, Section 9.2.1 provided evidence that the developed decision support model presented in this thesis is able to behave in a similar manner to previously published models.

In Section 9.2.2, the decision support model developed in this thesis was modified with some assumptions to functionally match previously published models [64, 65] to replicate experiments from them. These two models were chosen as all the required information to execute the developed model was included in their existing experiments. The results of the modified model and other models have been discussed and presented in Table 9.2. The results demonstrate that the modified model was able to obtain better or similar results to those generated using published models in all three experiments. The results presented in this chapter provide further evidence that the developed decision support model is able to provide valid results relating to the coordination of emergency service resources to MCIs.

9.3 Summary

This chapter , in conjunction with Chapters 6, 7, and 8, fully addressed **RQ2**. it has discussed two validation techniques, namely grounding and calibration techniques. The grounding technique has been used to determine the ability of the developed decision support model discussed in Chapters 6 to 8 to generate similar observations to those models reviewed in Chapter 3. Furthermore, the calibration technique has been used to demonstrate the ability of the developed decision support model with some modifications to generate results that are comparable to those of existing models when applying the same existing experiments. In the next chapter, definitions of the case study areas will be provided, and a number of experiments will be discussed.

Chapter 10. Case study areas and experiments

10.1 Introduction

This chapter defines two case study areas in which Mass Casualty Incident (MCI) environments are modelled, namely central London and Birmingham city centre. Furthermore, a number of experiments are defined to simulate the coordinated emergency response to the MCIs modelled in these two UK cities. The decision support model to coordinate the response of emergency service resources to MCIs discussed in Chapters 6 to 8 is used to generate the results from these experiments. Appendix C presents an overview of the set-up of the two case study areas, including the definition of an MCI-affected area, the specification of the key locations, the extraction of the road network of the MCI-affected area, and the visualisation of an MCI-affected area. This chapter aims to discuss **RQ3**, which was initially introduced in Chapter 1 and is restated below.

How can such modelling assist with multiple near-simultaneous MCIs?

In Section 10.2, two case study areas in two cities in the UK are discussed. In Section 10.3, a comprehensive definition of all the MCI environment parameter values (discussed in Chapter 7) and explanations for defining these parameters are provided. Consequently, Section 10.4 presents a number of distinct experiments in terms of the combinations of the defined parameters.

10.2 Case study areas

Two case study areas in two cities in the UK, central London and Birmingham city centre, were considered to simulate the coordinated emergency response to multiple MCIs. Each case study area is unique with regard to the city's layout, road network, and the numbers and key locations of incident sites, ambulance stations, fire and rescue stations, and hospitals. The MCI-affected area in each case study area was defined based on the density of ambulance stations, fire and rescue stations, and hospitals in 100 km^2 of that area, which is the size limit of an area offered by DigiMap per a single request [89]. In other words, an MCI-affected area was defined as occupying a position that covered the locations of all hypothetical incident sites and maximised the number of ambulance stations, fire and rescue stations, and hospitals located in 100 km^2 in that area. Note that ambulance stations, fire and rescue stations, or hospitals located outside the defined MCI-affected area would not be involved in response to MCIs, as discussed in Section 7.1 (Chapter 7).

Hospitals selected in the defined MCI-affected area must have Major Trauma Centres in which acute, surgical, and rehabilitative services are available for casualties in all health classifications and/or an Emergency and Accident Department [2]. This ensured that casualties would be delivered to hospitals where proper lifesaving interventions could be provided. However, the aim of this research is to coordinate the pre-hospital response of emergency services' resources to multiple MCIs. Therefore, the treatment services provided at hospitals were not taken into consideration since these relate to the post-hospital response, which is outside the scope of this research.

Four sites were assumed to be associated with hypothetical incidents located in each case study area, which is the maximum number of incident sites that occurred in an important MCI terrorism event in recent times in the UK (the 2005 London bombings) [128]. The locations of the hypothetical incidents for each case study area were chosen in popular locations that are often likely to be crowded, including parks, railway or bus stations, or stadiums.

10.2.1 Central London

Central London is the first case study area considered and was chosen due to it being a densely populated area in addition to having a significant number of emergency resources and hospitals. Furthermore, it has been subjected in recent times to a number of MCI 'terrorism' events, including the 2005 London bombings.

A hypothetical incident was assumed to occur at the British Museum (BM), which is a public museum in the Bloomsbury area dedicated to human history, art, and culture. Another incident was assumed to occur at the Embankment underground station (EUS), a London Underground station on the Circle, District, Northern and Bakerloo lines in Westminster. A further hypothetical incident was assumed to occur at Hyde Park (HP), one of the eight Royal Parks in London, which hosts gardens, historic sites, and outdoor activities. An additional hypothetical incident site was assumed to occur at Oxford Circus (OC), a London Underground station on the Central, Bakerloo, and Victoria lines, located at the junction of Regent and

Oxford Street. The key locations considered in the affected geographical area of central London, in addition to the hypothetical incident sites, are listed below.

- Seven ambulance stations: Bloomsbury ambulance station (BAS), Fulham ambulance station (FAS), London ambulance station (LAS), Oval ambulance station (OAS), St John's Wood ambulance station (SJWAS), Waterloo ambulance station (WAAS), and Westminster ambulance station (WEAS).
- Seven fire and rescue stations: Dowgate fire station (DFS), Euston fire station (EFS), Fulham fire station (FFS), Old Kent Road fire station (OKRFS), Paddington fire station (PAFS), Peckham fire station (PEFS), and Soho fire station (SFS).
- Six hospitals: Chelsea and Westminster Hospital (CWH), Guy's Hospital (GH), King's College Hospital (KCH), St Mary's Hospital (SMH), Royal London Hospital (RLH), and University College Hospital (UCH).

The locations of ambulance stations, fire and rescue stations, hospitals, and the hypothetical incident sites (green, black, red circles, and blue, respectively) with the road network denoted by grey lines in the defined MCI-affected geographical area of central London are shown in Figure 10.1. The area can be identified from the map's scale in which the top right and bottom left easting and northing coordinates are 535624.8, 184321 and 523647.7, 176081.6, respectively.

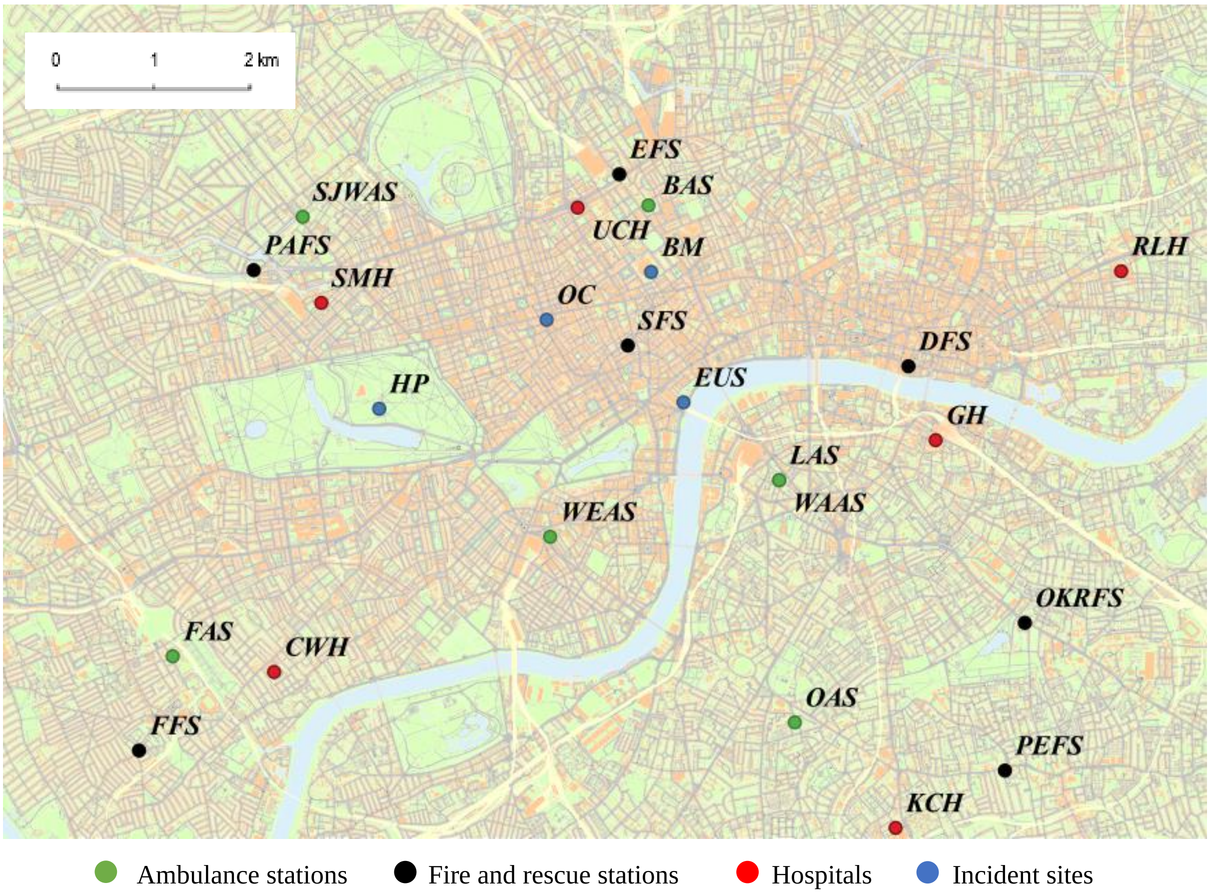


Figure 10.1: Topography layer of the defined MCI-affected geographical area of central London.

10.2.2 Birmingham city centre

Birmingham was selected for the second case study area due to its status as the UK's second most populous city, and so the choice of this area enables the consideration of the emergency response in a different city layout and locations of emergency service resources, including ambulance and fire and rescue stations and hospitals. Four hypothetical incidents were assumed to occur at four locations in Birmingham city centre, namely: Birmingham Arena (BA), Birmingham New Street (BNS), Cannon Hill Park (CHP), and Sunset Park (SP). The BA is an indoor entertainment centre and sporting venue which has been the largest indoor arena in the UK since it was opened. BNS is the main railway station located in the centre of Birmingham. The CHP is a county park located in south Birmingham where various indoor and outdoor activities take place. The SP was designed as part of a local regeneration project and is used as an outdoor events space. The following key locations, in addition to the four hypothetical incident sites, in the affected geographical area of Birmingham, were considered.

- Two ambulance stations: West Bromwich ambulance station (WBAS) and West Midlands ambulance station (WMAS).
- Four fire and rescue stations: Billesley fire station (BFS), Hay Mills fire station (HMFS), Highgate fire station (HFS), and west Bromwich fire station (WBFS).
- Two hospitals: Birmingham City Hospital (BCH) and Queen Elizabeth Hospital (QEH).

Figure 9.2 presents the locations of the ambulance and fire and rescue stations, hospitals, and hypothetical incident sites (green, black, red, and blue circles, respectively) with the road network denoted by grey lines in the defined MCI-affected geographical area of Birmingham. The area can be identified from the map's scale in which the top right and bottom left easting and northing coordinates are 409099, 289887 and 395739, 282417, respectively.

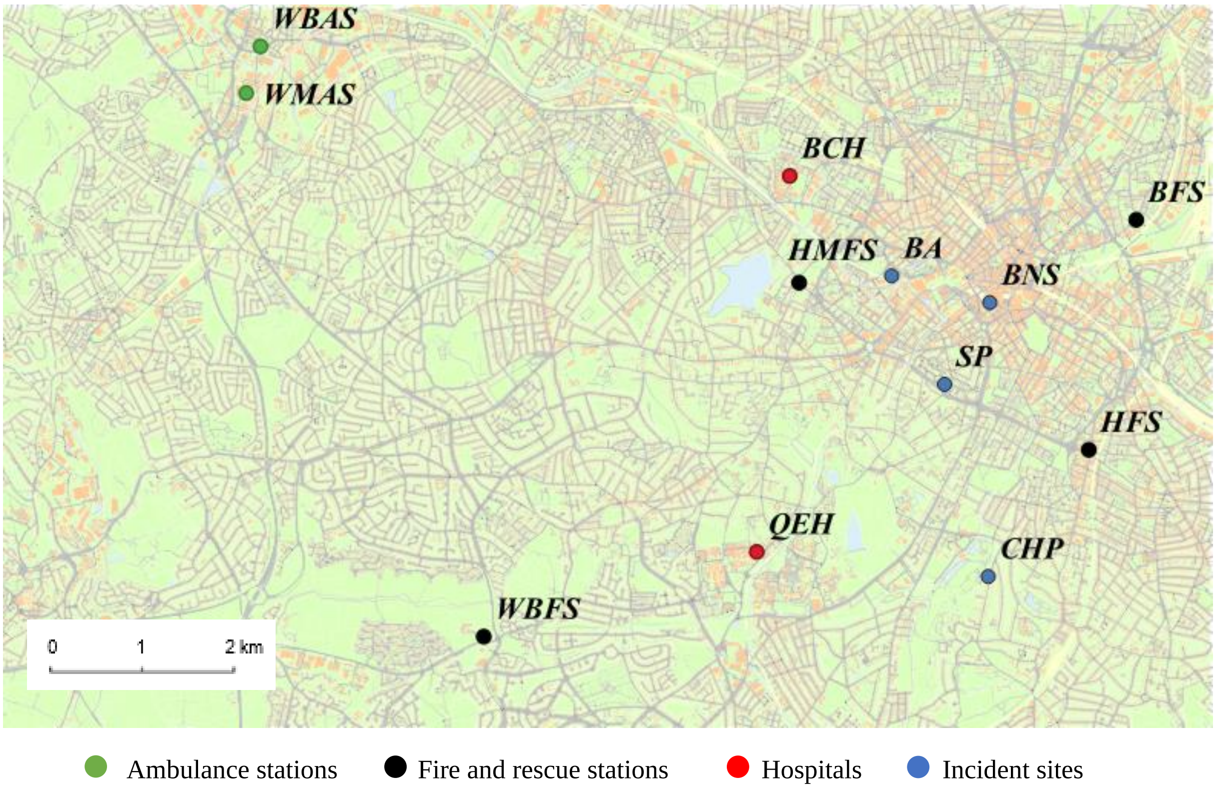


Figure 10.2: Topography layer of the defined MCI-affected geographical area of Birmingham city centre.

10.3 Defining parameter values

This section provides a comprehensive definition of all parameter values based on the literature. Defining parameter values prior to designing the experiments enables specifying the number of distinct experiments to be carried out, and it supports understanding the defined experiments. These parameters include the definition of key locations in a case study area, the day and time of each hypothetical incident, the distribution of casualties between incident sites and their initial health profiles, and the distribution of emergency responders and vehicles between ambulance and fire and rescue stations.

10.3.1 Key locations in a case study area

The key locations in a case study area include incident sites, ambulance and fire and rescue stations, and hospitals. In each case study area, four incidents (n_{is}) were selected to occur in four popular locations (l_{is}), as discussed in Sections 10.2.1 and 10.2.2 for the case study area of central London and Birmingham city centre, respectively. Furthermore, the number and locations of ambulance stations (n_{as}, l_{as}), fire and rescue stations (n_{fs}, l_{fs}), and hospitals (n_h, l_h) are as defined for central London and Birmingham city centre (Sections 10.2.1 and 10.2.2, respectively). In the case study area of central London, four incident sites, seven ambulance stations, seven fire and rescue stations, and six hospitals were considered, and their locations were specified in Figure 10.1. In the case study area of Birmingham city centre, four incident sites, two ambulance stations, four fire and rescue stations, and two hospitals were considered, and their locations were specified in Figure 9.2.

10.3.2 Hypothetical incident occurrence: day and time

The MCI event is assumed to be on Saturday and begins at 13:00 pm Greenwich Mean Time (GMT), accounting for the fact that Saturdays in the UK are likely to be busy based on previously published statistics [129]. Two scenarios represented the occurrence times of incident sites are defined.

- Initially, two incidents will occur at 13:00pm GMT, and two subsequent incidents will occur at 13:25:00 and 13:25:20pm GMT.
- One hypothetical incident is assumed to occur at 13:00pm GMT, and then 30 minutes elapse between the occurrence of each subsequent incident (three subsequent incidents).

The purposes of defining different initiation times for the hypothetical incidents are to:

- examine the ability of the developed decision support model to handle different scenarios in relation to the occurrence times of incidents;
- investigate the effect of occurrence times of incidents on the response to MCIs.

10.3.3 Casualties

In previous literature, a maximum of 150 casualties have been utilised across an incident site [72, 75], making it difficult to distribute casualties evenly. In these experiments, therefore, 200 casualties were used that were evenly distributed across all four incident sites. When defining experiments, both equal and unequal distribution of casualties among the four incident sites ($n_{C_{is}}$) in a case study area necessary to be considered. This is to enable investigation of the effects of the initial distribution of casualties on the allocation of emergency responders to the tasks associated with casualties at incident sites and the allocation of casualties to hospitals in each case study area. The distribution of casualties is defined as follows.

- Equal distribution of casualties means that each of the four incident sites in each case study area is allocated the same number of casualties ($n_{C_{is}}$= 50).
- Unequal distribution of casualties means that at each of the four incident sites in each case study is as follows, 40% (80), 30% (60), 20% (40), and 10% (20), respectively. The distributions of casualties described above are similar to previously reported experiments in the work of Repoussis et al. [64].

At each of the four incident sites in each case study area, 50% of casualties were assumed to be trapped ($n_{c_{is}^{t}}$), as previously described in the work of Wilson et al. [65]. A trapped casualty at an incident site refers to an individual who is incapable of moving or escaping due to being trapped under debris or any other situation that restricts their mobility. Furthermore, casualties at each incident site were allocated a severity of the injury as follows: severe (25%), moderate (25%), and mild (50%). These assumptions correspond to those previously described in the literature [96], where casualties were classified as immediate (25%), urgent (25%), and delayed (50%), respectively.

10.3.4 Emergency responders and vehicle responders

The total number of emergency responders considered at all stations (n_{er}) was assumed to be 140, where 70 emergency responders were assumed to be initially located at all ambulance stations, and the same number of emergency responders were assumed to be initially located at all fire and rescue stations. This assumption aligns with the previous work of Rezapour et al. [61], where 70 emergency responders (search and rescue responders (SAR) and medical units) were considered in response to an MCI; however, the key difference to the definitions described in this chapter is that the initial locations of these responders were not specified.

At each type of station, emergency responders were assumed to have a standard (60%) and an advanced degree of expertise (40%) in performing the assigned tasks. The emergency responders with a standard degree of expertise were paramedics ($n_{er,as}^{PA}$=42) and fire and rescue responders (FAR) ($n_{er,fs}^{FAR}$=42) distributed among ambulance and fire and rescue stations, respectively. Emergency responders with an advanced degree of expertise were Hazardous Area Response Team (HART) ($n_{er,as}^{HART}$=14) and Medical Emergency Response Incident Team (MERIT) ($n_{er,as}^{MERIT}$=14) distributed among ambulance stations, and SAR ($n_{er,fs}^{SAR}$=28). A higher percentage was allocated to emergency responders with a standard degree of expertise when compared to those with an advanced degree of expertise based on previously published statistics [130].

The experiments with an unequal distribution of emergency responders allow comparison with equally distributed experiments. This is to understand the effect of the initial location of emergency responders on the allocation of tasks associated with casualties. The distribution of emergency responders is defined as follows.

- Equal distribution of emergency responders among ambulance stations in a case study area indicates that each ambulance station was allocated the same number of emergency responders of each type, namely HART, MERIT, and paramedic responders. Furthermore, the same applies to emergency responders of each type, namely FAR and SAR, located at each fire and rescue station. The number of emergency responders initially located at each station is dependent on the number of ambulance and fire and rescue stations specified for each case study area, as defined in Section 9.2.
- Unequal distribution of emergency responders among ambulance and fire and rescue stations in a case study area indicates that 50% of the station locations in a case study area had the highest number of emergency responders and vehicles, similar to previously described experiments [64, 66]. The number of emergency responders located at each station is dependent on the number of ambulance and fire and rescue stations specified for each case study area, as defined in Section 9.2.

Standard ambulances ($n_{ev,as}^{SA}$=50) are defined in accordance with the experiment previously described in the work of Repoussis et al. [64]. Standard ambulances were distributed among ambulance stations in a case study area and are used to transport paramedics to incident sites and, subsequently, casualties to hospitals. The number of emergency vehicles of other types, namely HART ambulances ($n_{ev,as}^{HART}$=10), MERIT ambulances ($n_{er,as}^{MERIT}$=10), fire engines ($n_{ev,fs}^{FE}$=20), and incident support vehicles ($n_{ev,fs}^{ISV}$=10), were assumed sufficient to transport up to four emergency responders of the same type (n_{ev}=100), in accordance with previous research [84, 85]. Thus, the distribution of emergency vehicles among ambulance and fire and rescue stations follows the definition of emergency responders among these stations.

The total number of emergency responders (n_{er}=140) and vehicles (n_{ev}=100) is fixed in all experiments, regardless of whether the number of ambulance stations or fire and rescue stations is different between the case study areas. Fixing the number of emergency responders in all experiments allows understanding if the initial location of emergency responders affects the emergency response to MCIs generated for each case study area, similar to the purpose of defining previously reported experiments [64].

10.4 Defining experiments

As previously discussed in Section 9.2 regarding the definition of the parameter values associated with the MCI environment, the timing of hypothetical incidents occurring at four sites, the distribution of casualties among incident sites, and the distribution of emergency responders among fire and rescue stations, can take one of two definitions. Therefore, 2^3 distinct experiments are defined in terms of specific combinations of the definitions of the aforementioned parameter values, given that the other parameters were assigned the same value for all experiments. The 2^3 experiments are applied to two case study areas of central London and Birmingham city centre, leading to 16 (2^3 x 2 = 16) distinct experiments.

Table 10.1 and Table 10.2 provide the definitions for all 16 experiments used throughout the case study areas of central London (experiments E1.L to E8.L) and Birmingham city centre (experiments E1.B to E8.B), respectively. Table 10.1 and Table 10.2 include the number (n_{is}) and location of the incident sites (l_{is}), day of the incidents occurred (d_{is}), and time of the incidents occurred (t_{is}). Furthermore, they include the number of all casualties at incident sites ($n_{c,is}$), the percentage of trapped casualties ($n_{c_{is}^{t}}$), and the percentage of casualties of each severity level of injury. Moreover, they specify the number (n_{as}) and location of ambulance stations (l_{as}), the number of paramedics ($n_{er,as}^{pa}$), standard ambulances ($n_{ev,as}^{SA}$), HART responders ($n_{er,as}^{HART}$), HART ambulances ($n_{ev,as}^{HART}$), MERIT responders ($n_{er,as}^{MERIT}$) and MERIT ambulances ($n_{ev,as}^{MERIT}$) initially located at ambulance stations. In addition, the number (n_{fs}) and location of fire and rescue station (l_{fs}), the number of FAR responders ($n_{er,fs}^{FAR}$), fire engines ($n_{ev,fs}^{FE}$), SAR responders ($n_{er,fs}^{SAR}$), and incident support vehicles ($n_{ev,fs}^{ISV}$) initially located at fire and rescue stations, the number of emergency responders (n_{er}) and vehicles (n_{ev}), and the number (n_h) and location of hospitals (l_h) are indicated in Table 10.1 and Table 10.2.

Table 10.1: Design of experiments associated with the case study area of central London.

E	Incident sites			Casualties					Ambulance stations								Fire and rescue stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is} and t_{is}	$n_{c,is}$	$n_{c^t_{is}}$ (%)	Health profile (%)			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n^{pa}_{er,as}$	$n^{SA}_{ev,as}$	$n^{HART}_{er,as}$	$n^{HART}_{ev,as}$	$n^{MERIT}_{er,as}$	$n^{MERIT}_{ev,as}$			$n^{FAR}_{er,fs}$	$n^{FE}_{ev,fs}$	$n^{SAR}_{er,fs}$	$n^{ISV}_{ev,fs}$			n_h	l_h
E1.L	4	BM	Sun 13:00:00	50	50	25	25	50	7	BAS	6	7	2	2	2	2	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	2	2	2		EFS	6	3	4	2				GH
		EUS	Sun 13:00:00	50	50	25	25	50		LAS	6	7	2	2	2	2		FFS	6	3	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	3	4	1				SMH
		HP	Sun 13:25:00	50	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	3	4	1				RLH
										WAAS	6	7	2	1	2	1		PEFS	6	3	4	1				UCH
		OC	Sun 13:25:20	50	50	25	25	50		WEAS	6	8	2	1	2	1		SFS	6	2	4	1				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		
E2.L	4	BM	Sun 13:00:00	80	50	25	25	50	7	BAS	6	7	2	2	2	2	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	2	2	2		EFS	6	3	4	2				GH
		EUS	Sun 13:00:00	60	50	25	25	50		LAS	6	7	2	2	2	2		FFS	6	3	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	3	4	1				SMH
		HP	Sun 13:25:00	40	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	3	4	1				RLH
										WAAS	6	7	2	1	2	1		PEFS	6	3	4	1				UCH
		OC	Sun 13:25:20	20	50	25	25	50		WEAS	6	8	2	1	2	1		SFS	6	2	4	1				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		

E, experiment; BM, British Museum; EUS, Embankment underground; HP, Hyde Park; OC, Oxford Circus; BAS, Bloomsbury ambulance station; FAS, Fulham ambulance station; LAS, London ambulance station; OAS, Oval ambulance station; SJWAS, St John’s Wood ambulance station; WAAS, Waterloo ambulance station; WEAS, Westminster ambulance station; DFS, Dowgate fire station; EFS, Euston fire station; FFS, Fulham fire station; OKRFS, Old Kent Road fire station; PAFS, Paddington fire station; PEFS, Peckham fire station; SFS, Soho fire station, CWH, Chelsea and Westminster Hospital; GH, Guy’s Hospital; KCH, King’s College Hospital, SMH, St Mary’s Hospital; RLH, Royal London Hospital; UCH, University College Hospital; n_{is}, the number of incident sites; l_{is}, location of incident sites; d_{is} and t_{is}, day and time of the occurrence of incident sites, respectively; $n_{c,is}$, number of casualties at incident sites; $n_{c^t_{is}}$, number of trapped casualties at incident sites; n_{as}, number of ambulance stations; l_{as}, location of ambulance stations; $n^{pa}_{er,as}$ and $n^{SA}_{ev,as}$, number of paramedics and standard ambulances located at ambulance stations, respectively; $n^{HART}_{er,as}$ and $n^{HART}_{ev,as}$, number of Hazardous Area Response Team (HART) responders and ambulances located at ambulance stations, respectively; $n^{MERIT}_{er,as}$ and $n^{MERIT}_{ev,as}$, number of Medical Emergency Response Incident Team (MERIT) responders and ambulances located at ambulance stations, respectively; n_{fs}, number of fire and rescue stations; l_{fs}, location of fire and rescue stations; $n^{FAR}_{er,fs}$ and $n^{FE}_{ev,fs}$, number of Fire and Rescue (FAR) and fire engines located at fire and rescue stations, respectively; $n^{SAR}_{er,fs}$ and $n^{ISV}_{ev,fs}$, number of Search and Rescue (SAR) responders and incident support vehicles located at fire and rescue stations, respectively; n_{er} and n_{ev}, number of emergency responders and vehicles, respectively; n_h, number of hospitals; l_h, location of hospitals.

Table 10.1: Design of experiments associated with the case study area of central London (cont.)

E	Incident sites			Casualties					Ambulance stations								Fire and rescue stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is} and t_{is}	$n_{c,is}$	$n_{c_{is}^t}$ (%)	Health profile (%)			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$			$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
E3.L	4	BM	Sun 13:00:00	50	50	25	25	50	7	BAS	8	8	3	2	3	2	7	DFS	7	4	7	2			6	CWH
										FAS	8	7	3	2	3	2		EFS	7	4	7	2				GH
		EUS	Sun 13:00:00	50	50	25	25	50		LAS	8	7	3	2	3	2		FFS	8	4	6	2				KCH
										OAS	3	7	2	1	2	1		OKRFS	5	2	2	1				SMH
		HP	Sun 13:25:00	50	50	25	25	50		SJWAS	5	7	1	1	1	1		PAFS	5	2	2	1				RLH
										WAAS	5	7	1	1	1	1		PEFS	5	2	2	1				UCH
		OC	Sun 13:25:20	50	50	25	25	50		WEAS	5	7	1	1	1	1		SFS	5	2	2	1				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		
E4.L	4	BM	Sun 13:00:00	80	50	25	25	50	7	BAS	8	8	3	2	3	2	7	DFS	7	4	7	2			6	CWH
										FAS	8	7	3	2	3	2		EFS	7	4	7	2				GH
		EUS	Sun 13:00:00	60	50	25	25	50		LAS	8	7	3	2	3	2		FFS	8	4	6	2				KCH
										OAS	3	7	2	1	2	1		OKRFS	5	2	2	1				SMH
		HP	Sun 13:25:00	40	50	25	25	50		SJWAS	5	7	1	1	1	1		PAFS	5	2	2	1				RLH
										WAAS	5	7	1	1	1	1		PEFS	5	2	2	1				UCH
		OC	Sun 13:25:20	20	50	25	25	50		WEAS	5	7	1	1	1	1		SFS	5	2	2	1				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		

Table 10.1: Design of experiments associated with the case study area of central London (cont.)

E	Incident sites			Casualties					Ambulance stations								Fire and rescue stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is} and t_{is}	$n_{c,is}$	$n_{c_{is}^{t}}$ (%)	Health profile (%)			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$			$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
E5.L	4	BM	Sun 13:00:00	50	50	25	25	50	7	BAS	6	7	2	2	2	2	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	2	2	2		EFS	6	3	4	2				GH
		EUS	Sun 13:30:00	50	50	25	25	50		LAS	6	7	2	2	2	2		FFS	6	3	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	3	4	1				SMH
		HP	Sun 14:00:00	50	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	3	4	1				RLH
										WAAS	6	7	2	1	2	1		PEFS	6	3	4	1				UCH
		OC	Sun 14:30:00	50	50	25	25	50		WEAS	6	8	2	1	2	1		SFS	6	2	4	1				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		
E6.L	4	BM	Sun 13:00:00	80	50	25	25	50	7	BAS	6	7	2	2	2	2	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	2	2	2		EFS	6	3	4	2				GH
		EUS	Sun 13:30:00	60	50	25	25	50		LAS	6	7	2	2	2	2		FFS	6	3	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	3	4	1				SMH
		HP	Sun 14:00:00	40	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	3	4	1				RLH
										WAAS	6	7	2	1	2	1		PEFS	6	3	4	1				UCH
		OC	Sun 14:30:00	20	50	25	25	50		WEAS	6	8	2	1	2	1		SFS	6	2	4	1				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		

Table 10.1: Design of experiments associated with the case study area of central London (cont.)

E	Incident sites			Casualties					Ambulance stations								Fire and rescue stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is} and t_{is}	$n_{c,is}$	$n_{c_{is}^{t}}$ (%)	Health profile (%)			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$			$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
E7.L	4	BM	Sun 13:00:00	50	50	25	25	50	7	BAS	8	8	3	2	3	2	7	DFS	7	4	7	2			6	CWH
										FAS	8	7	3	2	3	2		EFS	7	4	7	2				GH
		EUS	Sun 13:30:00	50	50	25	25	50		LAS	8	7	3	2	3	2		FFS	8	4	6	2				KCH
										OAS	3	7	2	1	2	1		OKRFS	5	2	2	1				SMH
		HP	Sun 14:00:00	50	50	25	25	50		SJWAS	5	7	1	1	1	1		PAFS	5	2	2	1				RLH
										WAAS	5	7	1	1	1	1		PEFS	5	2	2	1				UCH
		OC	Sun 14:30:00	50	50	25	25	50		WEAS	5	7	1	1	1	1		SFS	5	2	2	1				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		
E8.L	4	BM	Sun 13:00:00	80	50	25	25	50	7	BAS	8	8	3	2	3	2	7	DFS	7	4	7	2			6	CWH
										FAS	8	7	3	2	3	2		EFS	7	4	7	2				GH
		EUS	Sun 13:30:00	60	50	25	25	50		LAS	8	7	3	2	3	2		FFS	8	4	6	2				KCH
										OAS	3	7	2	1	2	1		OKRFS	5	2	2	1				SMH
		HP	Sun 14:00:00	40	50	25	25	50		SJWAS	5	7	1	1	1	1		PAFS	5	2	2	1				RLH
										WAAS	5	7	1	1	1	1		PEFS	5	2	2	1				UCH
		OC	Sun 14:30:00	20	50	25	25	50		WEAS	5	7	1	1	1	1		SFS	5	2	2	1				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		

Table 10.2: Design of experiments associated with the case study area of Birmingham city centre.

E	Incident sites			Casualties					Ambulance stations								Fire stations						n_{er}	n_{ev}	Hospitals	
						Health profile					Emergency responders and vehicles								Emergency responders and vehicles							
	n_{is}	l_{is}	$d_{is}$and t_{is}	$n_{c,is}$	$n_{c_{is}^t}$ (%)	Severe	moderate	mild	n_{as}	l_{as}	$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$	n_{fs}	l_{fs}	$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
E1.B	4	BA	Sun 13:00:00	50	50	50	50	50	2	WBAS	21	25	7	5	7	5	4	BFS	10	5	7	3			2	BCH
		BNS	Sun 13:00:00	50	50	50	50	50										HMFS	10	5	7	3				
		CHP	Sun 13:25:00	50	50	50	50	50		WMAS	21	25	7	5	7	5		HFS	11	5	7	2				QEH
		SP	Sun 13:25:20	50	50	50	50	50										WBFS	11	5	7	2				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		
E2.B	4	BA	Sun 13:00:00	80	50	50	50	50	2	WBAS	21	25	7	5	7	5	4	BFS	10	5	7	3			2	BCH
		BNS	Sun 13:00:00	60	50	50	50	50										HMFS	10	5	7	3				
		CHP	Sun 13:25:00	40	50	50	50	50		WMAS	21	25	7	5	7	5		HFS	11	5	7	2				QEH
		SP	Sun 13:25:20	20	50	50	50	50										WBFS	11	5	7	2				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		

E, experiment; BA, Birmingham Arena; BNS, Birmingham New Street; CHP, Cannon Hill; SP, Sunset Park; WBAS, West Bromwich ambulance station; WMAS, West Midlands ambulance station; BFS, Billesley fire station; HMFS, Hay Mills fire station; HFS, Highgate fire station; WBFS, west Bromwich fire station; BCH, Birmingham City Hospital; QEH, Queen Elizabeth Hospital;n_{is}, the number of incident sites; l_{is}, location of incident sites; d_{is} and t_{is}, day and time of the occurrence of incident sites, respectively; $n_{c,is}$, number of casualties at incident sites; $n_{c_{is}^t}$, number of trapped casualties at incident sites; n_{as}, number of ambulance stations; l_{as}, location of ambulance stations; $n_{er,as}^{pa}$ and $n_{ev,as}^{SA}$, number of paramedics and standard ambulances located at ambulance stations, respectively; $n_{er,as}^{HART}$ and $n_{ev,as}^{HART}$, number of Hazardous Area Response Team (HART) responders and ambulances located at ambulance stations, respectively; $n_{er,as}^{MERIT}$ and $n_{ev,as}^{MERIT}$, number of Medical Emergency Response Incident Team (MERIT) responders and ambulances located at ambulance stations, respectively; n_{fs}, number of fire and rescue stations; l_{fs}, location of fire and rescue stations; $n_{er,fs}^{FAR}$ and $n_{ev,fs}^{FE}$, number of Fire and Rescue (FAR) and fire engines located at fire and rescue stations, respectively; $n_{er,fs}^{SAR}$ and $n_{ev,fs}^{ISV}$, number of Search and Rescue (SAR) responders and incident support vehicles located at fire and rescue stations, respectively; n_{er} and n_{ev}, number of emergency responders and vehicles, respectively; n_h, number of hospitals; l_h, location of hospitals.

Table 10.2: Design of experiments associated with the case study area of Birmingham city centre (cont.)

E	Incident sites			Casualties					Ambulance stations								Fire stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is}, t_{is}	$n_{c,is}$	$n_{c^t_{is}}$ (%)	Health profile			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n^{pa}_{er,as}$	$n^{SA}_{ev,as}$	$n^{HART}_{er,as}$	$n^{HART}_{ev,as}$	$n^{MERIT}_{er,as}$	$n^{MERIT}_{ev,as}$			$n^{FAR}_{er,fs}$	$n^{FE}_{ev,fs}$	$n^{SAR}_{er,fs}$	$n^{ISV}_{ev,fs}$			n_h	l_h
E3.B	4	BA	Sun 13:00:00	50	50	50	50	50	2	WBAS	24	35	8	6	8	6	4	BFS	12	6	9	3			2	BCH
		BNS	Sun 13:00:00	50	50	50	50	50										HMFS	12	6	9	3				
		CHP	Sun 13:25:00	50	50	50	50	50		WMAS	18	15	6	4	6	4		HFS	8	4	6	2				QEH
		SP	Sun 13:25:20	50	50	50	50	50										WBFS	8	4	6	2				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**40**	**20**	**30**	**10**	**140**	**100**		
E4.B	4	BA	Sun 13:00:00	80	50	50	50	50	2	WBAS	24	35	8	6	8	6	4	BFS	12	6	9	3			2	BCH
		BNS	Sun 13:00:00	60	50	50	50	50										HMFS	12	6	9	3				
		CHP	Sun 13:25:00	40	50	50	50	50		WMAS	18	15	6	4	6	4		HFS	8	4	6	2				QEH
		SP	Sun 13:25:20	20	50	50	50	50										WBFS	8	4	6	2				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**40**	**20**	**30**	**10**	**140**	**100**		

Table 10.2: Design of experiments associated with the case study area of Birmingham city centre (cont.)

E	Incident sites			Casualties					Ambulance stations								Fire stations						n_{er}	n_{ev}	Hospitals	
						Health profile					Emergency responders and vehicles								Emergency responders and vehicles							
	n_{is}	l_{is}	d_{is}, and t_{is}	$n_{c,is}$	$n_{c_{is}^{t}}$ (%)	Severe	moderate	mild	n_{as}	l_{as}	$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$	n_{fs}	l_{fs}	$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
E5.B	4	BA	Sun 13:00:00	50	50	50	50	50	2	WBAS	21	25	7	5	7	5	4	BFS	10	5	7	3			2	BCH
		BNS	Sun 13:30:00	50	50	50	50	50										HMFS	10	5	7	3				
		CHP	Sun 14:00:00	50	50	50	50	50		WMAS	21	25	7	5	7	5		HFS	11	5	7	2				QEH
		SP	Sun 14:30:00	50	50	50	50	50										WBFS	11	5	7	2				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		
E6.B	4	BA	Sun 13:00:00	80	50	50	50	50	2	WBAS	21	25	7	5	7	5	4	BFS	10	5	7	3			2	BCH
		BNS	Sun 13:30:00	60	50	50	50	50										HMFS	10	5	7	3				
		CHP	Sun 14:00:00	40	50	50	50	50		WMAS	21	25	7	5	7	5		HFS	11	5	7	2				QEH
		SP	Sun 14:30:00	20	50	50	50	50										WBFS	11	5	7	2				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**42**	**20**	**28**	**10**	**140**	**100**		

Table 10.2: Design of experiments associated with the case study area of Birmingham city centre (cont.)

E	Incident sites			Casualties					Ambulance stations								Fire stations						n_{er}	n_{ev}	Hospitals	
						Health profile					Emergency responders and vehicles								Emergency responders and vehicles							
	n_{is}	l_{is}	d_{is}, and t_{is}	$n_{c,is}$	$n_{c_{is}^{t}}$ (%)	Severe	moderate	mild	n_{as}	l_{as}	$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$	n_{fs}	l_{fs}	$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
E7.B	4	BA	Sun 13:00:00	50	50	50	50	50	2	WBAS	24	35	8	6	8	6	4	BFS	12	6	9	3			2	BCH
		BNS	Sun 13:30:00	50	50	50	50	50										HMFS	12	6	9	3				
		CHP	Sun 14:00:00	50	50	50	50	50		WMAS	18	15	6	4	6	4		HFS	8	4	6	2				QEH
		SP	Sun 14:30:00	50	50	50	50	50										WBFS	8	4	6	2				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**40**	**20**	**30**	**10**	**140**	**100**		
E8.B	4	BA	Sun 13:00:00	80	50	50	50	50	2	WBAS	24	35	8	6	8	6	4	BFS	12	6	9	3			2	BCH
		BNS	Sun 13:30:00	60	50	50	50	50										HMFS	12	6	9	3				
		CHP	Sun 14:00:00	40	50	50	50	50		WMAS	18	15	6	4	6	4		HFS	8	4	6	2				QEH
		SP	Sun 14:30:00	20	50	50	50	50										WBFS	8	4	6	2				
				200							**42**	**50**	**14**	**10**	**14**	**10**			**40**	**20**	**30**	**10**	**140**	**100**		

10.5 Summary

This chapter partially addressed RQ1 by presenting two case study areas in two cities in the UK, namely central London and Birmingham city centre, in order to simulate a coordinated emergency response to MCIs. Furthermore, a comprehensive definition and explanation of all parameter values have been provided prior to designing the experiments to enable specifying the number of distinct experiments to be carried out using the developed decision support model, and it supports understanding the experiments defined. Consequently, 16 distinct experiments have been specified and summarised in Table 10.1 and Table 10.2. The next chapter will report and discuss the application of the decision support model using the 16 experiments.

Chapter 11. Results and discussion

11.1 Introduction

A Mass Casualty Incident (MCI) is an event causing casualties that may require rescuing, triage and lifesaving treatment that is beyond the standard resources of the emergency services [13, 14]. The emergency response to an MCI requires the involvement of multiple agencies, including ambulance and police services, fire departments, hospitals, community organisations, and volunteers [14]. In order to minimise the impact of an MCI on morbidity and mortality, emergency services aim to simulate MCIs, train, and prepare activities that are essential for an effective emergency response to an MCI event. Effective emergency response is crucial for reducing the impact of MCIs on public health, safety, and infrastructure [40]. To ensure an effective response to an MCI, simulations are commonly utilised, which aligns with a recent cabinet office report [7]; however, the question remains as to whether these simulations truly replicate MCIs that could occur, such as 9/11 or the London bombing attacks [128]. Although emergency services may be effective working in isolation, for example, ambulance and paramedics, ensuring emergency services from all sectors are suitably prepared to collaborate with colleagues and other emergency services is essential to ensure an optimal response to an MCI. However, ensuring all emergency responders are available and cordoning off suitable incident sites in large cities when simulating MCIs is expensive and logistically very difficult.

One approach to minimise suffering and save lives in MCIs is to simulate MCIs using computational models [61, 65-72, 74, 75], which have been reviewed in Chapter 3. Two examples of such computational models are by the authors Hawe et al. [66] and Bae et al. [73], Who both developed decision support models. A multi-agent-based model developed by Hawe et al. [66] aimed to identify an optimal approach for allocating fire engines, firefighters, ambulances, and paramedics to two separate incidents. The authors observed that a higher proportion of emergency vehicles were dispatched to the incident site, where a greater number of immediate casualties were located. Although this approach seems logical, without data relating to the health classification of casualties at incident sites, the allocation of emergency responders may be insufficient or excessive, both resulting in a sub-optimal emergency response to an MCI. Furthermore, in a more recent study, Bae et al. [73] developed an agent-based model with the aim of optimising the allocation of casualties to hospitals. The authors investigated the association between emergency responder expertise and the expected number of survivors, highlighting a clear association where higher levels of expertise resulted in an increase in the number of survivors. Although the work of Hawe et al. [66] and Bae et al. [73] shows promise, with both aligning with requirements 14 and 9 of what a decision support model must include (Chapter 4), these studies did not include information in their models relating to casualties health profiles or include information from an evolving MCI. These studies do, however, demonstrate that their decision support models provided valid results and were effective at modelling MCIs.

Although there is a body of evidence demonstrating that simulations of MCIs may provide a useful tool to prepare for MCIs, significant challenges and limitations of modelling remain in the literature, particularly 1) incorporating information relating to the evolving and ever-changing environment of an MCI, 2) comprehensive modelling of health profiles of casualties that enables the health status of casualties to be dynamically simulated and adjust emergency resources allocation accordingly, and 3) modelling multiple emergency responders with different levels of experience and knowledge, as demonstrated in Chapter 5 (summarised in Table 5.1). Although this is not an exhaustive list, these are a few key elements that must be considered in any novel decision support models being developed [65, 66, 73]. Furthermore, in a similar manner to the 9/11 attack and the London bombings, there are likely to be multiple incident sites and a continually evolving MCI environment. Any models must have the capacity to manage and incorporate the dynamic occurrence of new incident sites and additional casualties. Alongside additional incidents and incidents sites that could occur, decision support models must also be able to manage the changing health profiles of casualties from their initial assessment at the incident site to their arrival at their allocated hospital.

The decision support model developed in this thesis has been developed accounting for the limitations previously discussed (Chapters 6 to 8). The primary aim of this chapter is to assess the efficacy of the developed decision support model to coordinate an emergency response to an MCI in two different case study areas (central London and Birmingham city centre) using the sixteen experimental conditions described in Chapter 10. This chapter provides a continuation of the exploration of **RQ3**, which was restated in Chapter 10.

11.2 Simulating the coordinated emergency response to MCI in central London

The results presented in this section are from simulating experiments E1.L to E8.L in the case study area of central London. In all experiments, E1.L to E8.L, the number and location of incident sites, ambulances, fire and rescue stations, hospitals, the total number of casualties and their initial health profiles, the total number of emergency responders and all types of vehicles initially located at ambulance and fire and rescue stations were all as defined in the case study area (Chapter 10). However, a key difference in experiments E1.L to E1.8 is in relation to the occurrence times of new incidents, distributions of casualties among new incident sites, and the total number of emergency responders and all types of vehicles initially located at each ambulance and fire and rescue station. In experiments E1.L to E4.L, four hypothetical incidents occurred in the case study area of central London (Chapter 10, Table 10.1). The first two incidents occurred at the British Museum (BM) and Embankment underground station (EUS) and occurred on a Saturday afternoon at 13:00pm GMT. This was subsequently followed by one hypothetical incident at Hyde Park (HP) at 13:25 GMT and, subsequently, a final incident occurring at Oxford Circus (OC) that occurred 20 seconds following the incident at HP. However, in experiments E5.L to E8.L, although the incident locations remained the same, there was an adjustment in the timing of the incidents. The primary incident occurred at the incident site BM on a Saturday afternoon at 13:00pm GMT. This was then followed by three separate incidents at EUS, HP, and OC incident sites, each occurring sequentially 30 minutes following the initial incident at the BM incident site Chapter 10 (Section 10.2.1). In experiments E1.L, E3.L, E5.L, and E7.L, each of the four incident sites (BM, EUS, HP, and OC) in central London were allocated the same number of casualties ($n_{C_{is}}$= 50). In contrast, in experiments E1.L, E2.L, E5.L, and E6.L, the number of casualties were distributed unequally across the incident sites BM ($n_{C_{is_1}}$=80), EUS ($n_{C_{is_2}}$=60), HP ($n_{C_{is_3}}$=40), and OC ($n_{C_{is_4}}$=20), respectively. Furthermore, in all experiments, E1.L to E8.L, the number and types of emergency responders and emergency vehicles located at the ambulance and fire and rescue stations were distributed equally. Although the number of emergency responders located at each station was the same in all experiments, the absolute number was dependent on the number of ambulance and fire and rescue stations specified in the case study area as defined in Chapter 10 (Table 10.1). In contrast, in experiments E3.L, E4.L, E7.L, and E8.L, all types of emergency responders and vehicles located at the ambulance and fire and rescue stations have been distributed unequally. The number of emergency responders located at each station is dependent on the number of ambulance and fire and rescue stations specified in the case study area as defined in Chapter 10

(Table 10.1). A full detailed explanation of all sixteen experiments has been presented in Chapter 10 (Table 10.1).

The results from experiments E1.L to E8.L are presented. Firstly, the timelines of the coordinated responses, representing the occurrence times of incidents and 1) the arrival time, presented as the mean of the first responder team to each incident as part of the pre-determined attendance (PDA) response plan; 2) the final immediate and urgent casualty arrival times at the assigned hospitals, and 3) completion times of the four incident sites. All times presented in the timelines are presented in hours and minutes and are on Greenwich Mean Time (GMT). Secondly, the four objective functions f_1(x)-f_4(x) are presented. Objective function f_1(x) relates to the arrival time at the assigned hospital of the immediate casualties across all incident sites. Objective function f_2(x) relates to the arrival time at the assigned hospital of the final urgent casualties across all incident sites. Objective function f_3(x) relates to the total processing times of all casualties. The processing time of each casualty begins when the first task associated with that casualty, which is locating the casualty (Task 1), is performed by an allocated emergency responder, and it ends when the final task associated with that casualty, which is unloaded the casualty from the standard ambulance at his/her assigned hospital (Task 10), is completed. Objective function f_4(x) relates to the emergency response time, defined as the time from when the PDA response plan is executed to when the final casualty of any health classification type across all incident sites is delivered to the assigned hospital. A detailed description of all four objectives ($f_1(x)$, $f_2(x)$, $f_3(x)$, and $f_4(x)$) is presented in Chapter 8 (Section 8.3). The number of emergency responders of all types allocated to perform tasks associated with casualties at the four incident sites (BM, EUS, HP, and OC) is presented as the mean. Finally, the number of casualties that arrived at each hospital in central London is presented. Furthermore, the number of casualties of each health classification (immediate, urgent, delayed, and dead) when they arrived at their assigned hospitals is presented. All data are presented as the mean (± SD) from the 50 repeated experiments (n=50), and data presented as % is the % of a total of the mean unless otherwise stated. Definitions of the four health classifications of casualties can be found in Chapter 2 (Section 2.3.3).

11.2.1 New incidents occurring in close succession (experiments E1.L to E4.L)

It is clear from the timeline presented in Figure 11.1 that the arrival time of the first emergency response team at incident sites BM and EUS was the same in experiments E1.L to

E4.L, which was likely to be due to the PDA response plan at incident sites BM and EUS, generated using the greedy heuristic algorithm (GHA) developed in Chapter 8 (Section 8.2.1). In the PDA response plan, the emergency responders are deployed to incident sites that are in the closest proximity to their initial locations, as previously discussed in Chapter 6 (Section 6.3). Figure 11.1 depicts the timelines of emergency responders presented as the mean response time in hours. The occurrence times of incidents and 1) the arrival time of the first responder team to an incident as part of the PDA response plan, 2) the final immediate and urgent casualty arrival times at the assigned hospitals, and 3) completion times of the four incident sites from experiments E1.L to E4.L (Figure 11.1).

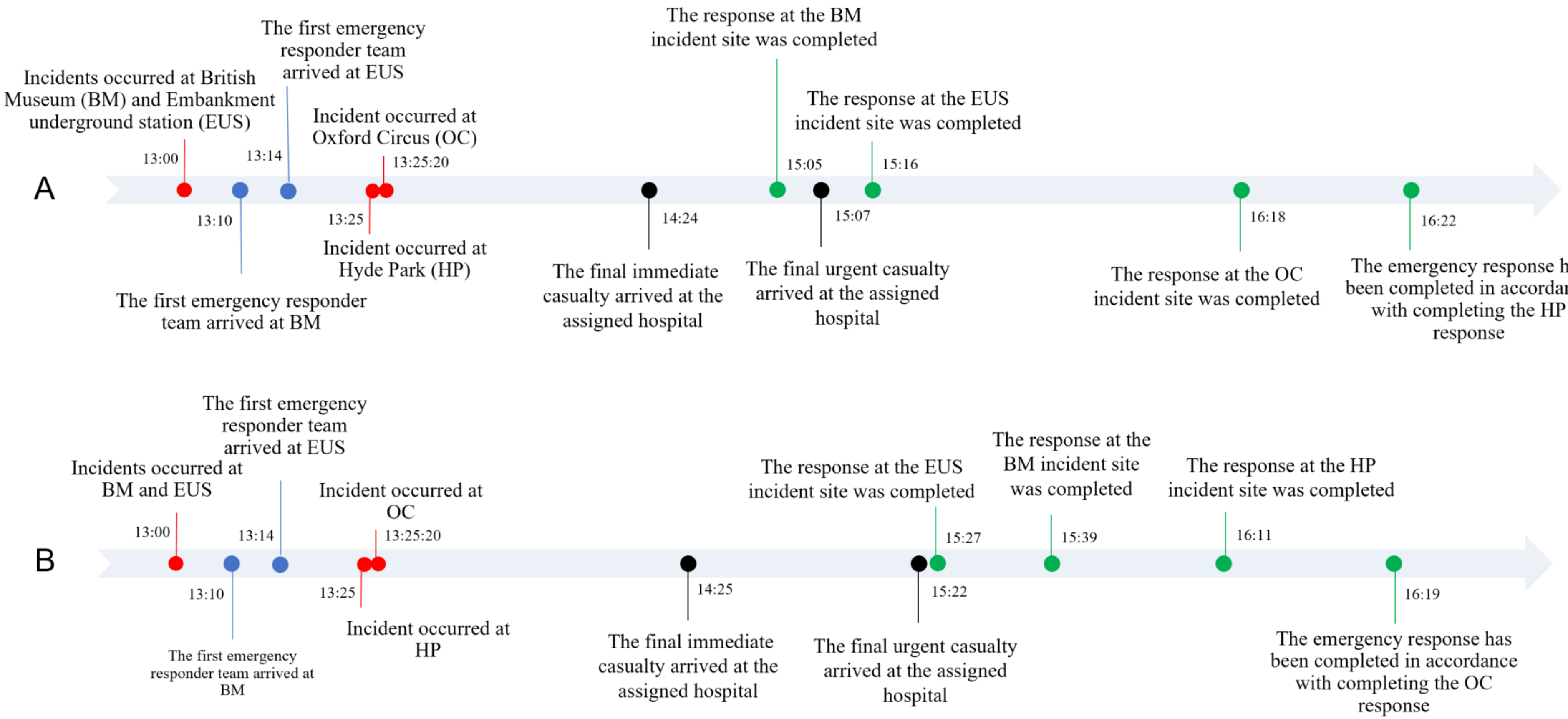


Figure 11.1: Timelines of emergency responses to mass casualty incident from A) experiment E1.L, B) experiment E2.L, C) experiment E3.L, and D) experiment E4.L in the case study area of central London (based on 50 runs).

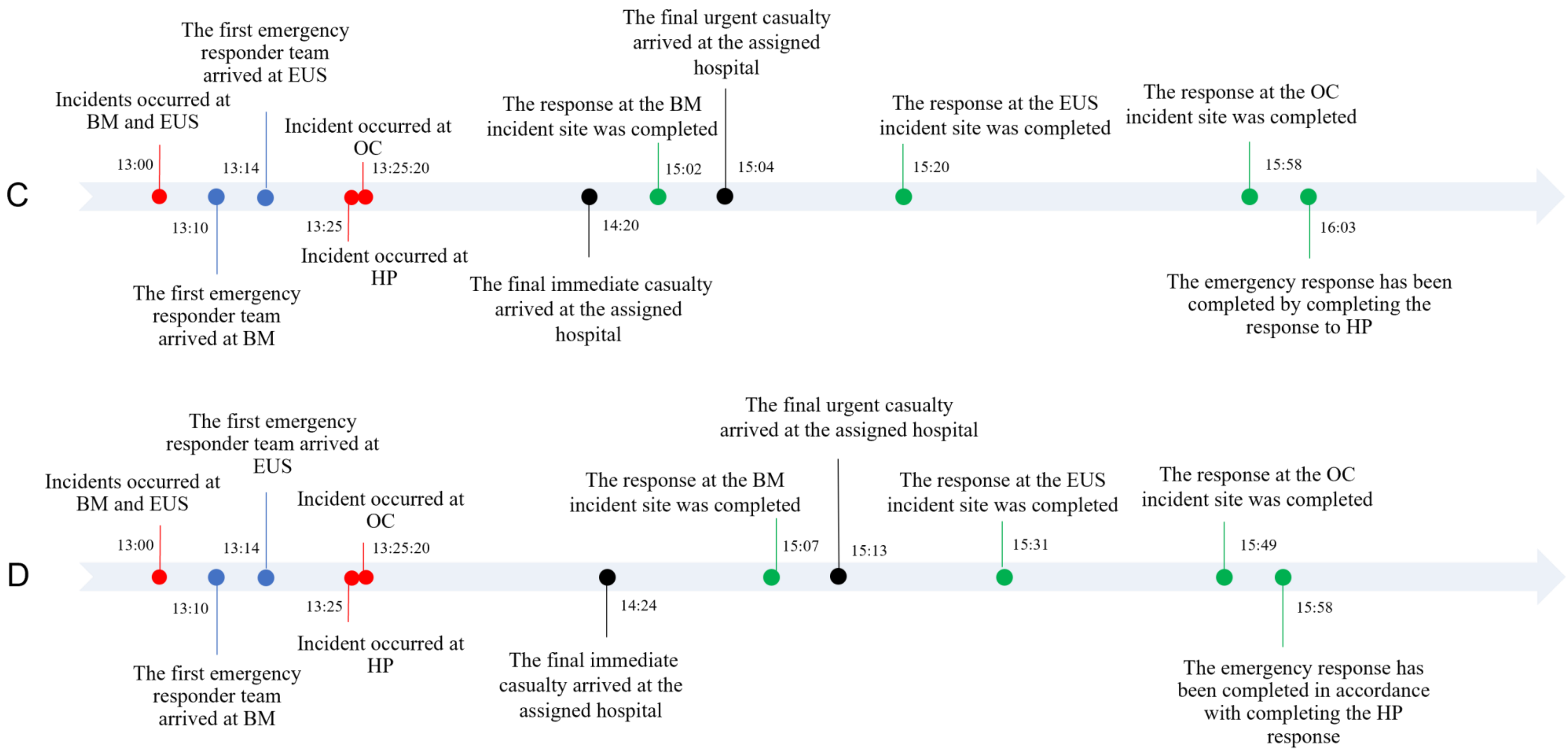


Figure 11.1: Timelines of emergency responses to mass casualty incident from A) experiment E1.L, B) experiment E2.L, C) experiment E3.L, and D) experiment E4.L in the case study area of central London (cont.).

These results in Figure 11.1 (A-D) clearly demonstrate that the response times at incident sites BM, EUS, HP, and OC were comparable. The response times at the incident BM were completed within 2.08 (±0.03), 2.03 (±0.05), and 2.17 (±0.01) hours in experiments E1.L, E3.L, and E4.L, respectively. However, the response time of 2.65 (±0.09) hours in experiment E2.L was the longest at the incident site BM (Figure 11.1 A-D). There was a large spread of response times for the incident site EUS, with 2.26 (±0.12), 2.45 (±0.05), 2.33 (±0.03), and 2.51 (±0.07) hours in experiments E1.L to E4.L, respectively (Figure 11.1 A-D). The response times at incident sites OC and HP were also comparable, 3.3 (±0.02) vs. 3.37 (±0.05) hours, 3.32 (±0.06) vs. 3.18 (±0.12) hours, 2.96 (±0.13) vs. 3.03 (±0.09) hours, and 2.82 (±00.10) vs. 2.97 (±0.04) hours in experiments E1.L to E4.L, respectively (Figure 11.1 A-D).

Initial allocation of emergency responders to incident sites

The results presented in Table 11.1 includes the number of all different types of emergency responders based on their initial locations, as described in experiments E1.L to E4.L, and the mean number of emergency responders allocated to each incident, BM, EUS, HP, and OC. Emergency responders were distributed among seven ambulance stations and seven fire and rescue stations. The seven ambulance stations were BAS, Fulham ambulance station (FAS), London ambulance station (LAS), Oval ambulance station (OAS), St John's Wood ambulance station (SJWAS), Waterloo ambulance station (WAAS), and Westminster ambulance station (WEAS). The seven fire and rescue stations are Dowgate fire station (DFS), Euston fire station (EFS), Fulham fire station (FFS), Old Kent Road fire station (OKRFS), Paddington fire station (PAFS), Peckham fire station (PEFS), and Soho fire station (SFS). It is clear that no emergency responders were allocated to incident sites HP and OC from their initial locations (Table 11.1). The lack of emergency responders at incident sites HP and OC is because the incidents at these sites were yet to occur (Chapter 10, Table 10.1). The sequence of events that unfolded in the simulations here, with different incidents occurring at different times, required the decision support model to reallocate emergency responders from their initial allocated incident sites, such as BM and EUS, which occurred earlier, to the new incident sites HP and OC. All results presented in this chapter have been rounded to the nearest integer for clarity and discussion purposes.

Table 11.1: Mean (±S.D) number of emergency responders of all types allocated to each incident site from their initial locations from experiments E1.L, E2.L, E3.L, and E4.L in the case study area of central London (based on 50 runs).

Experiments		E1.L					E2.L					E3.L					E4.L				
Incident sites		BM	EUS	HP	OC	T	BM	EUS	HP	OC	T	BM	EUS	HP	OC	T	BM	EUS	HP	OC	T
Ambulance stations	BAS	5	5	0	0	10	6	4	0	0	10	10	4	0	0	14	8	6	0	0	14
	FAS	7	3	0	0	10	7	3	0	0	10	9	5	0	0	14	4	10	0	0	14
	LAS	5	5	0	0	10	6	4	0	0	10	6	8	0	0	14	7	7	0	0	14
	OAS	5	5	0	0	10	7	3	0	0	10	2	5	0	0	7	3	4	0	0	7
	SJWAS	8	2	0	0	10	8	2	0	0	10	2	5	0	0	7	3	4	0	0	7
	WAAS	2	9	0	0	10	6	4	0	0	10	3	4	0	0	7	4	3	0	0	7
	WEAS	3	7	0	0	10	6	4	0	0	10	4	3	0	0	7	4	3	0	0	7
Fire and rescue stations	DFS	6	5	0	0	10	6	4	0	0	10	9	5	0	0	14	9	5	0	0	14
	EFS	7	3	0	0	10	7	3	0	0	10	6	8	0	0	14	11	3	0	0	14
	FFS	6	4	0	0	10	5	5	0	0	10	7	7	0	0	14	10	4	0	0	14
	OKRFS	5	5	0	0	10	6	4	0	0	10	5	2	0	0	7	4	3	0	0	7
	PAFS	6	4	0	0	10	7	3	0	0	10	2	5	0	0	7	4	3	0	0	7
	PEFS	1	9	0	0	10	3	7	0	0	10	3	4	0	0	7	4	3	0	0	7
	SFS	6	4	0	0	10	6	4	0	0	10	3	4	0	0	7	5	2	0	0	7
Total		**72** (±4)	**68** (±2)	**0**	**0**	140	**86** (±3)	**54** (±7)	**0**	**0**	140	**71** (±5)	**69** (±4)	**0**	**0**	140	**80** (±2)	**60** (±4)	**0**	**0**	140

E, experiment; BM, British Museum; EUS, Embankment underground; HP, Hyde Park; OC, Oxford Circus; T, total; BAS, Bloomsbury ambulance station; FAS, Fulham ambulance station; LAS, London ambulance station; OAS, Oval ambulance station; SJWAS, St John’s Wood ambulance station; WAAS, Waterloo ambulance station; WEAS, Westminster ambulance station; DFS, Dowgate fire station; EFS, Euston fire station; FFS, Fulham fire station; OKRFS, Old Kent Road fire station; PAFS, Paddington fire station; PEFS, Peckham fire station; SFS, Soho fire station.

The results presented in Table 11.1 highlight that the mean number of emergency responders of all types allocated to incident sites BM and EUS were comparable in experiments E1.L and E3.L, 72 (51%) vs. 68 (49%) and 71 (51%) vs. 69 (49%), respectively. However, in experiments E2.L and E4.L, the mean number of emergency responders of all types allocated to BM was larger than EUS, 86 (62%) vs. 54 (39%) and 80 (57%) vs. 60 (43%), respectively (Table 11.1). These results indicate that an incident site with a higher number of casualties was subsequently allocated a larger number of emergency responders of all types, which aligns with previous studies [64, 66]. The results presented in Table 11.1 indicate that the initial location of emergency responders is not the only factor impacting the allocation of emergency responders to each of the incident sites.

Reallocation of emergency responders to incident sites

As the MCI response continued to develop, subsequent incidents at sites HP and OC occurred. The decision support model was then able to modify the allocation of resources from incident sites BM and EUS to the new incidents occurring at sites HP and OC. The results presented in Table 11.2 shows how the mean number of emergency responders of all types allocated to incident sites BM, EUS, HP, and OC changed over hourly intervals in experiments E1.L to E4.L. In Table 11.2, the term ‘other’ indicates that emergency responders were not located at a specific incident site; instead they may have been travelling to an incident site or accompanying a casualty to an assigned hospital. The results presented in Table 11.2 demonstrate that a larger proportion of emergency responders was allocated to the incident sites with the largest number of casualties. For example, in experiment E2.L, the mean number of emergency responders at incident sites BM (27), EUS (30), HP (35), and OC (25) were comparable at 14:00pm GMT. However, at 15:00pm GMT, the mean number of emergency responders located at incident site BM was reduced from 27 to 5. These results indicate that the emergency response in relation to casualties was almost complete at incident site BM. In contrast, the mean number of emergency responders located at incident site OC increased from 25 to 49 (Table 11.2), indicating that more emergency responders had become available, and were relocated from other sites and to manage the increasing number of casualties (Table 11.2).

Table 11.2: Mean (±S.D) number of emergency responders of all types reallocated to other incident sites at hourly intervals following the initiation of the emergency response from experiments E1.L to E4.L in the case study area of central London (based on 50 runs).

Emergency response time	Incident sites	E1.L	E2.L	E3.L	E4.L
14:00	BM	27 (±5)	42 (±8)	29 (±4)	40 (±5)
	EUS	30 (±1)	34 (±5)	31 (±11)	30 (±8)
	HP	35 (±7)	33 (±7)	30 (±9)	24 (±7)
	OC	25 (±10)	15 (±9)	28 (±7)	16 (±5)
	Other	23 (±11)	16 (±6)	22 (±10)	30 (±11)
	Total	140	140	140	140
15:00	BM	5 (±3)	26 (±7)	3 (±1)	28 (±7)
	EUS	12 (±8)	11 (±3)	24 (±7)	5 (±2)
	HP	40 (±11)	53 (±15)	32 (±4)	32 (±11)
	OC	49 (±14)	31 (±8)	58 (±11)	41 (±7)
	Other	34 (±12)	19 (±8)	23 (±13)	34 (±12)
	Total	140±	140	140	140
16:00	BM	0	0	0	0
	EUS	0	0	0	0
	HP	20 (±6)	31 (±6)	106 (± 26)	128 (±31)
	OC	80 (±12)	80 (±19)	0	0
	Other	40 (±21)	29 (±23)	34 (±11)	12 (±8)
	Total	140	140	140	140

BM, British Museum; EUS, Embankment Underground Station; HP, Hyde Park; OC, Oxford Circus.

Objective functions

The mean time for the four objective functions, $f_1(x)$, $f_2(x)$, $f_3(x)$, and $f_4(x)$, from 50 replicates is depicted in Figure 11.2 and presented in hours from experiments E1.L (A), E2.L (B), E3.L (C) and E4.L (D).

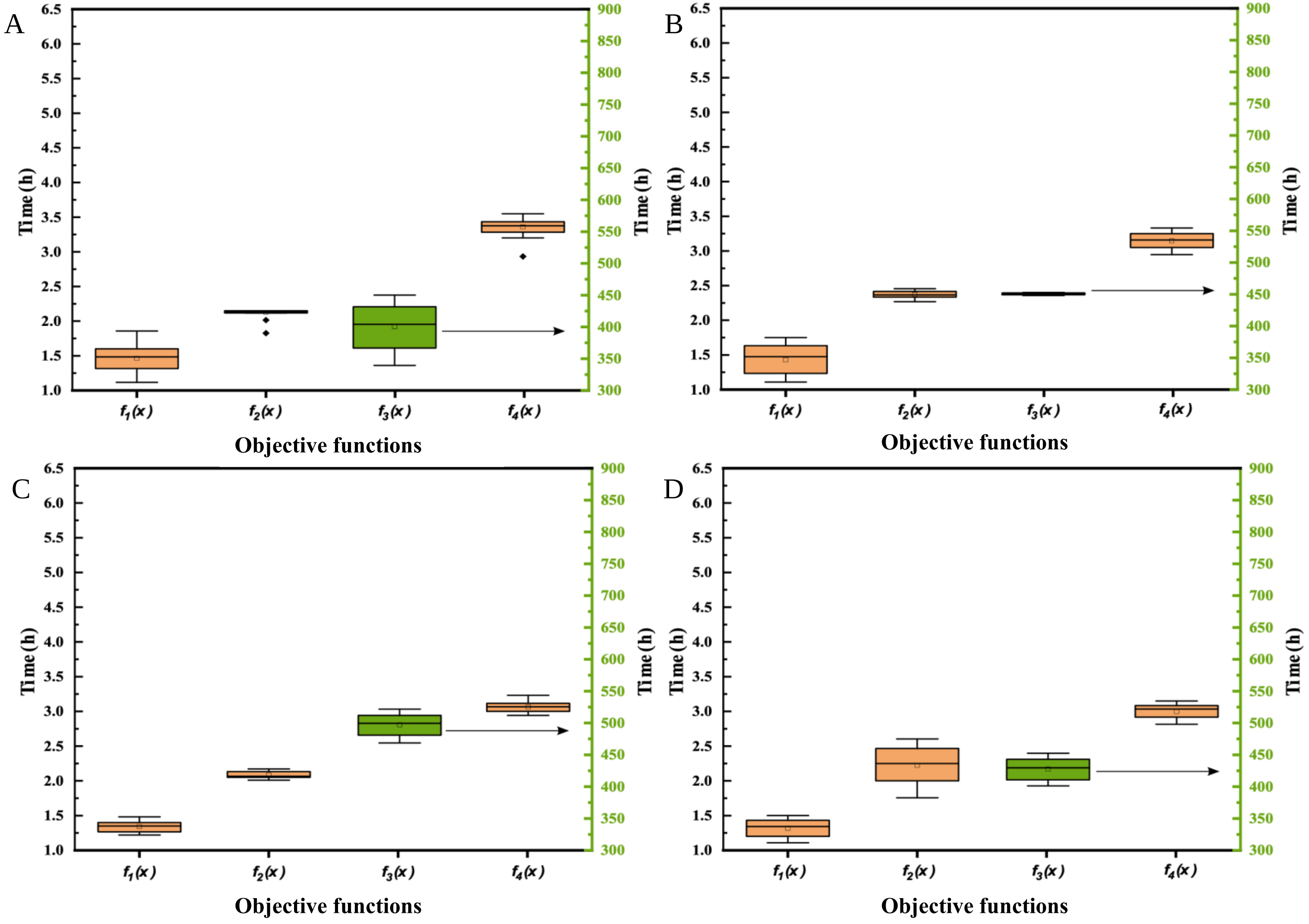


Figure 11.2: Boxplots presenting mean time in hours from the four objective functions for A) experiment E1.L, B) experiment E2.L, C) experiment E3.L, and D) experiment E4.L from the case study area of central London (based on 50 runs).

The results presented in Figure 11.2 highlight that the arrival time for the final immediate casualty at their assigned hospital ($f_1(x)$), from experiments E1.L to E4.L were comparable, 1.42 (±0.22), 1.43 (±0.21), 1.35 (±0.07), and 1.32 (±0.12) hours, respectively (Figure 11.2 A-D). In contrast, the arrival time presented in hours for the final urgent casualty to arrive at their assigned hospital ($f_2(x)$), in experiments E1.L and E3.L was 2.13 (±0.04) and 2.08 (±0.05). Interestingly, the time for the final urgent casualty to arrive at their assigned hospital ($f_2(x)$), in experiments E2.L and E4.L were longer 2.38 (±0.05) and 2.22 (±0.27), respectively (Figure 11.2 A-D). The total processing time for all casualties ($f_3(x)$) from experiments E3.L was the highest compared to those of other experiments (Figure 11.2 A-D). The processing times of casualties ($f_3(x)$) was 400 (±36), 450 (±1.55), 497 (±17), and 427 (±17) hours for experiments E1.L to E4.L, respectively (Figure 11.2 (A-D). The emergency response times ($f_4(x)$) from experiments E1.L to E4.L were comparable, 3.36 (±0.18), 3.31 (±0.11), 3.05 (±0.07), and 2.96 (±0.09) hours, respectively (Figure 11.2 A-D).

Allocating casualties to hospitals

In terms of allocating casualties to hospitals via standard ambulances, Table 11.3 presents the mean number of casualties delivered to each of the six hospitals defined in the case study area of central London. These are Chelsea and Westminster Hospital (CWH), Guy’s Hospital (GH), King’s College Hospital (KCH), St Mary’s Hospital (SMH), Royal London Hospital (RLH), and University College Hospital (UCH). In Table 11.3, the term ‘total’ refers to the number of casualties considered in experiments E1.L to E4.L. The numbers in bold presented in Table 11.3 identify the highest and lowest mean numbers of casualties allocated to hospitals UCH and KCH, respectively, from experiments E1.L to E4.L. The mean number of casualties allocated to hospitals UCH and KCH ranged between 60-66 and 11-16 in experiments E1.L to E4.L, respectively. Furthermore, the number of casualties arriving at CWH, GH, SMH, and RLH hospitals from experiments E1.L to E4.L were comparable (Table 11.3).

Table 11.3: Mean (±S.D) number of casualties that arrived at each of the six hospitals in the case study area of central London from experiments E1.L to E4.L (based on 50 runs).

Experiments	CWH	GH	KCH	SMH	RLH	UCH	Total
E1.L	22 (±6)	35 (±4)	**12** (±3)	35 (±3)	34 (±5)	**62** (±3)	200
E2.L	22 (±3)	36 (±2)	**12** (±3)	34 (±4)	30 (±2)	**66** (±6)	200
E3.L	21 (±7)	45 (±5)	**11** (±2)	34 (±2)	28 (±6)	**61** (±4)	200
E4.L	20 (±2)	44 (±6)	**16** (±4)	33 (±4)	27 (±5)	**60** (±8)	200

CWH, Chelsea and Westminster Hospital; GH, Guy's Hospital; KCH, King's College Hospital; SMH, St Mary's Hospital; RLH, Royal London Hospital; UCH, University College Hospital.

Health profiles of casualties

The data presented in Table 11.4 demonstrates that the health profiles of casualties upon arrival at their allocated hospitals were comparable across all experiments (Table 11.4). Furthermore, no mortalities among the casualties were reported.

Table 11.4: Severity of health profiles of casualties when they arrived at the assigned hospitals from experiments E1.L to E4.L in the case study area of central London (based on 50 runs).

Experiments	Health classification of casualties				Total
	Immediate	Urgent	Delayed	Mortality	
E1.L	48 (±2)	52 (±3)	100 (±2)	0	200
E2.L	48 (±1)	50 (±4)	102 (±2)	0	200
E3.L	48 (±3)	48 (±4)	104 (±1)	0	200
E4.L	46 (±1)	48 (±2)	106 (±5)	0	200

11.2.2 New incidents occur sequentially at 30-minute intervals following the primary incident (experiments E5.L to E8.L).

The experimental conditions in experiments E5.L to E8.L are the same as in experiments E1.L to E4.L. However, one key difference is that in experiments E4.L to E8.L, following the primary incident at incident site BM, occurring on a Saturday afternoon at 13:00pm GMT, sequential incidents occurred every 30 minutes at incident site EUS, HP, and OC. The modification of the timing of the incidents and new incident sites in experiments E4.L to E8.L is to replicate MCIs where multiple incidents could occur at varying times in an MCI geographical area. (Chapter 10, Section 10.3.2).

Timelines of emergency responses to MCI

During the MCI, when there is only one incident, it is only reasonable for all emergency responders to be allocated to that incident site. This was the case in experiments E5.L to E8.L, where the primary incident occurred at 13:00pm at the incident site BM, and subsequently, all types of emergency responders were allocated to BM as this was the only incident that had occurred (Figure 11.3). The first team of emergency responders arrived at the incident site BM at 13:10pm GMT from the BAS in experiments E5.L to E8.L (Figure 11.3 A-D). The timeline depicted in Figure 11.3 is presented as the mean response time in hours. The occurrence times of incidents and the 1) arrival time of the first responder team to an incident as part of the PDA response plan; 2) final immediate and urgent casualty arrival times to their assigned hospitals, and 3) completion times of the four incident sites from experiments E5.L to E8.L.

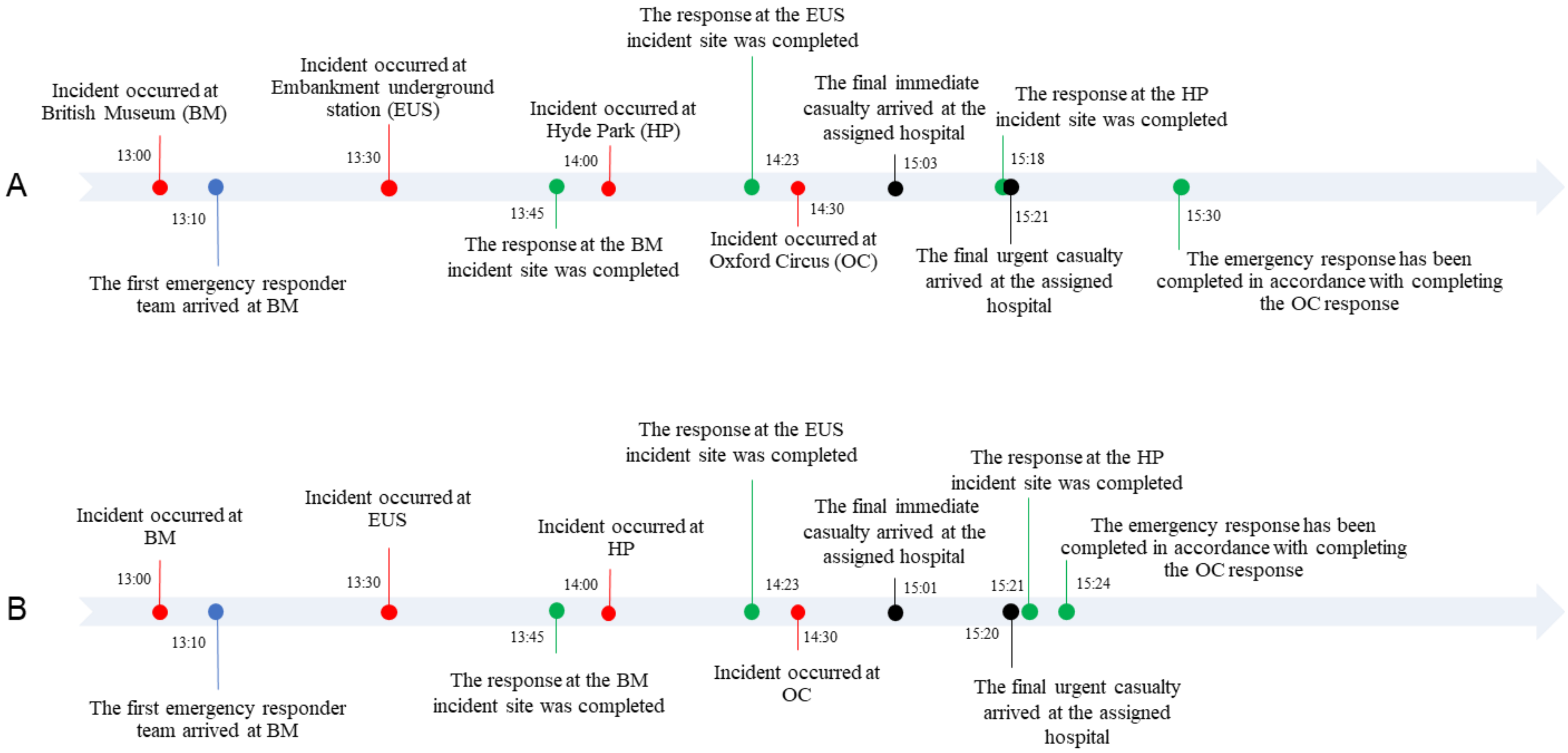


Figure 11.3: Timelines of emergency responses to mass casualty incident from A) experiment E5.L, B) experiment E6.L, C) experiment E7.L, and D) experiment E8.L in the case study area of central London (based on 50 runs).

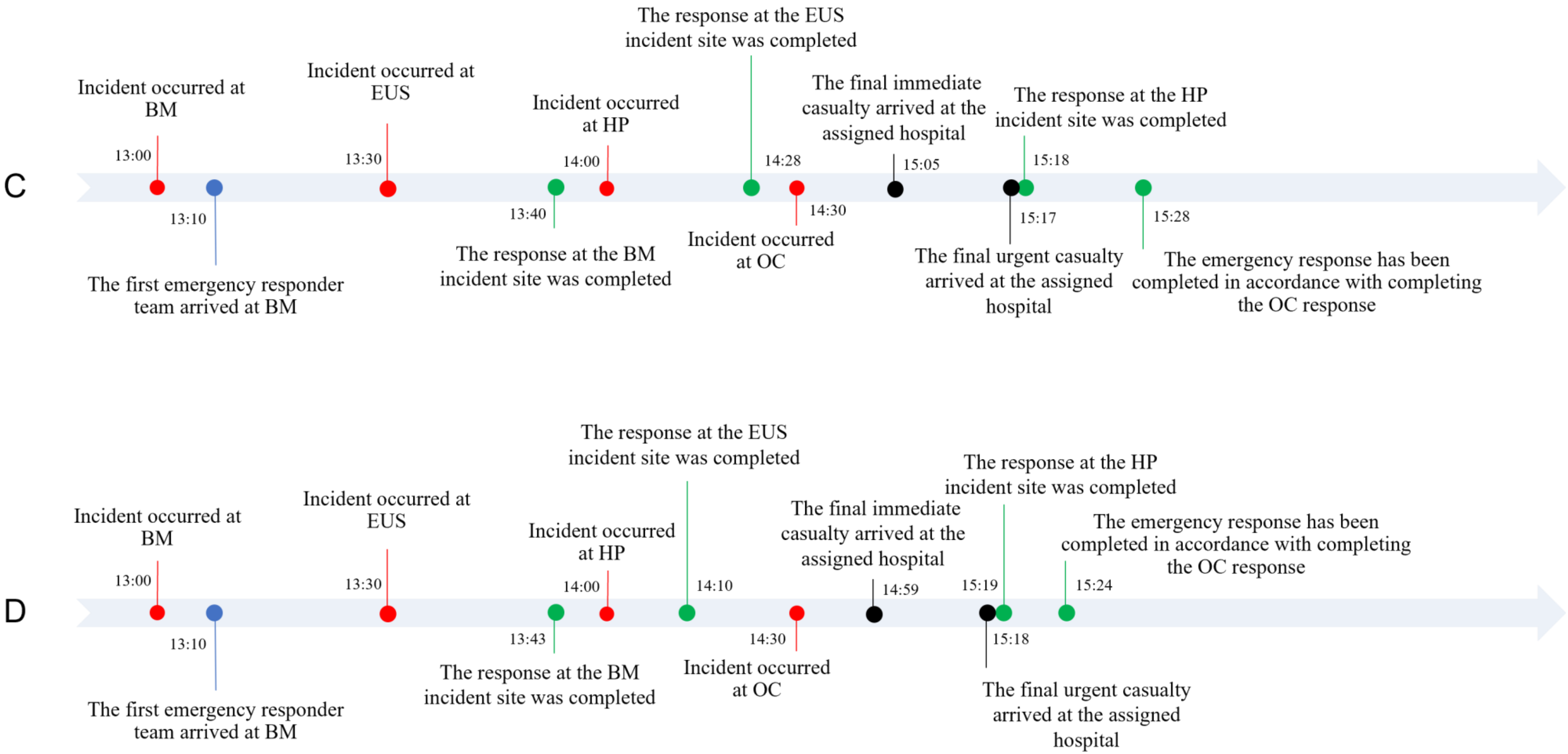


Figure 11.3: Timelines of emergency responses to mass casualty incident from A) experiment E5.L, B) experiment E6.L, C) experiment E7.L, and D) experiment E8.L in the case study area of central London (cont.).

The timelines in Figure 11.3 highlight that the complete emergency response was finished upon completion of the emergency response at the final incident site OC in experiments E5.L to E8.L. The potential reason for these differences in emergency response times is likely to be due to the different distribution of casualties.

Reallocating emergency responders to incident sites

Following the primary incident at incident site BM, the MCI response developed, and subsequent incidents occurred at 30-minute intervals at incident sites EUS, HP, and OC. The decision support model developed in this thesis was able to adapt and modify the distribution of emergency resources to each new incident site as they occurred. This required a reallocation of all types of emergency responders from the primary incident site, BM, to the three subsequent incident sites of EUS, HP and then OC as they occurred. The results presented in Table 11.5 represents the changes in the mean number of all types of emergency responders allocated to incident sites BM, EUS, HP, and OC at hourly intervals in experiments E5.L to E8.L. The term ‘other’ indicates that emergency responders were not located at a specific incident site; rather they may have been travelling to an incident site or transporting a casualty to an assigned hospital. The results presented in Table 11.5 demonstrate that a large proportion of the emergency responders were not allocated to a specific site but were either accompanying casualties to hospitals or were travelling to another incident site at 14:00 from experiments E5.L to E8.L.

Table 11.5: Mean (±S.D) number of emergency responders of all types reallocated to incident sites at hourly intervals following the initiation of the emergency response from experiments E5.L to E8.L in the case study area of central London (based on 50 runs).

Emergency response time	Incident sites	E5.L	E6.L	E7.L	E8.L
14:00	BM	0	0	0	0
	EUS	20 (±5)	15 (±7)	8 (±2)	26 (±8)
	HP	0	0	0	0
	OC	0	0	0	0
	Other	120 (±4)	125 (±14)	132 (±11)	114 (±6)
	Total	140	140	140	140
15:00	BM	0	0	0	0
	EUS	0	0	0	0
	HP	8 (±5)	13 (±5)	15 (±7)	11 (±3)
	OC	70 (±21)	70 (±16)	71 (±11)	39 (±9)
	Other	62 (±15)	57 (±11)	54 (±14)	90 (±18)
	Total	140	140	140	140

BM, British Museum; EUS, Embankment Underground Station; HP, Hyde Park; OC, Oxford Circus.

Objective functions

The time in hours, presented as the mean from the objective functions $f_1(x)$, $f_2(x)$, $f_3(x)$, and $f_4(x)$ is depicted in Figure 11.4 for experiments E5.L (A), E6.L (B), E7.L (C) and E8.L (D). The results presented in Figure 11.4 highlight that the mean values for the objective functions were comparable across experiments E5.L to E8.L. The mean arrival time presented as hours for the final immediate ($f_1(x)$) and urgent ($f_2(x)$) casualty to the assigned hospital in experiments E5.L 2.05 (±0.05) and 2.35 (±0.14), E6.L 2.01 (±0.05) and 2.33 (±0.13), E7.L 2.08 (±0.07) and 2.28 (±0.08) and E8.L 1.98 (±0.03) and 2.30 (±0.04) hours were similar, respectively (Figure 11.4 A-D). The highest and lowest mean processing time of casualties, $f_3(x)$, were 350 (±37) and 316 (±9) hours in experiment E7.L and E8.L, respectively. In contrast, the mean processing times of casualties from experiments E5.L and E6.L were comparable, 330 (±5) vs. 332 (±8) hours, respectively (Figure 11.4 A-D). The mean emergency response times ($f_4(x)$) from experiments E5.L to E8.L were similar 2.50 (±0.09), 2.57 (±0.08), 2.47 (±0.10), 2.40 (±0.05) hours (Figure 11.4 A-D).

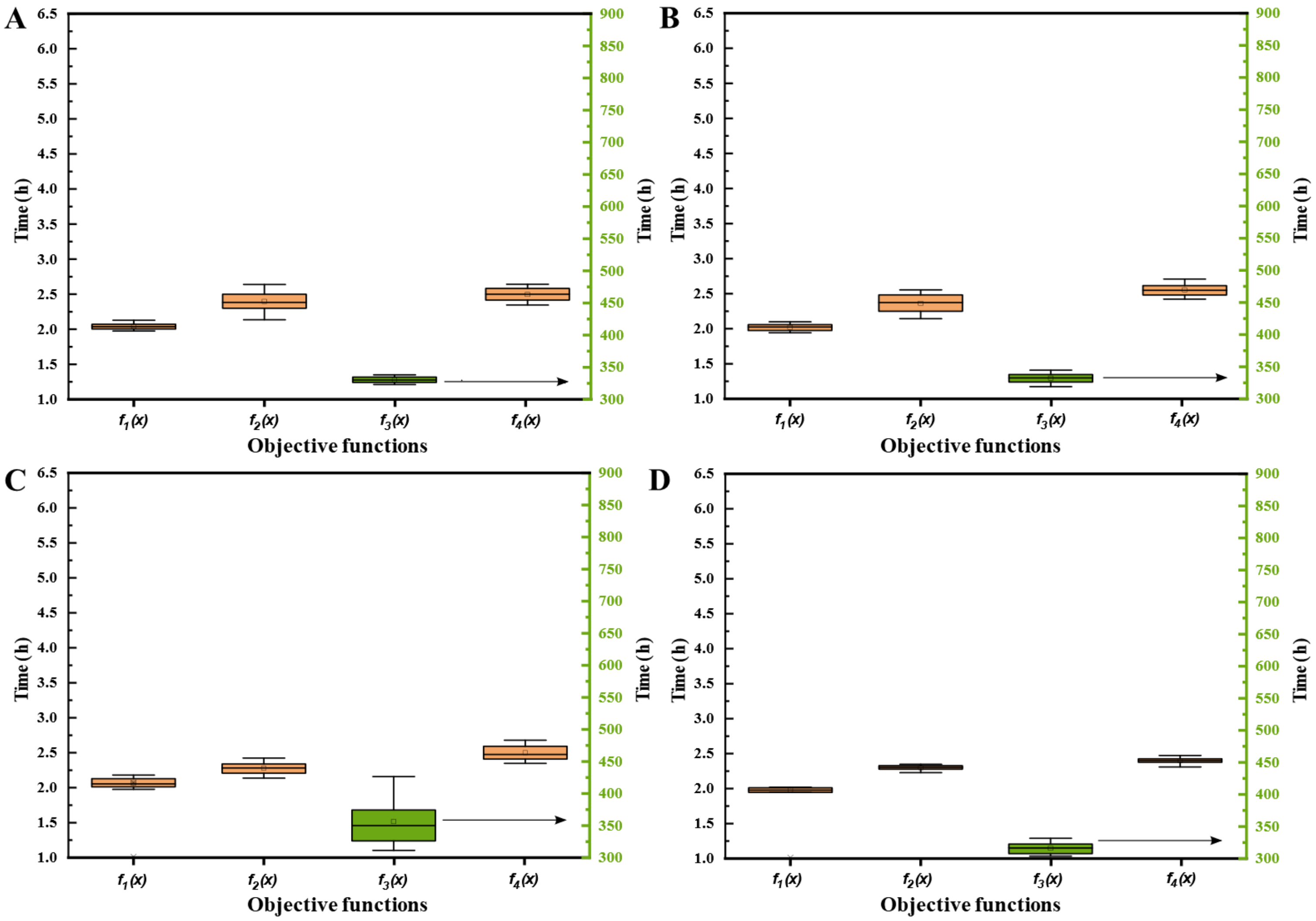


Figure 11.4: Boxplots presenting mean time in hours from the four objective functions for A) experiment E5.L, B) experiment E6.L, C) experiment E7.L, and D) experiment E8.L from the case study area of central London (based on 50 runs).

Allocating casualties to hospitals

The results presented in Table 11.6 relate to the allocation of casualties to their assigned hospitals, who were transported to their assigned hospitals using standard ambulances. The six hospitals presented in Table 11.6 are the hospital in the case study area of central London (Chapter 10, Section 9.2.1). The results presented in Table 11.6 are consistent with those presented in Table 11.3 from experiments E1.L to E4.L. The largest and lowest mean number of casualties were allocated to hospitals UCH and KCH in experiments E5.L to E8.L, respectively. These findings indicate that the vicinity of the hospitals in relation to the incident sites BM, EUS, HP, and OC had a significant impact on casualty allocation to hospitals. The casualties assigned to UCH were 55 (27.5%) in E5.L, 61 (30.5%) in E6.L, 52.5 (26.25%) in E7.L and 63 (31.5%) in E8.L. In contrast, KCH hospital received considerably fewer casualties, 15 (7.5%) in E5.L, 13 (6.5%) in E6.L vs. 13 (6.5%) in E7.L and 9 (4.5%) in E8.L (Table 11.6).

Table 11.6: Mean (±S.D) number of casualties allocated to each hospital from experiments E5.L to E8.L in the case study area of central London (based on 50 runs).

Experiments	CWH	GH	KCH	SMH	RLH	UCH	Total
E5.L	29 (±5)	43 (±2)	**15** (±6)	36 (±9)	23 (±6)	**55** (±2)	200
E6.L	22 (±2)	42 (±7)	**13** (±4)	40 (±11)	22 (±3)	**61** (±6)	200
E7.L	21 (±4)	45 (±2)	**13** (±3)	39 (±7)	29 (±4)	**53** (±4)	200
E8.L	23 (±4)	43 (±3)	**9** (±2)	37 (±8)	25 (±3)	**63** (±7)	200

CWH, Chelsea and Westminster Hospital; GH, Guy's Hospital; KCH, King's College Hospital, SMH, St Mary's Hospital; RLH, Royal London Hospital; UCH, University College Hospital.

Health profiles of casualties

The health profiles and severity of casualties' injuries upon arrival at their assigned hospitals are presented in Table 11.7. The results indicate a small improvement in casualty health profiles in experiments E7.L and E8.L, but overall, the health profiles and severity of casualties' injuries were similar across all experiments, with no mortalities.

Table 11.7: Severity of health profiles of casualties when they arrived at the assigned hospitals from experiments E5.L to E8.L in the case study area of central London (based on 50 runs).

Experiments	Health classification of casualties				Total
	Immediate	Urgent	Delayed	Mortality	
E5.L	50 (±2)	48 (±4)	102 (±4)	0	200
E6.L	48 (±4)	46 (±3)	106 (±6)	0	200
E7.L	46 (±6)	50 (±1)	104 (±5)	0	200
E8.L	48 (±3)	46 (±4)	106 (±2)	0	200

11.2.3 Results summary

The results obtained in experiments E1.L to E8.L presented in Figures 10.2 and 10.4 demonstrate an association between incident timings and the values of the objective functions. The objective function mean values obtained from experiments E1.L to E4.L (Figure 11.2) were lower than those obtained from experiments E5.L to E8.L (Figure 11.4), which is likely to be due to the delay of 30 minutes in the occurrence of subsequent events. Having a delay of 30 minutes offered emergency responders more time to complete activities at each incident site; however, it affected the objective function values.

The results presented in Table 11.1 indicates that the initial location of emergency responders was not the primary factor influencing the allocation of emergency responders to tasks at specific incident sites. Moreover, the geographical locations appeared to have a significant role to play in the allocation of emergency responders to incident sites. For example, the ambulance station BAS was the closest ambulance station to incident site BM, resulting in a larger proportion of the BAS emergency responders being allocated to BM when compared to EUS in experiments E2.L–E4.L (Table 11.1). In contrast, the geographical locations of the fire and rescue stations did not appear to be the only driving factor responsible for emergency responder allocation. For example, the lowest mean proportion of emergency responders from experiments E2.L to E4.L was allocated from the fire and rescue station OKPFS to the incident site EUS, despite OKPFS being closer to EUS than BM (Table 11.1). Furthermore, the findings presented in Table 11.1 revealed a linear regression between the initial number of casualties at an incident site and the mean proportion of emergency responders assigned to that incident site. When the number of casualties was evenly distributed among incident sites ($n_{C_{is}}$=50 at each site), the mean proportion of emergency responders assigned to the incident sites BM and EUS was 72 and 68, and 71 and 69 in experiments E1.L and E3.L, respectively (Table 11.1).

Interestingly, there was a larger allocation of emergency responders to the incident site BM, 86 and 54, when compared to EUS, 80 and 60 in experiments E2.L and E4.L, respectively (Table 11.1).

The results presented in Tables 10.3 and 10.6 confirm previously published work [64], where Repoussis et al. (2016) reported that the distance of the incident site in relation to the location of hospitals was important when allocating casualties to hospitals, which was confirmed in the central London case study area. For example, UCL and KCH hospitals in central London were the closest and furthest away hospitals to the incident sites, respectively (Chapter 10, Figure 10.1), and subsequently received the largest and lowest allocation of casualties in experiments E1.L to E8.L.

11.3 Simulating the coordinated emergency response to an MCI in Birmingham city centre

This section is structured in the same manner as Section 10.2. In experiments E1.B to E8.B, the number of incident sites, total number of casualties, the initial health profiles of casualties, and the total number of emergency responders and vehicles will be the same as in experiments E1.L to E8.L In the case study area of central London, but will be in the second case study area of Birmingham city centre (Chapter 10, Table 11.3). Furthermore, the incident site locations, the number and location of ambulance stations, fire and rescue stations, and hospitals, and the number of emergency responders and vehicles initially located at each station were modified to simulate available emergency service resources available in Birmingham city centre.

11.3.1 New incidents occurring in close succession (experiments E1.B to E4.B)

In experiments E1.B to E4.B, four hypothetical incidents were simulated in the case study area of Birmingham city centre. The first two incidents occurred at the same time on a Saturday afternoon at 13:00pm GMT at incident sites Birmingham Arena (BA) and Birmingham New Street (BNS). This was subsequently followed by one hypothetical incident at Cannon Hill Park (CHP) at 13:25pm GMT, and a final incident 20 seconds following the incident at CHP was simulated to occur at Sunset Park (SP).

In experiments E1.B and E3.B, each of the four incident sites (BA, BNS, CHP, and SP) in the case study area of Birmingham city centre were allocated the same number of casualties

($n_{C_{is}}$= 50). In contrast, in experiments E2.B and E4.B, casualties were distributed across the four incident sites unequally, BA ($n_{C_{is_1}}$=80), BNS ($n_{C_{is_2}}$=60), CHP ($n_{C_{is_3}}$=40), and SP ($n_{C_{is_4}}$=20). Furthermore, in experiments E1.B and E2.B, all emergency responders and emergency vehicle types located at the ambulance and fire and rescue stations were distributed equally. The number of emergency responders at each station was dependent on the number of ambulance and fire and rescue stations specified in the case study (Chapter 10, Table 11.2). In contrast, in experiments E3.B and E4.B, all types of emergency responders and vehicles located at the ambulance and fire and rescue stations were distributed unequally, but the numbers available were dependent on the resources available in the case study area (Chapter 10, Table 11.2).

Timelines of emergency responses to MCI

The primary emergency response was initiated at 13:00pm GMT at incident sites BA and BNS. All available emergency resources were subsequently allocated to these two sites (Figure 11.5 A-D). The first team of emergency responders arrived at incident sites BA and BNS from Hay Mills (HMFS) and Billesley fire station (BFS) at 13:14 and 13:12pm GMT, respectively (Figure 11.5 A-D). The arrival times of the first emergency responder arriving at each incident site, BA and BNS, were the same in experiments E1.B to E4.B as a result of using the GHA to generate the PDA response plan. Figure 11.5 depicts the timelines of the emergency response generated from experiments E1.B to E4.B.

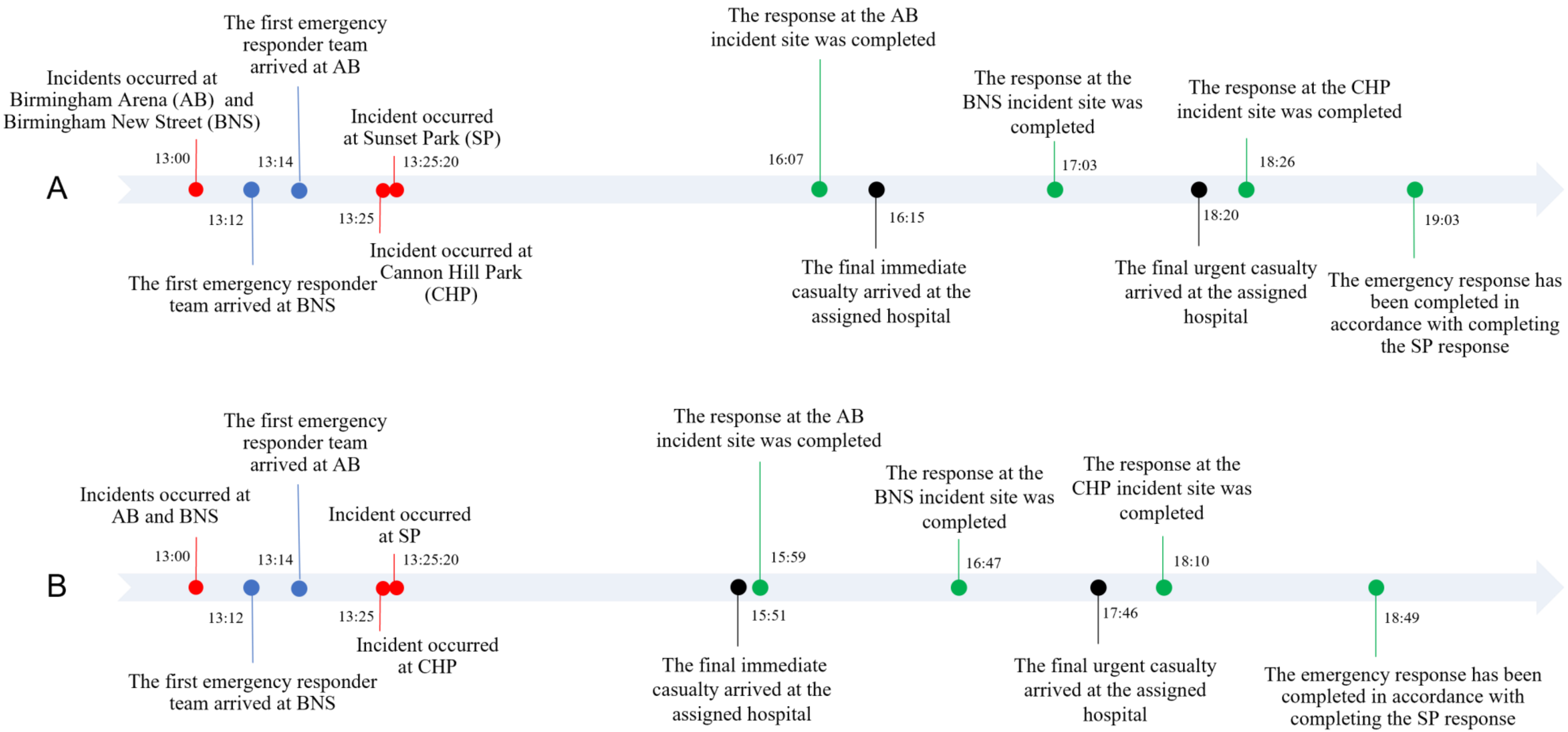


Figure 11.5: Timelines of emergency responses to mass casualty incident from A) experiment E1.B, B) experiment E2.B, C) experiment E3.B, and D) experiment E4.B in the case study area of Birmingham city centre (based on 50 runs).

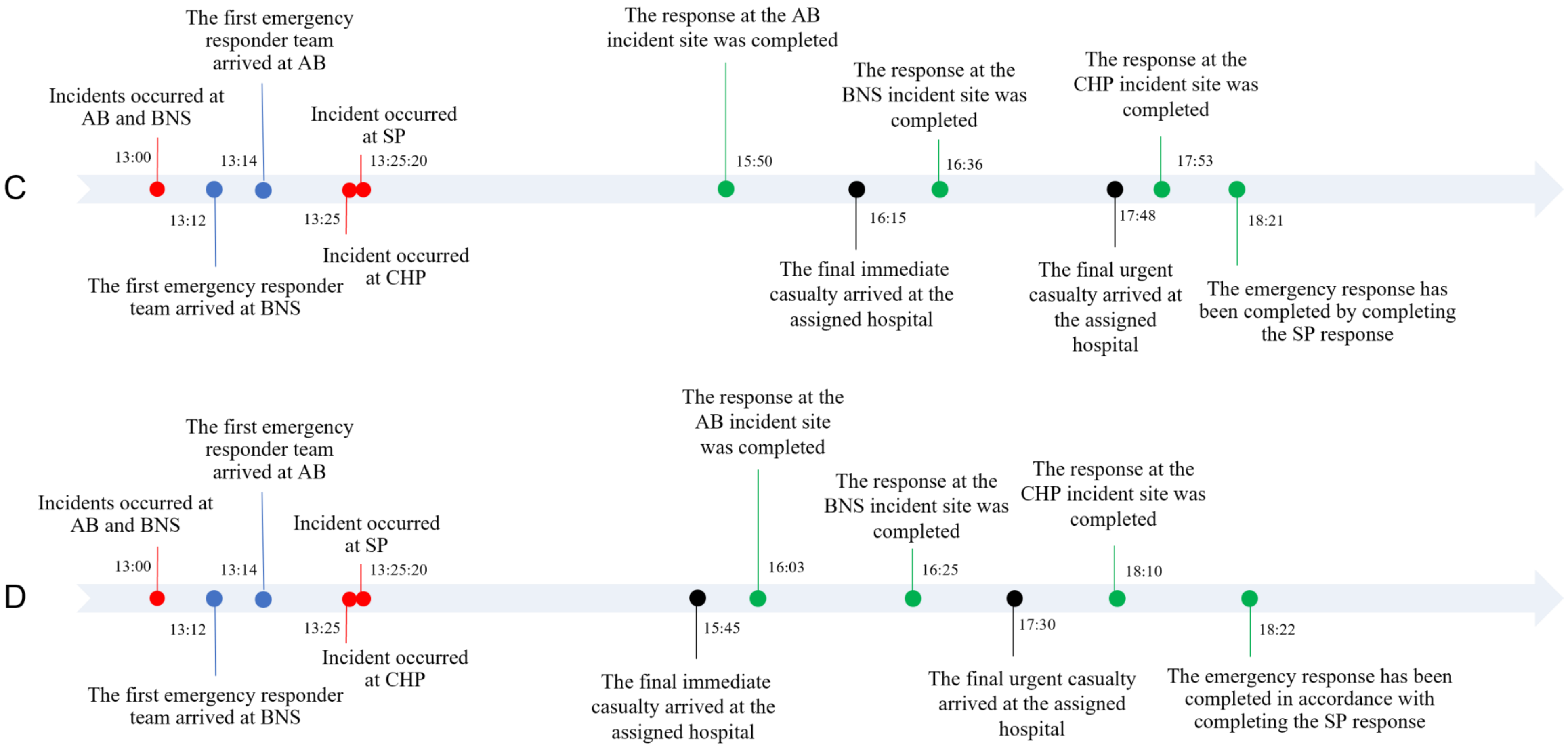


Figure 11.5: Timelines of emergency responses to mass casualty incident from A) experiment E1.B, B) experiment E2.B, C) experiment E3.B, and D) experiment E4.B in the case study area of Birmingham city centre (cont.).

The timelines in Figure 11.5 highlight that the emergency response was completed when the final emergency responders at incident site SP had completed all of their tasks associated with the casualties in experiments E1.B to E4.B. The mean response time in experiments E3.L and E4.L were comparable, 5.35 (±0.60) and 5.37 (±0.49) hours, respectively (Figure 11.5 C). The slowest emergency response completion time was in experiment E1.B, with a mean completion time of 6.05 (±0.40) hours (Figure 11.5 A).

Initial allocation of emergency responders to incident sites

The results presented in Table 11.8 represents the total and mean numbers of all different types of emergency responders based on their initial locations and following their allocation to incident sites BA, BNS, CHP, and SP in experiments E1.B to E4.B. Emergency responders were distributed among two ambulance stations and four fire and rescue stations. The two ambulance stations were West Bromwich (WBAS) and West Midlands ambulance station (WMAS). The four fire and rescue stations were BFS, HMFS, Highgate (HFS), and West Bromwich fire stations (WBFS). It is clear from the results presented in Table 11.8 that no emergency responders were allocated to the incident sites CHP and SP from their initial locations, which is likely to be a result of the timing of the incidents at CHP and SP occurring following the primary incidents at incident sites BA and BNS (Chapter 10, Table 11.2). In a similar manner to the London city centre simulations, following the development of two new incident sites, CHP and SP, there was a reallocation of some emergency responders to these two new incident sites.

Table 11.8: Mean (±S.D) number of emergency responders of all types allocated from their initial locations to each incident site from experiments E1.B to E4.B in the case study area of Birmingham city centre (based on 50 runs).

Experiments		E1.B					E2.B					E3.B					E4.B				
Incident sites		BA	BNS	CHP	SP	T	BA	BNS	CHP	SP	T	BA	BNS	CHP	SP	T	BA	BNS	CHP	SP	T
Ambulance stations	WBAS	18	17	0	0	35	20	15	0	0	35	21	19	0	0	40	23	17	0	0	40
	WNAS	18	17	0	0	35	18	17	0	0	35	15	15	0	0	30	16	14	0	0	30
Fire and rescue stations	BFS	10	7	0	0	17	9	8	0	0	17	8	13	0	0	21	9	12	0	0	21
	HMFS	7	10	0	0	17	9	8	0	0	17	15	6	0	0	21	12	9	0	0	21
	HFS	10	8	0	0	18	12	6	0	0	18	4	10	0	0	14	9	5	0	0	14
	WBFS	8	10	0	0	18	10	8	0	0	18	8	6	0	0	14	8	6	0	0	14
Total		**71** (±3)	**69** (±4)	**0**	**0**	140	**78** (±6)	**62** (±3)	**0**	**0**	140	**71** (±4)	**69** (±4)	**0**	**0**	140	**77** (±5)	**63** (±7)	**0**	**0**	140

BA, Birmingham Arena; BNS, Birmingham New Street; CHP, Cannon Hill; SP, Sunset Park; T, total; WBAS, West Bromwich ambulance station; WMAS, West Midlands ambulance station; BFS, Billesley fire station; HMFS, Hay Mills fire station; HFS, Highgate fire station; WBFS, west Bromwich fire station.

The results presented in Table 11.8 confirm that the developed decision support model was able to incorporate new information relating to new incidents occurring at new incident sites as the MCI developed by relocating emergency resources from one incident site to another. These results confirm that the decision support model behaved in the same manner for experiments E1.B to E4.B as it had previously for experiments E1.L to E4.L, demonstrating its reliability in different case study areas. The number of emergency responders of all types allocated to incident sites BA and BNS was identical in experiments E1.B and E3.B (Table 11.8). Interestingly, the mean number of emergency responses of all types allocated BA, 78 (55%) and 62 (44%) was moderately larger than BNS 77 (55%) and 63 (45%) for experiments E2.B and E4.B, respectively (Table 11.8). These results further support the suggestion that the allocation of emergency resources was dependent on the number of casualties, evident when comparing incident sites BA and BNS. Furthermore, the results presented in Table 11.8 indicate that the initial location of emergency responders had no impact on the allocation of emergency responders to each of the incident sites.

Reallocation of emergency responders to incident sites

As the MCI response developed, subsequent incidents occurred at incident sites CHP and SP. As anticipated, the decision support model was able to evolve and incorporate these new incident sites into its simulations. Following the new incidents at the incident sites CHP and SP, the allocation of emergency resources was subsequently modified, with the reallocation of emergency responders of all types from incident sites BA and BNS. The results presented in Table 11.9 is the changes in the mean number of emergency responders of all types allocated to incident sites BA, BNS, CHP and SP at hourly intervals following the primary emergency response in experiments E1.B to E4.B. The term ‘other’ indicates that emergency responders were not located at a specific incident site; rather they may have been travelling to an incident site or transporting a casualty to an assigned hospital. The results in Table 11.9 clearly demonstrate that a large proportion of emergency responders were allocated to the first two incident sites BA and BNS, which subsequently remained at these incident sites until 15:00pm GMT. The allocation of emergency responders for the initial two hours at the incident sites BA and BNS subsequently delayed the arrival of emergency responders at incident sites CHP and SP and is likely to have contributed to a prolonged emergency response greater than five hours. These findings indicate that a low density of emergency services resulted in a delayed and prolonged emergency response despite the number of emergency responders involved in the response.

Table 11.9: Mean (±S.D) number of emergency responders of all types reallocated to incident sites at hourly intervals following the initiation of the emergency response from experiments E1.B to E4.B in the case study area of Birmingham city centre (based on 50 runs).

Emergency response time	Incident sites	E1.B	E2.B	E3.B	E4.B
14:00	BA	39 (±11)	46 (±14)	39 (±12)	29 (±7)
	BNS	40 (±5)	41 (±9)	31 (±6)	42 (±5)
	CHP	23 (±4)	20 (±11)	37 (±13)	34 (±8)
	SP	19 (±6)	23 (±9)	11 (±7)	20 (±8)
	Other	19 (±7)	10 (±4)	22 (±10)	15 (±5)
	Total	140	140	140	140
15:00	BA	46 (±9)	43 (±11)	35 (±12)	36 (±15)
	BNS	43 (±9)	32 (±2)	28 (±4)	30 (±5)
	CHP	17 (±5)	25 (±8)	28 (±7)	29 (±12)
	SP	22 (±3)	16 (±4)	14 (±5)	19 (±7)
	Other	12 (±7)	24 (±9)	35 (±13)	26 (±7)
	Total	140	140	140	140
16:00	BA	5 (±3)	0	0	5 (±1)
	BNS	29 (±12)	34 (±7)	26 (±6)	28 (±4)
	CHP	43 (±9)	40 (±10)	48 (±13)	56 (±14)
	SP	29 (±11)	37 (±8)	46 (±11)	40 (±13)
	Other	34 (±14)	29 (±3)	20 (±7)	11 (±3)
	Total	140	140	140	140
17:00	BA	0	0	0	0
	BNS	2 (±1)	0	0	0
	CHP	68 (±17)	76 (±23)	59 (±10)	59 (±11)
	SP	45 (±11)	29 (±7)	75 (±22)	51 (±13)
	Other	25 (±15)	35 (±9)	6 (±3)	30 (±5)
	Total	140	140	140	140
18:00	BA	0	0	0	0
	BNS	0	0	0	0
	CHP	37 (±7)	14 (±2)	0	15 (±3)
	SP	86 (±13)	102 (±28)	124 (±26)	103 (±13)
	Other	17 (±4)	24 (±5)	16 (±5)	22 (±6)
	Total	140	140	140	140

BA, Birmingham Arena; BNS, Birmingham New Street; CHP, Cannon Hill; SP, Sunset Park.

Objective functions

The mean time from the objective functions $f_1(x)$, $f_2(x)$, $f_3(x)$, and $f_4(x)$ is presented as hours and is depicted in Figure 11.6 for experiments E1.B (A), E2.B (B), E3.B (C) and E4.B (D).

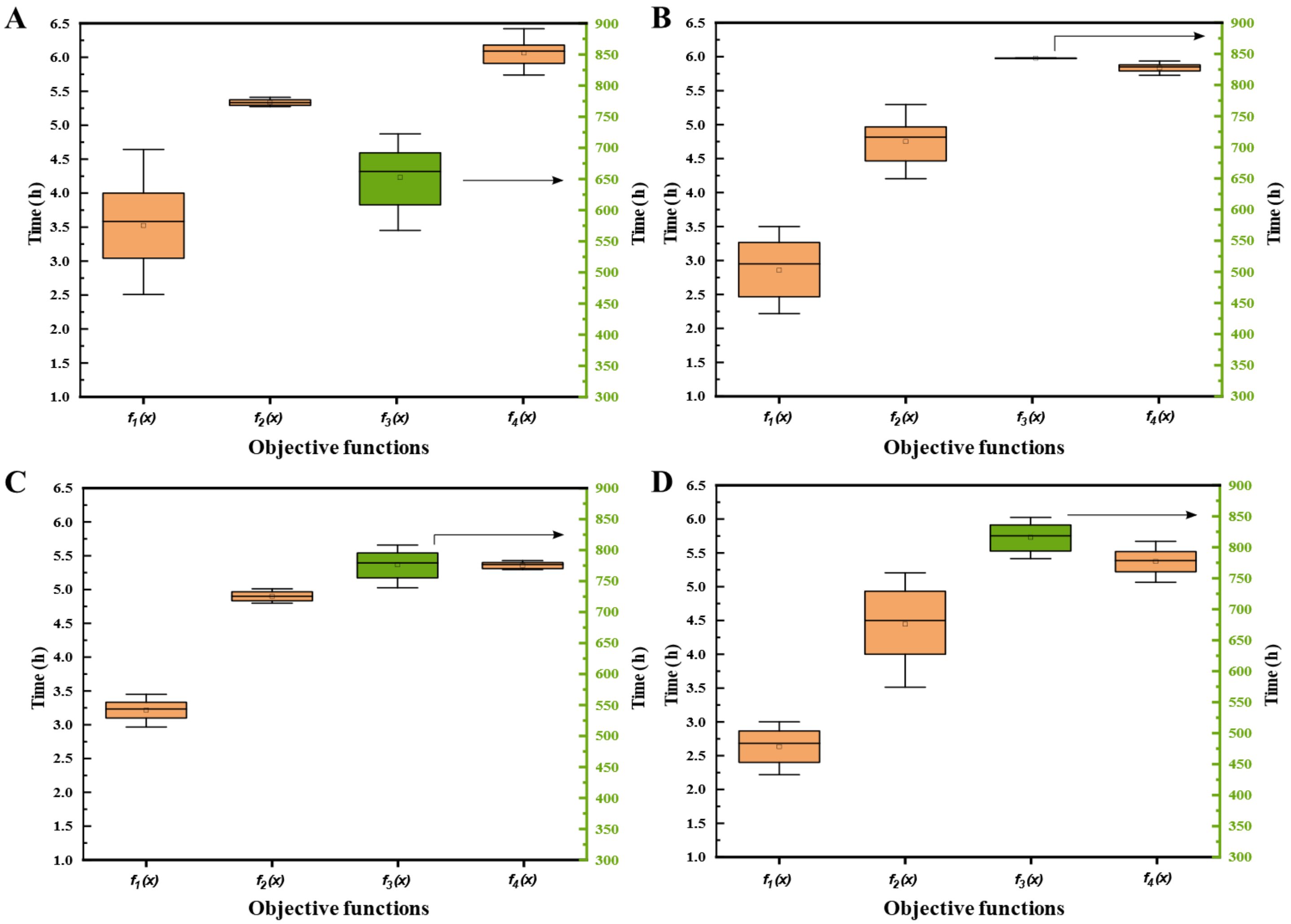


Figure 11.6: Boxplots presenting mean time from the four objective functions for A) experiment E1.B, B) experiment E2.B, C) experiment E3.B, and D) experiment E4.B in the case study area of Birmingham city centre (based on 50 runs).

The results depicted in Figure 11.6 clearly demonstrate that the values from objective functions $f_1(x)$-$f_4(x)$ in experiments E1.B to E2.B were higher than those in experiments E3.B to E4.B (Figure 11.6 A-D) due to the 100 new casualties who were introduced when the incidents at CHP and SP occurred in experiments E1.B to E2.B. This number of casualties is considerably higher than the 60 casualties who were introduced when the incidents at CHP and SP occurred in experiments E3.B to E4.B.

Allocating casualties to hospitals

In the case study area of Birmingham city centre, there are two hospitals, Birmingham City Hospital (BCH) and Queen Elizabeth Hospital (QEH). The casualty allocation to BCH in experiments E1.B was 110 (55%), 109 (54%) in E2.B, 101 (50%) in and 97 (48%) in E4.B. However, QEH received slightly less casualties across experiments: E1.B 90 (45%), E2.B 91 (45%), E3.B 99 (49%) and E4.B 93 (46%). These results indicate that the distance between BCH and QEH and the incident sites BA, BNS, and SP were similar, evident by the comparable casualty allocations.

Health profiles of casualties

The health profiles and severity of the injuries that were present when casualties arrived at their assigned hospitals in experiments E1.B to E4.B is presented in Table 11.10. These results clearly demonstrate that the highest proportion of casualties arriving at their assigned hospitals, over 40% required immediate care, signifying that their injuries were severe (Table 11.10). Furthermore, in the case study area of central London, there were no mortalities. However, this was not the case in the case study area of Birmingham city centre. The mean number of mortalities arriving at the assigned hospitals in experiments E1.B to E4.B was 8 (9%), 14 (7%), 20 (10%) and 20 (10%), respectively. The remaining results for casualties requiring urgent and delayed medical attention is presented in Table 11.10.

Table 11.10: Severity of health profiles of casualties when they arrived at the hospitals from experiments E1.B to E4.B in the case study area of Birmingham city centre (based on 50 runs).

Experiments	Health classification of casualties				Total
	Immediate	Urgent	Delayed	Mortality	
E1.B	92 (±6)	42 (±4)	48 (±2)	8 (±4)	200
E2.B	82 (±7)	44 (±8)	40 (±7)	14 (±3)	200
E3.B	94 (±11)	46 (±3)	40 (±5)	20 (±6)	200
E4.B	90 (±9)	50 (±6)	40 (±3)	20 (±6)	200

11.3.2 New incidents occur sequentially at 30-minute intervals following the primary incident (experiments E5.B to E8.B).

The experimental procedures for E5.B to E8.B were a repeat of experiments E1.B to E4.B; however, the occurrence of the incidents was modified. The primary incident occurred at the BA incident site on a Saturday afternoon at 13:00pm GMT, which was then following by three new incidents at incident sites BNS, CHP, and SP, with each occurring at 30-minute intervals (Figure 11.7).

Timelines of emergency response to MCI

The primary incident occurred at 13:00pm GMT at the incident site BA. As this was the only MCI at the time, all types of emergency responders were allocated to this site (Figure 11.7 A-D). The first team of emergency responders arrived at incident site BA from HMFS at 13:14pm GMT (Figure 11.7 A to D). The arrival time of the first team to incident site BA was the same for experiments E5.B to E8.B as a result of executing the GHA. Figure 11.7 depicts the timelines of emergency responders presented as the mean response time in hours. The occurrence times of incidents and the mean (1) arrival time of the first responder team to an incident as part of the PDA response plan; (2) final immediate and urgent casualty arrival times at the assigned hospitals, and (3) completion times of the four incident sites from experiments E5.B to E6.B.

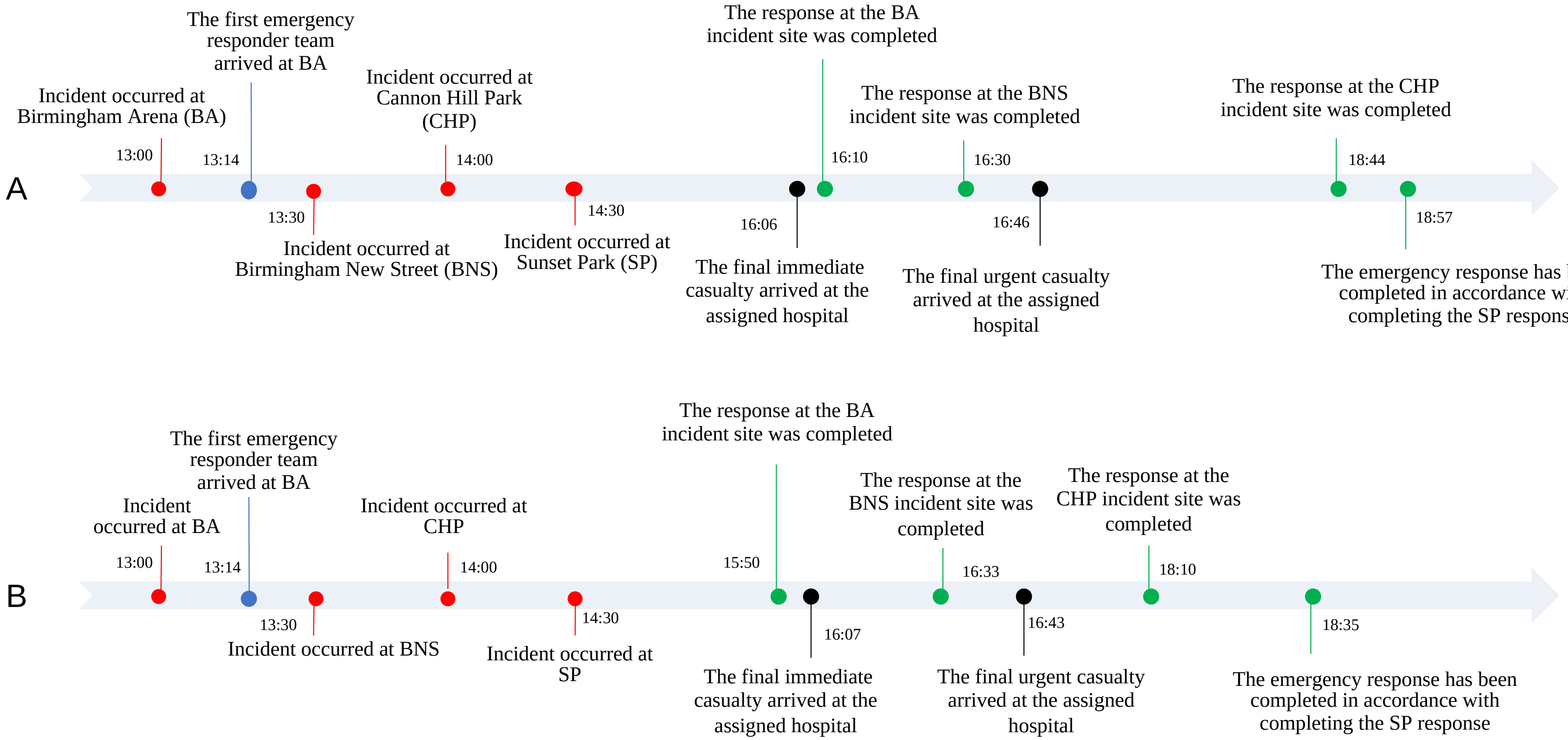


Figure 11.7: Timelines of emergency responses to mass casualty incidents from A) experiment E5.B, B) experiment E6.B, C) experiment E7.B and D) experiment E8.B in the case study area of Birmingham city centre (based on 50 runs).

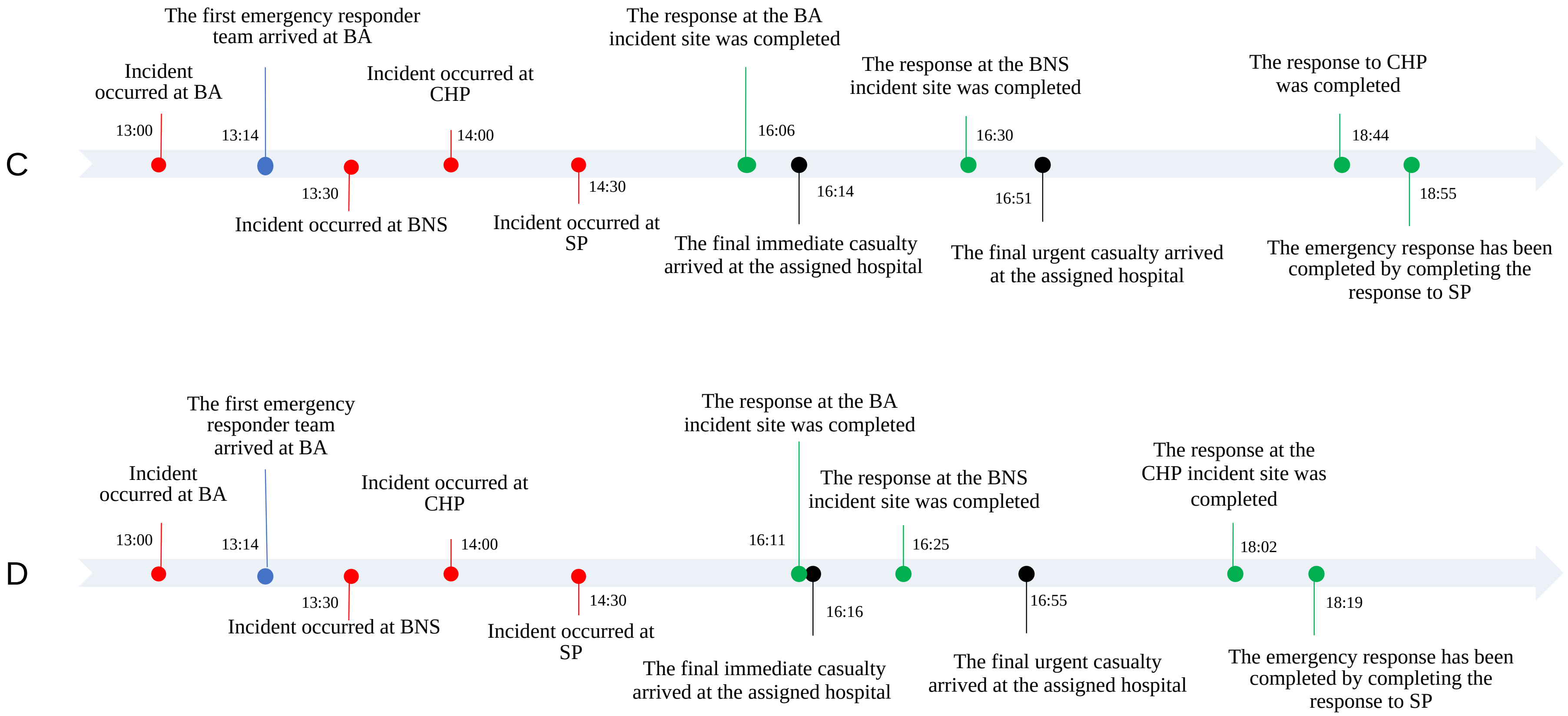


Figure 11.7: Timelines of emergency responses to mass casualty incident from A) experiment E5.B, B) experiment E6.B, C) experiment E7.B and D) experiment E8.B in the case study area of Birmingham city centre (cont.).

The timelines in Figure 11.7 from experiments E8.5 to E8.B illustrates that the emergency response was completed when all tasks associated with casualties at incident site SP were finished. The fastest emergency response time was in experiment E8.B, 5.27 (±0.11) hours (Figure 11.7 D), and the slowest response time was in experiment E5, 5.95 (±0.15) hours (Figure 11.7 A).

Reallocating emergency responders to incident sites

As the MCI response continued to develop, the decision support model was able to include subsequent incidents and incident sites at BNS, CHP and SP into the simulation model. The allocation of the emergency resources was then modified to ensure all casualties could be treated effectively and promptly. Initially all emergency responders were allocated to incident site BA, which was then modified, resulting in a reallocation of emergency responders to the new incident sites BNS, CHP and SP as they occurred. The results presented in Table 11.11 from experiments E5.B to E8.B show the changes in mean number of all types of emergency responders allocated to incident sites BA, BNS, CHP, and SP at hourly intervals, following the primary emergency response at incident site BA. The term ‘other’ indicates that emergency responders were not located at a specific incident site, rather they may be travelling to an incident site or transporting casualties to their assigned hospitals. The results regarding the mean number of emergency responders presented in Table 11.11demonstrate that a high proportion of emergency responders were allocated to incident sites BA and BNS at 14:00 and 15:00pm GMT from experiments E5.L to E8.L when compared to those of the other incident sites. As the incidents at BA and BNS occurred first, it is no surprise why these emergency responses were completed before those at incident sites CHP and SP (Table 11.11 A-D).

Table 11.11: Mean (±S.D) number of emergency responders of all types reallocated to other incident sites at hourly intervals following the initiation of the emergency response from experiments E5.B to E8.B in the case study area of Birmingham city centre (based on 50 runs).

Emergency response time	Incident sites	E5.B	E6.B	E7.B	E8.B
14:00	BA	43 (±10)	38 (±13)	46 (±5)	41 (±16)
	BNS	39 (±6)	48 (±11)	25 (±10)	33 (±9)
	CHP	0	0	0	0
	SP	0	0	0	0
	Other	58 (±22)	54 (±15)	69 (±30)	66 (±20)
	Total	140	140	140	140
15:00	BA	36 (±9)	40 (±3)	45 (±11)	32 (±7)
	BNS	41 (±5)	34 (±7)	31 (±3)	34 (±14)
	CHP	32 (±10)	20 (±12)	30 (±9)	32 (±6)
	SP	11 (±4)	27 (±9)	24 (±11)	22 (±5)
	Other	20 (±11)	19 (±16)	10 (±6)	20 (±7)
	Total	140	140	140	140
16:00	BA	3 (±1)	1 (±2)	4 (±1)	8 (±5)
	BNS	20 (±11)	18 (±3)	16 (±9)	10 (±7)
	CHP	52 (±17)	59 (±12)	40 (±10)	58 (±11)
	SP	50 (±10)	41 (±21)	65 (±10)	21 (±12)
	Other	15 (±7)	22 (±7)	15 (±8)	43 (±20)
	Total	140	140	140	140
17:00	BA	0	0	0	0
	BNS	0	0	0	0
	CHP	69 (±11)	80 (±5)	75 (±20)	54 (±13)
	SP	33 (±6)	43 (±12)	45 (±15)	60 (±21)
	Other	38 (±10)	17 (±9)	20 (±13)	26 (±10)
	Total	140	140	140	140
18:00	BA	0	0	0	0
	BNS	0	0	0	0
	CHP	31 (±2)	14 (±11)	36 (±6)	2 (±1)
	SP	86 (±12)	97 (±22)	86 (±15)	98 (±29)
	Other	23 (±6)	29 (±7)	18 (±9)	40 (±16)
	Total	140	140	140	140

BA, Birmingham Arena; BNS, Birmingham New Street; CHP, Cannon Hill; SP, Sunset Park.

Objective functions

The mean time presented in hours from the objective functions $f_1(x)$, $f_2(x)$, $f_3(x)$, and $f_4(x)$ is depicted in Figure 11.8 for experiments E5.B (A), E6.B (B), E7.B (C) and E8.B (D).

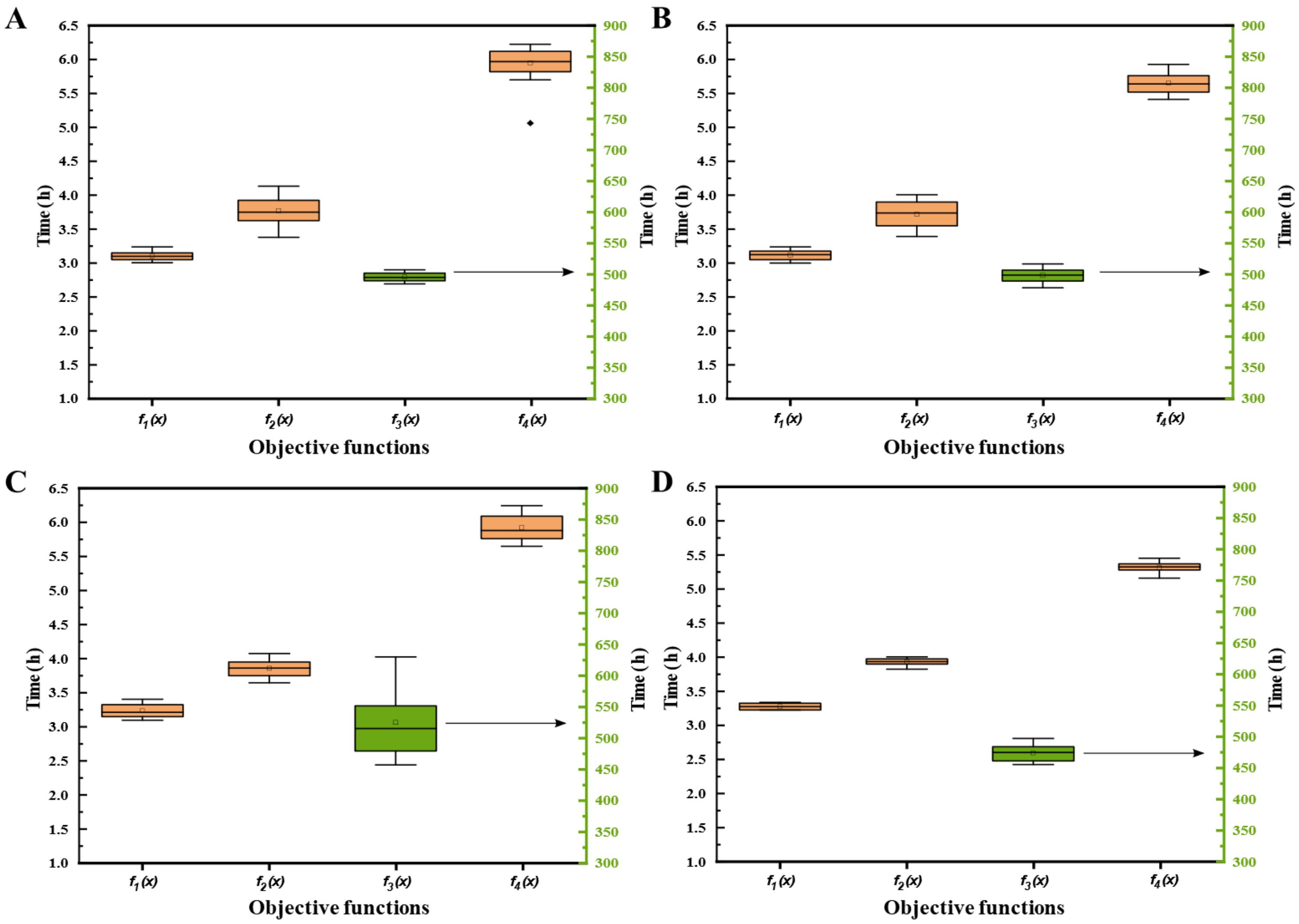


Figure 11.8: Boxplots presenting mean time in hours from the four objective functions for A) experiment E5.B, B) experiment E6.B, C) experiment E7.B, and D) experiment E8.B from the case study area of Birmingham city centre (based on 50 runs).

The results presented in Figure 11.8 illustrate that the mean arrival times at hospital of the final casualty requiring immediate medical attention, $f_1(x)$, the mean arrival times at hospital of the final casualty requiring urgent medical attention, $f_2(x)$, and the processing time of casualties, $f_3(x)$, in experiments E5.B-E8.B. It is clear from Figure 11.8 that response times were similar across experiments E5.B 3.11, 3.77, and 496, E6.B 3.12, 3.72, and 498, E7.B 3.24, 3.86, and 525, and E8.B 3.27, 3.93, and 474 hours, for objective function ($f_1(x), f_3(x)$ and $f_3(x)$, respectively (Figure 11.8 A-D). In Figure 11.8(A), the value of the objective function $f_4(x)$ of an emergency plan that lies outside the overall distribution pattern of the values of the same function from other emergency plans is called an outlier. The reader is referred to Appendix D for a comprehensive discussion regarding the anticipated factors contributing to getting such a value.

Allocating casualties to hospitals

As previously stated in experiments E1.B to E4.B, there were two hospitals, BCH and QEH in the case study area of Birmingham city centre. The mean casualty allocation to BCH in experiments E5.B was 109 (45%), 103 (51%) in E6.B, 103 (51%) in E7.B and 92 (46%) in E8.B. However, QEH received slightly less casualties across experiments: E5.B 91 (45%), E6.B 97 (48%). E7.B 97 (48%) and E8.B 92 (46%). These results indicate that the distance between BCH and QEH and the incident sites BA, BNS, and SP were similar, evident by the comparable casualty allocations.

Health profiles of casualties

The health profiles and severity of the injuries that were present when casualties arrived at their assigned hospitals in experiments E5.B to E8.B is presented in Table 11.10. These results clearly demonstrate that the highest proportion of casualties arriving at their assigned hospitals, over 30% required immediate care, signifying that their injuries were severe (Table 11.12). Furthermore, in the case study area of central London, there were no mortalities. However, this was not the case in the case study area of Birmingham city centre. The mean number of mortalities arriving at the assigned hospitals in experiments E4.B to E8.B was 12 (6%), 8 (4%), 12 (6%) and 4 (2%), respectively. The remaining results for casualties requiring urgent and delayed medical attention is presented in Table 11.10.

Table 11.12: Severity of health profiles of casualties when they arrived at the hospitals from experiments E5.B to E8.B in the case study area of Birmingham city centre (based on 50 runs).

Experiments	Health classification of casualties				Total
	Immediate	Urgent	Delayed	Mortality	
E5.B	74 (±2)	68 (±8)	46 (±2)	12 (±4)	200
E6.B	70 (±5)	70 (±6)	52 (±3)	8 (±2)	200
E7.B	68 (±3)	66 (±6)	54 (±1)	12 (±5)	200
E8.B	68 (±4)	70 (±4)	58 (±3)	4 (±8)	200

11.3.3 Results summary

The mean objective function values for $f_1(x)$ to $f_4(x)$ in experiments E1.B to E8.B were similar, regardless of the 30-minute time lapse for subsequent incidents occurring at other incident sites (Figures 10.6 and 10.8). The findings in experiments E5.B to E8.B suggest that 30 minutes was sufficient for emergency responders to complete their assigned tasks associated with casualties at one incident site prior to being reallocated to subsequent incidents at new incident sites.

The results from the case study area of Birmingham city centre suggest that the location of ambulance, fire and rescue stations in relation to incident sites may have had a detrimental effect on emergency responders by impeding their ability to promptly arrive at the first incident site. The delayed arrival of emergency responders to the first incident site BA resulted in subsequent delays in reallocating a sufficient number of emergency responders in a timely manner to subsequent incidents (Tables 10.9 and 10.10). Although these delays may appear trivial, the findings from experiments E1.B to E8.B suggest that this delayed response had a direct effect on casualties, with a >2% number of fatalities and >30% number of casualties requiring immediate medical attention, indicating that their injuries were severe upon arriving at their allocated hospitals. Furthermore, the findings in experiments E1.B to E8.B align with those of Rezapour et al. [61], where any delay in treatment and transport of casualties to hospitals, such as remaining at the incident site for prolonged periods of time, is likely to be responsible for the increased severity of injuries casualties sustained, and ultimately leading to an increase in mortality. Moving forward, establishing small bases of ambulance and fire and rescue stations close to historical incident sites or to public areas in case study areas that may lack emergency service resources, e.g., the case study area of Birmingham city centre, may reduce travel time and improve response time to ensure prompt arrival of emergency responders to incident sites and thus reduce injury severity and mortality. Further research is required to identify optimal locations for establishing bases of ambulance and fire and rescue stations in relation to incident sites to maximise emergency resources and optimise emergency response in the MCI-affected area.

The mean proportion of emergency responders assigned to the incident sites BA and BNS were both 71 and 69 in experiments E1.B and E3.B, respectively (Table 11.8). However, in experiments E2.B and E4.B, there was a larger proportion of emergency responders allocated to the incident site BA, with 68 and 77, respectively (Table 11.8). The findings in Table 11.8 demonstrate a clear association between the initial number of casualties at incident sites and the allocation of emergency responders to incident sites.

The findings of casualties to hospitals allocation from experiments E1.B to E8.B, confirm similar findings from the case study area of central London, where the geographical location of the hospital in relation to the incident sites had a significant impact on casualty allocation to hospitals. In principle, allocating casualties to the closest hospitals in an attempt to reduce the transport time and minimise the risk to casualties is rational. However, this may result in the closer hospitals becoming overwhelmed, subsequently increasing the risk to casualties as they may not receive appropriate care in a time dependent manner, confirming the previous work of Repoussis et al. [64].

11.4 Discussion

Although MCIs are not common events, effective simulations and modelling of MCIs could have a profound effect on the coordination of emergency responders and therefore reduce morbidity and mortality. The decision support model developed in this thesis has been developed accounting for common limitations in the literature, whilst using real life data relating to the case study areas of central London and Birmingham city centre, as discussed earlier in this chapter.

In this thesis, the lexicographic approach has been used to define the priority level of objective functions $f_1(\text{x})$-$f_4(\text{x})$, discussed in Chapter 8 (Section 8.3). The approach refers to the preferences imposed to order the defined objective functions according to their respective significance. Objective function $f_1(\text{x})$ was ordered first because it is associated with the casualties who require immediate medical attention and have therefore sustained critical casualties and who are at the highest risk of losing their lives. Objective function, $f_2(\text{x})$, which relates to casualties that require urgent medical attention but are deemed not to be as severe as those casualties requiring immediate care (f_1(x)), was ranked in second place. Reducing the time casualties waited for treatment and the time required for emergency responders to perform all of their associated tasks in relation to casualties was ordered as number three (f_3(x)). Objective function f_4(x) was ranked in fourth place, as a delay in the time casualties had to wait for medical treatment (f_3(x)) was ranked higher than the emergency response time f_4(x).

The results presented in Figures 10.2, 10.4, 10.6 and 10.8 are the mean values of the four objective functions with a clear hierarchy from objective function $f_1(x)$ to objective function $f_4(x)$. However, the mean values of objective function $f_3(x)$ are not comparable with objective functions $f_1(x)$, $f_2(x)$, and $f_4(x)$, because objective function $f_3(x)$ relates to all casualties at all incident sites, meaning the times are not suitable for comparison. The arrival time at the assigned hospitals for the final immediate casualty across all incident sites ($f_1(x)$) in all experiments was lower than the mean values of objective functions $f_2(x)$, $f_3(x)$ and $f_4(x)$. Similarly, the mean emergency response times ($f_4(x)$) in all experiments was higher than the mean values of objective functions $f_1(x)$ and $f_2(x)$. The results presented in this chapter using the lexicographic approach are comparable to previously published research using similar techniques [65, 131].

The timelines presented in Figures 10.1, 10.3, 10.5, and 10.7, clearly demonstrate that the arrival time at the hospital of the final casualty requiring immediate medical was earlier than the arrival time of the final urgent casualty to the assigned hospital. Furthermore, the arrival time at the hospital of the final urgent casualty requiring medical attention was always earlier than the arrival time of the final delayed casualty to the assigned hospital, which also signified the completion of the emergency response to the MCI. The data presented in this chapter demonstrates that the decision support model incorporating the lexicographic approach was able to triage and priorities casualties' injuries based on severity, and thus aim to minimise morbidity and mortality. Future research should aim to develop similar approaches, where models for simulating MCIs is able to prioritise multiple objective functions and can improve the response to an MCI by ensuring the arrival of their most critical casualties to the assigned hospital as quickly as possible, and in doing so reduce mortalities.

The results observed in Sections 11.2 and 11.3 in both case study areas, central London and Birmingham city centre demonstrated the generation of the objective function values was influenced by the number of parameters. Particularly, there was a clear effect on the objective function values when accounting for the times at which incidents occurred at incident sites occurred, casualty distribution, and hospital locations, allocation of emergency responders to tasks at incident sites, and the allocation of casualties to hospitals. Nevertheless, one clear finding from this chapter was that the initial location of emergency responders had little or no impact upon assigning emergency responders to tasks at incident sites. Furthermore, the results in Sections 11.2 and 11.3 for both case study areas in central London and Birmingham city centre will be compared to study the rational of the differences in the overall results between the case study area of central London and Birmingham city centre, despite the same number of emergency responders and vehicles being available in the simulations.

11.4.1 Objective functions of the post-PDA response plans

The results obtained in experiments E1.L to E8.L and experiments E1.B to E8.B revealed an association between the times at which incident sites occurred and the values of the objective functions. In the case study area of central London, the emergency response at incident sites was completed in a time ranging from 43-60 minutes in experiments E5.L to E8.L. In contrast, the mean objective function values for $f_1(x)$ to $f_4(x)$ in experiments E1.B to E8.B were comparable despite the 30-minute intervals between the occurrence of new incidents. However, when comparing with the 43–60 minute completion times in the case study area of London, the completion of the emergency response at the incident sites in Birmingham city centre was considerably longer, ranging from 170-245 minutes in experiments E5.B to E8.B. These findings provide a novel insight relating to both preparedness of a city to an MCI and the impact of multiple incidents occurring. Although there was a clear delay in the completion times of Birmingham 170-245 vs. 43-60 minutes in London, there did not appear to be any difference in the arrival of casualties to hospitals or mortality rates when comparing experiments E1.B to E4.B with E5.B to E8.B in the Birmingham case study area. In contrast, there was a clear increase in the response time in the later incidents when compared with the earlier incidents in central London. Despite this prolonged time for the latter experiments, there was no increase injury severity (immediate vs. urgent, etc.) or mortality, which is likely to be due to the preparedness of central London. The preparedness of any location to respond to an MCI is crucial. Furthermore, developing approaches as to how cities are to reduce mean objective function times as those reported in this chapter, whilst ensuing no delay in medical care and reducing mortality is the goal for any emergency response to an MCI. Further work is therefore required to investigate how to optimise emergency responses in cities that may not be as prepared, such as the comparison between central London and Birmingham city centre reported in this chapter.

The level of preparedness in this context refers to the density of ambulance, fire and rescue stations, and hospitals in the 100 km^2 of the MCI-affected geographical area. The MCI-affect area was previously defined and discussed in Chapter 7 (Section 7.2). Large metropolitan cities around the world, such as central London, are well prepared for MCI events due to their well-distributed ambulance and fire and rescue stations, meaning a rapid response, fewer casualties, and more hospitals to manage MCI events. Although Birmingham city centre is a large metropolitan city, it is deemed to have an adequate level of preparedness, where the location of ambulance, fire and rescue stations, and hospitals can significantly impact the response to an MCI event. The findings in this chapter clearly demonstrate that the mean values of objective functions $f_1(x)$ to $f_4(x)$ from experiments E1.L to E8.L (Figures 10.2 and 10.4) were lower than those from experiments E1.B to E8.B (Figures 10.6 and 10.8). The results of this chapter clearly demonstrate that an increase in preparedness has a clear effect on objective functions resulting in casualties waiting for less time before being treated and arriving at hospitals in a shorter time.

The results reported in Sections 10.2 and 10.3 for the case study areas of central London and Birmingham city centre, respectively, indicate that the city layout, emergency services and hospital locations have a considerable impact upon a cities response to MCIs. These results are further substantiated when we account for the fact that the number of emergency responders and vehicles considered in both case study areas were the same. Despite the same resources being available, in the simulations the density of ambulance, fire and rescue stations, and hospital locations in respect to their proximity to the incident sites in the case study area of central London led to an improved response to MCIs, in terms of the mean values of objective functions and casualties' health classifications upon arriving at hospitals. Although the findings here are clear, further work is required to ascertain if these findings can be replicated using different incident sites whilst minimising any bias when selecting incident sites. Furthermore, it may be of interest to examine a variety of different allocation strategies similar to those previously conducted by Hawe et al. [66]. A deeper insight into a how a cities preparedness impacts upon an emergency response to MCIs, and how preparedness can be improved is important for providing an optimal emergency response when accounting for the emergency services available.

11.4.2 Emergency responder allocation to specific tasks at incident sites

In order to arrive at an incident site in the shortest space of time, the initial location of emergency responders appears to be pivotal when developing a decision support model that can simulate a coordinated emergency response to an MCI. For example, if an emergency responder is located close to an incident site, this would ultimately result in a more rapid response time. However, as previously indicated in Chapter 5 (Section 5.3.3), there are inconsistencies in the literature, where some research has, and others have not included the initial location of emergency responders in their decision support models. For example, the initial locations of the emergency responders was included in the work of Hawe et al. [66], however, the authors did not study the effect of the initial location of these emergency responders when allocating emergency responders to tasks associated with casualties at incident sites. Instead, Hawe et al. [66] designed a number of emergency responder allocation strategies and then compared them to ascertain the optimum strategy in terms of reducing the response time. In contrast, the work of Wang et al. [72] and Rauner et al. [75] developed decision support models in relation to MCIs specific to terrorist attacks in the United States, but used unspecified locations. Both studies failed to acknowledge initial locations of emergency responders, presuming that the emergency responders were already at the site where the MCI occurred. Furthermore, the work of Wilson et al. [65] developed a decision support model of a terrorist attack in the UK, and although the authors incorporated a variety of emergency responder, the initial locations of these emergency responders or whether they were presumed to already be at the incident site was unclear. These examples demonstrate key limitations in previous literature, which have been accounted for in the current decision support model, which also identified just how important this information could be in real life MCIs. Although the findings in this chapter provide important insight, there remains the question as to whether during a high-profile MCI, sufficient emergency responders are automatically allocated to the MCI site at the same time the incident occurs. This could only be compared by comparing emergency responses to the exact same MCIs in reality, which is unlikely to ever occur. However, this chapter does clearly demonstrate that the incorporation of the emergency responders initial location in conjunction with casualty numbers, is important to identify real-life scenarios in order for major cities to prepare and optimise responses to a potential MCI event.

Although this chapter clearly demonstrates that the initial location of emergency responder improved emergency response times, the findings presented in Tables 10.1 and 10.8 indicate that the initial locations of emergency responders did not impact upon the assignment of tasks at incident sites. Although further research is required to investigate why this is the case, it may be because the estimated number of casualties reported as part of the PDA response was not correct. That is, the first emergency responders arriving at the incident sites are responsible for reporting on the estimated number of casualties as part of the PDA response plan. This report subsequently influences the number of emergency responders allocated to these incident sites from the ambulance and fire and rescue stations in the MCI-affected area. This was especially evident when the number of reported casualties at the incident site was greater than the actual number of reported casualties as in experiments E2.L to E4.L and E2.B to E4.B. Previous research in the domain of coordinating emergency responses [62, 64, 65, 72, 73, 75] has previously assumed knowledge relating to MCIs, such as the PDA response or the information relating to the MCI. In this chapter we have implemented the PDA response and information relating to the MCI into the simulations, accounting for aspects that can influence outcomes. Moving forward, further research is required to compare the effects of assuming information vs. acquiring real time information from previous emergency responses relating to the PDA response plan on the initial allocation of emergency responders to tasks associated with casualties.

The results presented in Tables 10.1 and 10.8 revealed an association between the initial number of casualties at an incident site and the mean proportion of emergency responders assigned to that incident site, where more casualties mean more allocation of emergency responders. These findings are consistent with previous research [61, 64, 66] and current MCI guidelines, where emergency responders are allocated on a need basis (i.e., more casualties need more emergency responders). In an earlier study by Rezapour et al. [61], the authors studied the effect of mixed ratios of immediate and delayed casualties at an incident site on the allocation of emergency responders. The authors observed that the proportion of emergency responders allocated at the incident site was high, regardless of the casualty mixed ratios (immediate and urgent). In a similar manner to the results presented in this chapter, Repoussis et al. [64] reported that the number of casualties at an incident site influenced the allocation of emergency responders to incident sites and the overall response time. Repoussis et al. [64] also identified that the response time to an incident site with a large number of casualties could be reduced by assigning a larger proportion of emergency responders to those incident sites. However, the authors did not confirm if allocating a larger proportion of emergency responders in this manner could affect other incident sites or overall response time, as reported in this chapter.

Hawe et al. [66] investigated a variety of different allocation strategies in an attempt to optimise response time. The authors compared nine different allocation strategies for allocating emergency vehicles and responders to two incident sites based on the distribution of casualties between the two incident sites. The optimal strategy, resulting in a faster emergency response time, was based on allocating an even distribution of emergency vehicles and responders to each incident site when casualties were distributed equally. Hawe et al. [66] also reported that the emergency response time was reduced when large proportions of emergency responders were allocated to the incident site with the highest number of casualties, again confirming the findings presented in this chapter. Moving forward, further work studying the effects of allocation based on the severity of casualties and the degree of expertise of emergency responders is required in an attempt to ascertain if incorporating this information can improve emergency response time. The results discussed in this section indicate that the proximity of incident sites to fire and rescue stations and ambulance stations does influence emergency responder allocation. However, this is not the only important factor involved in the allocation of emergency responders to tasks associated with casualties at incident sites. Therefore, the initial location, number of emergency responders, emergency responder expertise and experience, as well as the number of casualties at all incident sites, must be incorporated into future decision support models when allocating emergency responders to tasks associated with casualties at incident sites.

11.4.3 Casualty allocation to hospitals

In this chapter, we have clearly demonstrated that in the case study areas of central London, experiments E1.L to E8.L and Birmingham city centre, experiments E1.B to E8.B that the distribution of casualties among incident sites was not the only factor involved in hospital assignment. These results are in alignment with the previously published work of Repoussis et al. [64], who also reported that the distance of the incident site in relation to the location of hospitals was important when allocating casualties to hospitals, confirmed in both case study areas, central London and Birmingham city centre. Although allocating casualties to closer hospitals appears rationale, this is also somewhat worrying, as hospitals may not have the capacity, experience, and facilities to treat specific injuries in casualties. The findings demonstrate the need for a more suitable allocation system that is not based solely on hospital location and may assist in distributing casualties more appropriately. For example, the allocation of casualties requiring immediate and urgent medical care to closer hospitals whilst allocating all other casualties to hospitals further away may be one approach. Such an approach would distribute the workload amongst the hospitals while ensuring casualty safety is the main priority.

An additional alternative could be through the use of small field hospitals that can be established by emergency medical services in the MCI-affected, where casualties can be triaged and treated at the incident site, reducing immediate and urgent casualties. This would reduce the pressure and workload on hospital staff and emergency services, an approach echoed by the advanced medical posts previously used in central European countries such as Austria and Germany [132]. The work of Niessner et al. [132] demonstrated that the appropriate allocation of medical staff to advanced medical posts significantly reduced emergency response time and mortality. Although these findings are promising, further research is required to identify the most appropriate location for the advanced medical posts to be located, accounting for the severity of the incidents and the capacity of hospitals to treat casualties in the MCI-affected area. Further research is required to study the impact of establishing advanced medical posts on emergency response time and providing casualties with medical care in the MCI event.

11.5 Summary

Using the developed decision support model, the results presented in this chapter from simulating a coordinated emergency response to an MCI in the two case study areas, central London and Birmingham city centre from sixteen experiments previously described in Chapter 10, are presented. The findings in this chapter are presented alongside the timelines of the emergency response to multiple MCIs as they unfolded. The results in this chapter include: 1) the mean proportion of emergency responders initially allocated to the primary incident sites, 2) the changes in emergency responder allocation to new incidents and incident sites as the MCIs developed, 3) the mean and standard deviation of the four objective functions, 4) the mean number of casualties allocated to hospitals, and 5) the health profiles of the casualties upon arrival at their assigned hospitals.

This chapter , in conjunction with Chapter 10, fully addressed **RQ3**. The results presented in this chapter demonstrate that the decision support model developed in this thesis was able to be effectively applied to the two case study areas discussed in Chapter 10. Furthermore, this chapter demonstrates that the decision support model was able to elicit a coordinated response of emergency services resources and incorporate new and developing information as the MCI developed. One key finding from this chapter is that the proximity of emergency responders to incident sites was not the only factor involved when allocating emergency responders to incident sites in case study areas in central London and Birmingham city centre. Although further work is required to confirm this, the PDA report may play a key role in allocating emergency responders to incident sites. Furthermore, the results in this chapter revealed the presence of an association between the number of emergency responders assigned to an incident site and the number of casualties at a specific incident site, aligning with previous work [61, 64, 66] and current MCI recommendations. Another important finding presented here is that the distribution of casualties across incident sites was not the sole factor influencing hospital assignment. Instead, the findings in this chapter clearly demonstrate that the geographical location of the hospital in relation to the incident site was important in both case study areas when allocating casualties to hospitals, corroborating previously published research [64]. The development and research into advanced medical posts close to incident sites is one area of research that the findings presented here to support in terms of preparedness. Further research into advanced medical posts may be beneficial in optimising emergency resources and reducing delays in medical intervention.

A subsequent important finding from this chapter is the importance of a case study areas preparedness, accounting for emergency service locations and resources, hospital location and geographical layout. The findings here revealed that the mean values from all four of the objective functions were lower in the case study area of London when compared with Birmingham. These results are further substantiated by the fact that the same number of emergency responders and vehicles were considered in both case study areas, controlling for confounding variables. Although these findings are promising, further research is required to ascertain if these findings can be replicated using different incident sites, minimising any potential selection bias present in the current study. In accordance with findings from previous research and in this chapter, any extension in the time casualties have to wait for treatment at incident sites has a clear detrimental effect on casualty health and may have contributed to an increase in mortality reported in Birmingham city centre. Consideration may be given to establishing small bases of ambulance and fire and rescue stations in an attempt to increase the preparedness of cities for an MCI event. Based on the findings presented in this chapter, the implementation of a dynamic optimisation-based model enables the coordination of the emergency response and simultaneous allocation of emergency service resources to multiple locations in a complex MCI environment. In the next chapter, the developed decision support model will be evaluated in relation to a decision support model’s requirements identified in Chapter 4.

Chapter 12. Evaluate the decision support model

12.1 Introduction

Evaluating a developed model against its requirements can aid in identifying any potential limitations or problems. For instance, it may reveal areas where the model struggles or underperforms, which can then be addressed through additional development or optimisation. Furthermore, it is an important process to ensure that the model meets the desired requirements and is effective for its intended application. Without this evaluation, it may be challenging to determine whether the model is truly effective or whether it requires additional refinement.

This chapter aims to evaluate the developed model against the requirements of a new decision support model that were identified in Chapter 4 and summarised in Table 4.1. This evaluation will focus on how well the developed model satisfies the identified requirements for modelling an MCI environment (RME1-RME29) and coordination decisions (RCD1-RCD3).

12.2 Evaluation of the ability of the decision support model to coordinate the emergency service resources following an MCI

In this section, the ability of the developed model to coordinate the response of emergency service resources to MCIs, including its strengths and weaknesses, is described. The strengths and weaknesses of the developed model are defined based on assessing the developed model against the requirements of modelling an MCI environment (RME1-RME29) and the requirements of coordinated decisions (RCD1-RCD3) that have previously been discussed and defined in Chapter 4.

12.2.1 Modelling an MCI environment

As in Chapter 7 (Section 7.2), an MCI-affected area refers to the geographical area where incidents as part of an MCI may occur that subsequently result in a significant number of casualties with varying degrees of injury severity. An MCI-affected geographical area was defined in a position that covered the locations of all hypothetical incident sites and maximised the number of ambulance stations, fire and rescue stations, and hospitals located in the defined area. However, ambulance stations, fire and rescue stations, or hospitals located outside the defined MCI-affected area were not considered in response to MCIs. All hospitals considered in the defined area must have an Emergency and Accident department and are considered Major Trauma Centres in which acute, surgical, and rehabilitative services are available for casualties in all health classifications in accordance with the previously published report [91]. When modelling an MCI environment, the requirements indicated in Chapter 4 (RME1-RME29) must be satisfied, including: 1) road networks within the MCI-affected geographical area; 2) incident sites; 3) emergency service resources; 4) hospitals; 5) casualties.

Road network of an MCI-affected geographical area

The following must be considered when modelling the road network within an MCI-affected area: RME1 '*model a realistic road network of an MCI-affected geographical area*', RME2 '*extract the accurate distance between key locations of interest in the MCI-affected geographical area*', RME3 '*define credible travel times of emergency vehicles*. To ensure RME1-RME3 are all considered when modelling the road network of an MCI-affected geographical area.

Strengths

In relation to RME1, the GIS dataset of Great Britain was used to identify realistic road networks in the two case study areas [89] and was provided by Ordnance Survey (OS) [90]. The road networks within the geographical networks of the MCI were modelled using an undirected graph with a given length in kilometres that consisted of a set of nodes representing road junctions and a set of arcs that joined the nodes, representing the road links.

Although satisfying REM1 alone is important, this is also important for REM2 and enables the identification of the locations of incident sites, ambulance stations, fire and rescue stations, and hospitals. A detailed representation of a realistic road network in the MCI-affected geographical area in which incidents may occur, including the use of the GIS data, is essential to determine the distance between any two key locations of interest. The northing and easting coordinates of these locations were used to identify each location in relation to the road network.

Finally, ensuring that REM1 and REM2 are satisfied is important for determining if the emergency responder travel times between specific locations using the road network under consideration are credible, ensuring REM3 is satisfied. As previously described, utilisation of the GIS dataset enables the extraction of accurate distances between key locations of interest within the road network being studied. Credible travelling times between these locations can be calculated based on the accurate distances obtained and the defined speed of emergency vehicles. Furthermore, it is crucial to ensure that any simulations account for the speed that emergency vehicles are able to achieve based on the time of day and the day of the week in order to simulate the road traffic. To ensure valid and reliable emergency responder times between locations, the average speed of ambulance vehicles reported by the London Ambulance Service was used [81] due to the absence of such data. The findings of the coordinated responses previously presented in Chapter 11 that were generated from the 16 experiments defined in Chapter 10 demonstrated that the developed model was able to realistically simulate the travel times of emergency vehicles when transporting emergency responders from their initial locations to incident sites and when transporting casualties from incident sites to assigned hospitals.

Weaknesses

In relation to RME3, the use of average speeds of ambulance vehicles in central London provides an effective approach to validate the emergency vehicle response times using the developed model. However, due to the lack of information relating to the speed of emergency vehicles in Birmingham city centre, the average speeds of ambulance vehicles in central London were used in both case study areas. This could impact the overall findings presented in Chapter 10 (Section 10.1.2), given Birmingham city centre is different from central London in terms of geographic area. For instance, there may be less traffic in the city centre of Birmingham than in central London. In order to improve the accuracy of the results, it is necessary to take into account the precise speeds of the ambulance vehicles in the area under consideration.

Incident sites

Multiple hypothetical incidents were selected to occur in locations likely to be crowded in the case study areas of central London and Birmingham city centre (Chapter 10 Sections 10.2.1 and 10.2.2). The modelling of incident sites is related to RME4, '*define the number and specify of the locations of incident sites in the MCI-affected geographical area*', RME5 '*define the number of casualties at each incident site*', RME6 '*specify the location of the four zones at each incident site*', and RME7 '*the dynamic occurrence of incident sites in which additional sets of casualties need lifesaving interventions are introduced*'.

Strengths

In relation to REM4, the locations and number of incident sites were specific in each of the case study areas, central London (n_{is}=4) and Birmingham city centre (n_{is}=4). The four locations at each case study area were selected in public locations, such as public parks, railways, museums, and indoor entertainment centres. The simulations also incorporated the time and day when the incidents were due to take place, replicating what may happen in reality.

RME5 relates to the number of casualties initially located at each hypothetical incident site within each case study area. In Chapter 10, Section 10.3, two distribution of casualties, equal and unequal, were simulated to observe the effect of emergency responses when accounting for differing casualty numbers. The findings of these simulations and experiments involved have previously been described in Chapter 11 (Sections 11.2 and 11.3).

In associated with RME6, in the simulations in each case study area, four zones were identified at each incident site as nodes in the road network of the MCI-affected area and included Hot Zone (HZ), Casualty Clearing Station (CCS), Place of Safety (POS), and ambulance loading point (ALP). REM6 is important as this allows emergency responder specialities to be allocated to where they are needed most and complete tasks associated with casualties in these zones at an incident site. The movements of emergency responders between the four zones were included in the simulation of the MCI response to ensure the most appropriate allocation of emergency responders to the four zones. This approach is likely to replicate reality and have a significant effect on providing casualties with lifesaving and/or medical interventions in accordance with their health classification and the severity of their injuries.

In a manner similar to what may be expected in MCIs, REM7 is related to a dynamic MCI in which multiple incidents may occur at incident sites at different times, introducing additional sets of casualties who require lifesaving medical treatment. The developed model was incorporated and has previously been discussed in Chapters 6 to 8. In both case study areas, two initial incidents occurred at precisely the same time, which was subsequently followed by two subsequent events that occurred in close succession (E1.L to E4.L and E1.B to E4.B Furthermore, in subsequent experiments (E5.L to E8.L and E5.B to E8.B), one hypothetical incident was selected to occur at a specified time that was followed by three incidents, each occurring sequentially at 30-minute interval. The order of these sequential incidents was pre-defined. The results presented in Chapter 11 (Sections 11.2 and 11.3) demonstrate that the developed model is able to simulate the coordinated response of emergency responders when incidents occur at different times. This is promising and is important to reality, where any MCI response plans must be able to adapt and evolve to the rapidly changing environment of an MCI.

Weaknesses

When selecting incident sites (RME4), it is important to ensure any bias, either intentional or unintentional, is avoided. It is important to replicate these findings in a variety of incident sites to ensure the developed model is effective, regardless of the incident site location.

Emergency services' resources

The term 'emergency service resources' refers to ambulances, and fire and rescue stations and all associated emergency responders and vehicles. Emergency responders include paramedics and fire and rescue responders, and emergency vehicles include standard ambulances and fire engines.

Ambulance stations and the associated emergency responders and vehicles

The requirements associated with modelling ambulance stations are RME8 '*define the number and specify the locations of ambulance stations in the MCI-affected geographical area'*, RME9 '*specify the type of emergency responders located at each ambulance station*', and RME10 '*define the number of emergency responders of each type located at each ambulance station*'. The requirements associated with modelling emergency responders and vehicles associated with ambulance stations are RME11 '*define the degree of expertise of each type of emergency responder located at ambulance stations*', RME12 '*specify the type of emergency vehicle located at each ambulance station*', RME13 '*define the purpose of the use of each type of emergency vehicle at each ambulance station*', RME14 '*define the capacity of each type of emergency vehicle at each ambulance station*', and RME15 '*define the number of each type of emergency vehicle at each ambulance station*'.

Strengths

The GIS dataset, previously discussed in relation to REM2, enabled identifying the actual number and locations of ambulance stations in an MCI-affected area (RME8). When selecting the MCI-affected area, described previously in Chapter 7 (Section 7.2), care was taken to ensure that the maximum number and locations of ambulance stations were covered in 100 km^2.

In relation to RME9, three types of emergency responder, namely paramedics, Hazardous Area Response Team (HART) and Medical Emergency Response Incident Team (MERIT) responders, were initially located at each ambulance station. Furthermore, in the developed model, the specific skill set of each of the emergency responders described here was allocated with specific tasks at incident sites that aligned with their skill sets. This ensured that each emergency responder was capable of performing specific tasks associated with casualties in a particular zone at incident sites. Specifying the expertise of emergency in an MCI is crucial to ensure an optimal emergency response, as defined by REM11. To satisfy REM11, the developed model included two different degrees of expertise, advanced and standard, which have been determined for each type of emergency responder. As previously indicated in Chapter 7 (Section 7.5.2), the level of expertise and knowledge that an emergency responder has should match the assigned tasks associated with casualties in a particular zone at an incident site. HART and MERIT responders have an advanced degree of expertise in treating and triaging casualties at incident sites, whereas paramedics are able to treat and triage casualties; however, tasks are expected to be performed with a standard degree of expertise. Incorporating different emergency responders with varying skill sets and experience into the developed model is important to simulate reality.

To satisfy RME10 and RME15, the number of emergency responders and vehicles was determined based on previously published studies. Nevertheless, defining an accurate number of these resources based on realistic data could enhance the validity and reliability of the developed model.

The types of emergency vehicle are important as this is crucial to transport emergency responders to the assigned incident sites and/or casualties to the assigned hospitals. In relation to RME12 and RME13, the developed model included three types of emergency vehicles, MERIT ambulances, HART ambulances, and standard ambulances, all of which were initially located at each ambulance station in the MCI-affected geographical area, as discussed in Chapter 7 (Section 7.5.3). The MERIT, HART and standard ambulances are all capable of transporting emergency responders to incident sites. However, standard ambulances were also modelled to transport casualties to their allocated hospitals.

In relation to RME14, emergency vehicles initially located at ambulance stations were with the capacity to transport up to four emergency responders of the same type, in accordance with previously published studies [84, 85]. Furthermore, standard ambulances were modelled with the capability of transporting a paramedic to provide ongoing treatment where required and one or two casualties with the same health classification (e.g., pair of urgent casualties or pair of delayed casualties, or only one immediate).

Weaknesses

Regarding RME10 and RME15, providing accurate and informed information regarding all emergency responder resources when modelling an MCI is important to improve the validity and reliability of the developed model and represent what is likely to occur in reality.

Fire and rescue stations and the associated emergency responders and vehicles

The requirements associated with modelling fire and rescue stations are RME16 '*define the number and specify the locations of fire and rescue stations in the MCI-affected geographical area'*, RME17 '*specify the type of emergency responders located at each fire and rescue station*', and RME18 '*define the number of emergency responders of each type located at each fire and rescue station*'. The requirements associated with modelling emergency responders and vehicles associated with fire and rescue stations are RME19 '*define the degree of expertise of each type of emergency responder located at fire and rescue stations*', RME20 '*specify the type of emergency vehicle located at each fire and rescue station*', RME21 '*define the purpose of the use of each type of emergency vehicle at each fire and rescue station*', RME22 '*define the capacity of each type of emergency vehicle at each fire and rescue station*', and RME23 '*define the number of each type of emergency vehicle at each fire and rescue station*'.

Strengths

The actual number and locations of fire and rescue stations have been specified based on the area under consideration, as described previously in association with RME2, which satisfies REM16.

In relation to RME17, two types of emergency responders, search and rescue (SAR) and fire and rescue (FAR) responders, were initially located at each fire and rescue station in the MCI-affected geographical area. The speciality of SAR and FAR is important to include in any modelling as these emergency responders have specific expertise and can perform specific tasks associated with casualties, identifying them and rescuing those who are trapped at an incident site.

To satisfy RME18 and RME23, the number of emergency responders and vehicles was determined based on previously published studies. Nevertheless, defining an accurate number of these resources based on realistic data could enhance the validity and reliability of the developed model.

In relation to RME19, SAR and FAR emergency responders were classified as having advanced and standard expertise, respectively. The developed model incorporated two types of emergency vehicles, fire engines and incident support vehicles, both of which were initially located at each fire and rescue station in the MCI-affected geographical area and have been used to transport FAR and SAR responders to incident sites, respectively. Therefore, the developed model satisfied RME20 and RME21. These vehicles were modelled to transport up to four emergency responders of the same type in accordance with previous research [84, 85], which satisfied RME22.

Weaknesses

In a similar manner to RME10 and RME15, the accurate number of emergency responders (RME18) and vehicles (RME23) of each type initially located at each fire and rescue station was unavailable and has therefore been assumed, in accordance with a previously published research [61]. It is important to ensure that all information involved in modelling the MCIs environment is up-to-date and accurate to ensure the validity and reliability of the developed model.

Hospitals

Modelling hospitals is associated with RME24 ‘*define the number and specify the locations of hospitals located in the affected geographical area’* and RME25 ‘*define the casualty capacity level of each hospital*’.

Strengths

Defining the actual number, locations and capacity of hospitals is important to enabling the allocation of casualties to hospitals appropriately. RME24 were satisfied by defining the number and locations of each hospital involved in the MCI-affected area under consideration.

Due to the lack of information regarding hospital capacity, it was assumed that all hospitals could accommodate any number of casualties with any classification.

Weaknesses

In relation to RME25, hospital capacity should be defined based on accurate data that enable modelling the dynamic changes in staffing and facilities. The lack of real-life information relating to the capacity of the hospitals limits the accuracy of any decision support model. For example, if a model assumes 100 beds will be available at the hospital, and the model sends 100 casualties, but in reality, only 25 beds are available, then good significantly affect the clinical management of casualise. Future research may investigate approaches on how the capacities of hospitals may be modelled with a greater degree of accuracy.

Casualties

Modelling casualties is associated with RME26 '*model a realistic and comprehensive health profile for each casualty*', RME27 '*dynamic simulation of the health status of casualties*', RME28 '*define the tasks associated with casualties and the sequence of their performance by emergency responders'*, and RME29 '*Define the duration of each task associated with a casualty'*.

Strengths

In order to satisfy RME26, a comprehensive health profile for each casualty was modelled, including 15 different parameters, injuries, vital signs, degree of conciseness, triage decisions, and other important parameters defined in Chapter 7 (Section 7.7.1). The health profile of a casualty indicates the current health status of that casualty. It is essential to classify each casualty into one of four health categories, immediate, urgent, delayed, or dead, based on the severity of injuries. A full list of all the definitions of the four health classifications of casualties can be found in Chapter 2 (Section 2.3.3).

Satisfying RME26 enables simulating the health profiles of casualties dynamically by modelling the deterioration and improvement of their health due to the delay in providing and response to medical interventions, discussed in Chapter 6 (Section 6.4.2). Any delays in administering lifesaving interventions may result in the deterioration of casualties' health and could lead to death.

To satisfy RME28, ten tasks associated with casualties were modelled, Task 1: casualty at an incident site, Task 2: releasing a trapped casualty at an incident site, Task 3: performing primary triage for a casualty at an incident site, Task 4: administering on-site treatment for a casualty at an incident site, Task 5: moving a casualty to another zone at an incident site, Task 6: preparing a casualty for transportation to the assigned hospital at an incident site, Task 7: performing secondary triage for a casualty at an incident site, Task 8: loading a casualty into a standard ambulance in an ALP at an incident site, Task 9: accompanying a casualty in a standard ambulance when being transferred to the assigned hospital (during which treatment is provided if required) and Task 10: unloading a casualty from a standard ambulance upon arrival at the assigned hospital. All emergency responders have specific skill sets and expertise, and although this is beneficial, this adds further complexity to scheduling emergency responder tasks. For example, if a task associated with a casualty is assigned to an emergency responder, that task cannot be started until the previous tasks associated with the casualty has been completed. The association between tasks related to casualties, zones at each incident site and emergency responders of each type and the sequence of performing these tasks, as defined in Chapter 7 (Section 7.7.2).

The duration of the aforementioned ten tasks was defined. The duration of Tasks 1, 3, 9 and 10 was determined in accordance with previous research [65, 90, 111, 112]. Furthermore, the degree of expertise and knowledge of emergency responders and the health profiles of casualties were taken into account when defining the duration of these tasks, which replicates what would be expected to happen in reality (RME29). For example, two different emergency responders may be assigned the same type of task, but the more experienced may finish earlier. Similarly, a more severe injury to a casualty will require a longer duration for treatment and, therefore, a longer task time. Including such variations when modelling the duration of tasks associated with casualties is important to differentiate between casualties and facilitate providing lifesaving and/or medical interventions based on their need.

Weaknesses

In relation to RME29, the duration of Tasks 2 and 4-8 was assumed due to a lack of information. Ensuring accurate information is provided to any modelling is required to ensure that the model can be generalised and provide valid and reliable results. An explanation was provided in Chapter 7 (Section 7.5.3) about the assumptions made in relation to the duration of these tasks.

12.2.2 Coordination decisions

Following an MCI, the emergency services respond immediately, involving emergency resources and appropriately coordinating them in order to reduce suffering and save lives [13]. Three coordination decisions, previously defined in Chapter 4 (Section 4.3), must be satisfied when developing a decision support model to ensure a coordinated response to an MCI can be generated. These coordination decisions include RCD1: '*determine the best allocation and scheduling of emergency responders to undertake tasks associated with casualties located at incident sites for the PDA response plan',* RCD2: '*determine the best allocation and scheduling of tasks associated with casualties for the initial post-PDA response plan*', and RCD3: *'dynamically schedule and allocate (if required) of all tasks yet to be started in order to reflect the evolving MCI for the optimised post-PDA response plan, considering the aim to achieve a seamless transition from one optimised post-PDA response plan to another with minimal transition time*'.

Strengths

Regarding RCD1, the greedy heuristic algorithm (GHA) was developed to establish a PDA response plan involving all incident sites, as discussed in Chapter 8 (Section 8.2.1). Since the number of emergency responders considered in the PDA response depends on a number of factors, such as the type and severity of the incident [47], one emergency vehicle of each type, namely MERIT, HART, fire engine, and incident support vehicle, was assumed to be dispatched to each incident site transferring up to four emergency responders of the same type, in accordance with previously published research [84, 85]. The purpose of modelling these vehicles was to transport emergency responders to the assigned incident sites and/or casualties to the assigned hospitals, as indicated in Chapter 6 (Table 6.1). This was to ensure that the emergency responders allocated to each incident site were able to undertake any tasks associated with casualties until more emergency responders were dispatched. Upon activation of the PDA response plan in the MCI environment, the first emergency responders of the PDA response who arrived at each incident site reported the estimated number of casualties at that incident site, which necessitates more emergency vehicles and responders to be sent to the incident site or sites as a part of the post-PDA response. A full explanation of the GHA and all the described algorithms in this chapter are provided in Chapter 8 (Section 8.2).

Regarding RCD2, the genetic algorithm (GA) was developed to create a feasible initial post-PDA response plan involving all incident sites considered in the PDA response plan to be used as a starting point for the neighbourhood search algorithm (NSA). The initial post-PDA response plan was created based on the initial information reported following the execution of the PDA response plan. The initial post-PDA response plan was created by the GA and was then optimised using the NSA. Together this generated an optimised post-PDA response plan that could then be simulated in the MCI environment. The NSA consists of eight neighbourhood structures, NS1 to NS8, defined and discussed in Chapter 8 (Section 8.2.3). Four neighbourhood structures, NS1 to NS4, were developed to allow modifications to the allocation of emergency responders to the tasks associated with casualties at an incident site or sites. One neighbourhood structure, NS5, was designed to allow modification to the allocation of casualties to hospitals. Three neighbourhood structures, NS6 to NS8, were developed to allow modifications to the allocation of casualties to standard ambulances used for transportation to hospitals. In each iteration of the NSA, a number of checks are required to be performed in order to establish which neighbourhood structures may be applied to the current optimised post-PDA response plan. The generated optimised post-PDA response plan has been evaluated using the four objective functions previously defined in Chapter 8 (Section 8.3), ensuring the most effective post-PDA response plan is generated.

In relation to RCD3, during the execution of the optimised post-PDA response plan that was generated using the NSA, additional new information relating to the MCI may become available as the response unfolds. Such information may include

- confirming the number of casualties or providing an updated estimate of casualties at an incident site;
- identifying casualties with deteriorating health who require immediate lifesaving interventions;
- the completion of the MCI response at an incident site, resulting in a number of emergency responders becoming available to be allocated to another incident site;
- the occurrence of a new incident, or multiple incidents that occur as the MCI develops, resulting in additional casualties that require lifesaving interventions.

In addition, the approach to reduce the transition time between successive plans was developed to reduce the transition time between successive post-PDA response plans and attempt to ensure the seamless transition from one optimised plan to another (as possible). This approach was defined and discussed in Chapter 8 (Section 8.4). As indicated in Chapter 1 (Section 1.3), the term ‘transition time’ refers to the time when emergency responders may have no scheduled tasks to undertake due to the reallocation and rescheduling processes in order to generate a new optimised post-PDA response plan using the NSA. This approach aims to estimate the execution time of the NSA to generate a new optimised post-PDA response plan and then assign a task or a number of tasks that are yet to be started with a duration less than or equal to the execution time of the NSA to emergency responders to be carried out during the execution of the NSA, considering the sequence of performing tasks. Based on simulating the coordinated responses discussed in Chapter 11 (Section 11.2), this approach was most effective in the earlier stages of the response to incident sites, where most of the tasks associated with casualties had not begun. In the early stage of the emergency response, the number of tasks with short durations was high, but as the response to MCI developed, the duration of tasks increased. As the response to an incident site unfolds or approaches completion, the remaining tasks associated with casualties, such as transporting casualties to the assigned hospitals, can typically last for longer periods than the earlier tasks, such as treating casualties, and exceed the NSA's execution time. In such cases, emergency responders did not undertake any tasks during the execution of the NSA, often considered as a 'transition time'. The decision support meets the three coordination decision requirements, RCD1-RCD3, demonstrating that the model is robust and able to manage complex modelling scenarios, as discussed in Chapter 11.

12.3 Summary

This chapter has presented an evaluation of the decision support model to coordinate the response of emergency services' resources to MCIs in relation to the model's requirements identified in Chapter 4 and summarised in Table 4.1. Based on the presented evaluation, the strength and weaknesses of the model have been identified and discussed. Table 12.1 is an extended version of Table 5.1 (Chapter 5), which includes the evaluation of the developed model (highlighted in the table). In the next chapter, the conclusion and future work will be discussed.

Table 12.1: Evaluation of the decision support model.

Key elements of		Req.	[62]	[64]	[65]	[66]	[72]	[73]	[75]	The developed model
Modelling an MCI environment	RN	RME1	F	P	F	F	P	F	N	F
		RME2	F	N	F	F	N	F	N	F
		RME3	F	N	N	N	N	F	N	F
	IS	RME4	F	F	P	F	F	F	P	F
		RME5	N	F	N	N	F	F	F	F
		RME6	N	P	P	N	N	N	N	F
		RME7	N	N	F	N	N	N	N	F
	ESR	RME8	N	N	N	F	P	N	N	F
		RME9	N	N	P	F	P	N	P	F
		RME10	N	N	N	N	N	N	N	F
		RME11	N	N	N	N	N	N	N	F
		RME12	P	P	P	F	N	F	N	F
		RME13	F	F	F	F	F	F	F	F
		RME14	N	N	N	N	N	N	N	F
		RME15	N	P	N	F	N	N	N	F
		RME16	N	N	N	F	N	N	N	F
		RME17	N	N	P	F	N	N	N	F
		RME18	N	N	N	N	N	N	N	F
		RME19	N	N	N	N	N	N	N	F
		RME20	N	N	N	F	N	N	N	F
		RME21	N	N	N	F	N	N	N	F
		RME22	N	N	N	N	N	N	N	F
		RME23	N	N	N	F	N	N	N	F
	H	RME24	P	F	P	F	P	P	N	F
		RME25	F	P	P	N	P	F	N	F
	C	RME26	N	N	N	N	N	P	N	F
		RME27	N	N	F	N	F	F	F	F
		RME28	P	P	P	P	P	P	P	F
		RME29	N	P	P	N	P	N	P	F
Coordination decisions		RCD1	N	N	N	N	P	N	N	N
		RCD2	N	N	P	P	P	N	P	N
		RCD3	P	P	N	P	N	P	N	P

Req., requirements; MCI, mass casualty incident; RN, road network in the MCI-affected geographical; IS, incident sites; ESR, emergency services' resources; H, hospitals; C, casualties; RME, requirements of modelling MCI environment; RCD, requirements of coordination decisions; F, fully satisfy a particular requirement; P, can be viewed partially satisfy a particular requirement; N, did not satisfy a particular requirement.

Chapter 13. Conclusion and future work

13.1 Introduction

Developing a decision support model that is able to include the complexity associated with the reality of coordinating an emergency response to a mass casualty incident (MCI) has the potential to significantly improve the emergency response to an MCI, although there are a number of obstacles that must be overcome. A decision support model is intended to aid emergency response personnel in making coordination decisions regarding emergency resource allocation, triaging casualties, organising local infrastructure and many other factors involved in an MCI. Coordinating the activities of multiple emergency responders in a manner that maximises the efficacy of the response can be challenging.

A decision support model has been developed to coordinate emergency resources in response to an MCI, accounts for the key elements required for an effective model discussed in Chapter 3 (Section 3.3), including aspects relating to the MCI environment and the associated assumptions those required for effective and efficient coordinated decisions. The developed has also aimed to address the limitations of previously published models. Specific limitations that are well established in the literature include modelling a realistic Geographic Information System-based MCI environment, accounting for casualties with a range injuries from non-life threatening to life threatening, additional incident sites that occurred as the response unfolds, emergency responders with varying degrees of experience and knowledge, and ensuring that emergency response remains coordinated, whilst being able to adapt and evolve to the changing environment of a real life MCI.

13.2 Thesis summary

13.2.1 Background and foundations (related to objectives 1 to 4)

Ensuring that all emergency responders within a given MCI geographical environment are able to effectively collaborate and coordinate an emergency response that minimises suffering and saves lives is the aim of both emergency responses in reality and when simulating responses using models, including the developed decision support model. The complexity and emergency management cycles involved in MCIs were reviewed from a practical standpoint, specifically the coordination of emergency response in the context of preparedness, which is the specific focus of this thesis. Furthermore, incorporating first-hand experience from emergency responders into the developed decision support model, acknowledging the challenges that can be present during an MCI, and comparing this to standard clinical practice is important, which was discussed in Chapter 2. Identifying the challenges faced by emergency responders during an MCI can provide the foundations for defining the key problems, which for the purpose of this thesis was to identify effective decision support model that can facilitate an effective coordination of emergency resources during the response to an MCI.

Previously published state-of-the-art optimisation-based models have focussed in optimising the coordination of emergency resources during an MCI were reviewed in Chapter 3. Key elements that were identified, including those related to modeling an MCI environment and coordination decisions. The key elements of modeling an MCI environment were: 1) road network; 2) incident sites; 3) emergency services' resources; 4) hospitals; 5) casualties. Furthermore, the key coordination decisions considered in the literature reviewed concern the following allocation decisions: 1) allocating emergency responders to tasks associated with casualties at an incident site or sites; 2) allocating standard ambulances to casualties at an incident site; 3) allocating casualties to hospitals statically. Based on the review of the literature, the requirements that must be satisfied when designing a decision support model were defined in Chapter 4. Modelling an MCI environment requires satisfying 29 requirements (RME1-RME29). The most significant gap in the literature was to satisfy the requirements of coordination decisions (RCD1-RCD3). The defined requirements described in detail in Chapter 4 were used as a base to critically review the literature in Chapter 5, which identified areas for development in the literature that were addressed in this thesis.

13.2.2 Model development and validation (related to objectives 5 and 6)

Previously published models that have been developed to coordinate the response of emergency services to an MCI have shown promise, although key elements relating to modelling an MCI environment and coordination decisions are lacking. The decisions support model developed in this thesis has been designed based on the requirements identified in Chapter 4. It consists of three inter-related components, including the MCI environment, the coordination and management interface (CMI), and the pre-hospital response framework (PHRF), which were discussed in Chapters 6 to 8. When developing the decision support model, a particular focus was placed on the information that was initially collected at the MCI incident site, which was the basis for initiating an emergency response to the MCI. To ensure the decision support model replicated what would occur in reality, new information that was generated as the MCI developed was incorporated into the model. The new information was used to model interactions between the MCI environment, CMI and PHRF and ensured that the model was able to adapt and become responsive to events as they occurred, which optimised rescheduling and reallocation of emergency responders to additional incident sites and ensuring emergency service resources will fully utilised. The new information may include: 1) confirmation or modification of the number of casualties at an incident site, provided by the same emergency responders who were first to arrive at the incident site to control and command (CC) centre, 2) identifying casualties requiring immediate lifesaving treatment from emergency responders, 3) completion of the emergency response at an incident site confirmed by the CC following the collection of the final casualty by paramedics. Information relating to the completion of the emergency response at an incident site allowed for the reallocation of emergency responders to different incident sites where required and 4) information relating to the occurrence of a new incident or incidents as the MCI develops, resulting in further reallocation of emergency responders, where possible to manage and treat new casualties at new incident sites.

In the decision support model, the MCI environment was developed included realistic road networks, real life key locations of emergency responders and their bases of operations, including incident sites, ambulance, fire and rescue stations, and hospitals, described previously in detail (Chapter 7). In addition, the level of expertise and knowledge of emergency responders and the different types of emergency vehicles, which has often been overlooked in previous research, but was included in the developed decision support model. Another important aspect of modelling an MCI environment relates to the health profiles of casualties. As mentioned in Chapter 4 (Section 4.2.5), the health profile of a casualty refers to the current health status of a casualty, including information related to his/her injuries, vital signs and degree of consciousness, triage decisions, and other important parameters. Knowledge of the health profile of a casualty is essential in order to classify a casualty into one of the four health classifications, namely immediate, urgent, delayed, and dead, using a triage method. Definitions of the four health classifications of casualties can be found in Chapter 2 (Section 2.3.3). Based on the knowledge of the health profile of a casualty, the appropriate lifesaving and/or medical intervention can be provided by a particular type of emergency responders, which can be releasing a trapped casualty, providing on-site treatment, and/or transporting his/her to hospitals. Furthermore, modelling health profiles enables the status of casualties' health to be dynamically simulated during the response to MCIs. Each casualty at each incident site were assigned a number of tasks, such as 1) rescuing if trapped, 2) being triaged based on the health profile, 3) treated based on the injury severity and 4) transport to an allocated hospital. Each of the tasks allocated to each casualty were assigned a duration, except transport to hospital, that incorporated the expertise and knowledge of the emergency responder allocated to each of the task and the complexity of the task. Incorporating specific details as those described here into the decision support model facilitates an informed allocation of emergency resources to incident sites and casualties to hospitals, considering the severity level of casualties' injuries. To identify the duration required to transfer casualties to their assigned hospital, road-networks based on the geographical MCI area, average speeds of emergency vehicles, and day of week and time of day were all included.

Having designed the MCI environment, optimisation-based algorithms, including a greedy heuristic algorithm (GHA), a genetic algorithm (GA), and a neighbourhood search algorithm (NSA), used in PRHF were presented in Chapter 8. The application of GHA results in the generation of a pre-determined attendance (PDA) response plan. As indicated in Chapter 2 (Section 2.3.2), the PDA is designed according to past experience of MCIs and approved by experts based on their knowledge [13]. The PDA refers to the initial response to MCIs in which the type and number of resources and specialists, and the type of equipment, which needs to be sent have been agreed upon in advance [13, 46, 47]. As per the PDA response, the first team that arrives at the incident site is responsible for collecting information regarding the incident site, including the estimated number of casualties to declare the incident and start the emergency response. The CMI was then used to execute the GA to generate an initial optimised post-PDA response plan based on the information reported following the execution of the PDA response plan, which was created as a starting point for the NSA. Once the application of the GA was completed and the initial optimised post-PDA response plan was generated, the NSA optimised the initial post-PDA response plan created by the GA to generate an optimised post-PDA response plan. It was subsequently used to generate new optimised post-PDA response plans that reflected the status of the MCI as it evolved in response to new information becoming available as the MCI response unfolds. In order to execute a new post-PDA response plan, the execution of the current optimised post-PDA response plan was terminated. However, tasks that were started by emergency responders but were yet to be completed were not re-scheduled nor interrupted. In such a scenario, emergency responders might have no scheduled tasks to undertake due to the time taken by the NSA to generate a new optimised post-PDA response plan. Thus, within the PHRF, an approach was developed that was able to manage the transition between successive optimised post-PDA response plans by reducing the transition time from one optimised post-PDA response plan to another. Collectively, the aforementioned plans have provided a continuous coordinated response of the emergency service resources that can be implemented in an MCI environment.

In order to ensure the validity of the developed model, the model was validated using the grounding and calibration techniques discussed in Chapter 9, which are common techniques that have previously been used in the literature [12, 122]. The grounding technique assesses and validates the behaviour of the decision support model. This approach extrapolated the observations and key findings generated by the decision support model and compared them to the observations of previously published optimisation-based models reviewed in Chapter 3. However, to ensure the calibration technique is effectively utilised, the decision support model was modified to ensure its functionality was comparable to the previously published models under consideration. Modifying the decision support model was required in order to simulate the experiments described in the studies being compared, which then enabled the comparison of the results generated using the modified version of the decision support model to those reported in the studies being compared. Using the calibration techniques to validate the decision support model increased the confidence in the developed model by demonstrating that it can generate valid and reliable results relating to the coordination of the response of emergency services to MCIs.

13.2.3 Experimental analysis (related to objectives 7 and 8)

The decision support model was comprehensively assessed in two case study areas, central London, and Birmingham city centre (Chapter 11), where the sixteen experiments described in Chapter 10 were implemented. The assessment included a comprehensive evaluation of the decision support model's ability to effectively incorporate initial and dynamic information as the MCI developed, thereby optimising the emergency response. The experiments that were implemented in the two case study areas included information relating to the multiple incidents and incident sites occurring at different times, distribution of casualties among incident sites and distribution of emergency responders among emergency stations (ambulance and fire and rescue stations). The simulations in Chapter 11 demonstrated the efficacy of the model, identified which aspects of the experiments (e.g., the distribution of casualties, initial locations of emergency responders, and case study area) influenced the emergency response to the MCI, and that the decision support model was able to incorporate information from a dynamic and evolving MCI.

13.2.4 Model evaluation

The decision support model was evaluated against requirements that were set out in Chapter 4. There were 29 requirements related to modelling an MCI-environment (RME1-RME29) and three requirements related to coordination decisions (RCD1-RCD3). Chapter 12 (Table 12.1) showed that the decision support model satisfied the aforementioned requirements, which demonstrated that the model is robust and is able to address limitations of previously published models, including the realistic road network of the area under consideration, information relating to key locations of emergency services in that area, modelling comprehensive health profiles of casualties, which were used to simulate the health status of casualties, ensuring a continuous coordinated response of the emergency services' resources to be implemented in the MCI environment.

13.3 Future work

13.3.1 Coordination problem

The decision support model could be generalised to accommodate various types of MCI responses, including earthquakes and other natural disasters. It is possible to consider additional tasks associated with casualties with well-defined durations, such as providing food, water, shelter, and/or medicine to casualties who require it. In terms of emergency resources, extended resources, such as logistic suppliers and volunteers, can be modelled. The road network in the MCI-affected area should be replaced, and the road traffic should be modified to reflect the area under consideration. As a result, the number and locations of incident sites, ambulance stations, fire and rescue stations, and hospitals must be modified to reflect those located within the MCI-affected area under consideration. The modelling of the zones associated with each incident site, namely the hot zone, casualty cleaning station, place of safety, and ambulance loading point, must be revised in terms of their distances from the incident site. Different types of MCIs necessitate distinct settings for the location of these zones.

13.3.2 Parameterisation

The incorporation of health profiles pertaining to emergency responders was not addressed in the decision support model or previous literature. There is always a risk that emergency responders may be injured or even lose their lives when responding to emergency situations, and this risk may be increased during an MCI. The lack of resources and shortage of emergency responders is a genuine problem in developing worlds, especially in the UK [8, 16]. For example, a recent report demonstrated a lack of doctors in hospitals [133], and increased sickness and mental health caused a reduction in the number of paramedics. Although all of these variables undoubtedly increase the complexity of any models aiming to simulate emergency responses to an MCI,

New decision support models should not disregard the actual number of emergency responders and hospital capacities when triaging and allocating casualties, as this may affect the overall response in the area under consideration. Furthermore, they may also include assessing capacity of treatment sites outside of hospitals, such as advanced medical posts that have been previously used in central European countries such as Austria and Germany [132]. This level of specificity will produce valid and dependable simulations that may improve emergency response readiness for MCI events.

13.3.3 Optimisation-based algorithms

The GA was designed to to create an initial post-PDA response plan for use as a starting point in the application of the NSA. The interdependencies between emergency responders' schedules increased the complexity of developing the GA. This, in turn, increased the computation time of generating an initial post-PDA response plan, which can be counted as a limitation of using the GA. Although the time needed to generate an initial plan using the GA was reasonably high, the GA was able to generate the best initial plan in terms of the overall response time compared to four other approaches, as discussed in Chapter 8 (Section 8.2.2). A heuristic greedy algorithm could be designed and implemented to potentially deliver solution of a high quality with minimal computation time, in a manner that reflects how emergency responders would make decisions in the real world in the event of MCI [65].

The NSA described in Chapter 8 (Section 8.2.3) was designed in used to explore post-PDA response plans in the search space neighbouring the current solution using eight neighbourhood structures (NS1 to NS8). These structures were implemented in a highly consistent manner, where all neighbourhood structures consisted of a number of operations using the current MCI information as a base in exploring the neighbour possible solutions. Moving the NSA forward, an enhancement can be made to the NSA in order to increase the performance of the algorithm and the efficiency of finding improved plans, metrics of infeasible and non-improved plans can be employed as those of Tabu Search algorithm, to discourage the search from generating plans like those previously generated. Despite not being implemented in this thesis, this characteristic remains a promising area for future research.

Appendices

Appendix A: Critical review summary of the remaining models related to decision support to coordinate the emergency response to MCIs

This appendix aims to present a critical review summary of the remaining models, which in Chapter 5 have been initially evaluated against the key elements identified in Chapter 3 regarding an MCI environment and coordination decisions. As a result of the evaluation, these models have not been identified as being closely related to decision support to coordinate the emergency response to MCIs.

A.1 A critical review summary of the reviewed models

Table A.1 presents a critical review summary of the remaining 7 reviewed models [61, 67-71, 74], which in Chapter 5 have not been identified as being closely related to the decision support to coordinate the emergency response to MCIs. The 7 reviewed models [62, 64-66, 72, 73, 75], which in Chapter 5 have been identified as being closely related to key elements of a decision support model, have been critically discussed and reviewed in Chapter 5 and summarised in Table 5.2. However, they are included in Table A.1 for completeness (highlighted in Table A.1). The terms used in Table A.1 are as defined in Chapter 5 (Table 5.2).

Table A.1: A summary of the critical review of 14 reviewed models against the requirements of a decision support model defined in Chapter 4.

Key elements of		Requirements	[65]	[61]	[70]	[64]	[62]	[71]	[68]	[67]	[74]	[66]	[69]	[73]	[72]	[75]
Modelling an MCI environment	RN	RME1	F	N	N	P	F	N	P	N	N	F	N	F	P	N
		RME2	F	N	N	N	F	N	N	N	N	F	N	F	N	N
		RME3	N	N	N	N	F	N	N	N	N	N	N	F	N	N
	IS	RME4	P	F	N	F	F	P	P	P	N	F	P	F	F	P
		RME5	N	F	N	F	N	N	N	N	N	N	N	F	F	F
		RME6	P	N	N	P	N	N	N	N	N	N	N	N	N	N
		RME7	F	N	N	N	N	N	N	N	N	N	N	N	N	N
	ESR	RME8	N	N	N	N	N	N	N	N	N	F	N	N	P	N
		RME9	P	P	N	N	N	N	N	N	N	F	N	N	P	P
		RME10	N	P	N	N	N	P	N	N	P	N	N	N	N	N
		RME11	N	N	N	N	N	N	N	N	N	N	N	N	N	N
		RME12	P	N	P	P	P	N	N	N	N	F	N	F	N	N
		RME13	F	N	F	F	F	N	N	N	N	F	N	F	F	F
		RME14	N	N	N	N	N	N	N	N	N	N	N	N	N	N
		RME15	N	N	N	P	N	N	N	N	N	F	N	N	N	N
		RME16	N	N	N	N	N	N	F	N	N	F	N	N	N	N
		RME17	P	P	N	N	N	N	F	P	N	F	N	N	N	N
		RME18	N	P	N	N	N	N	F	N	N	N	N	N	N	N
		RME19	N	N	N	N	N	N	F	P	N	N	N	N	N	N
		RME20	N	N	N	N	N	N	N	N	N	F	N	N	N	N
		RME21	N	N	N	N	N	N	N	N	N	F	N	N	N	N
		RME22	N	N	N	N	N	N	N	N	N	N	N	N	N	N
		RME23	N	N	N	N	N	N	N	N	N	F	N	N	N	N
	H	RME24	P	N	P	F	P	N	N	N	N	F	N	P	P	N
		RME25	P	N	N	P	F	N	N	N	N	N	N	F	P	N
	C	RME26	N	N	N	N	N	N	N	N	N	N	N	P	N	N
		RME27	F	P	F	N	N	N	N	N	N	N	N	F	F	F
		RME28	P	P	P	P	P	P	N	P	P	P	N	P	P	P
		RME29	P	P	N	P	N	N	N	N	N	N	N	N	P	P
Coordination decisions		RCD1	N	N	N	N	N	N	N	N	N	P	N	N	N	N
		RCD2	P	P	P	P	N	N	P	N	P	P	P	P	N	N
		RCD3	P	N	N	N	P	P	N	P	N	N	N	N	P	P

MCI, mass casualty incident; RME, requirements of modelling MCI environment; RCD, requirement of coordination decisions; RN, road network in the MCI-affected geographical; IS, incident sites; ESR, emergency services' resources; H, hospitals; C, casualties; MCI, F, fully satisfy a particular requirement; P, can be viewed as partially satisfy a particular requirement; N, did not satisfy a particular requirement.

In terms of the requirements of modelling an MCI environment, Table A.1 shows that none of the requirements is fully considered or partially considered by all 14 reviewed models. Further, none of the reviewed models considers RME11, RME14, and RME22. In addition, Table A.1 shows that:

- 4, 3, and 7 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME1, respectively;
- 4, 0, and 10 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME2, respectively;
- 2, 0, and 12 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME3 and RME16, respectively;
- 6, 6, and 2 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME4, respectively;
- 5, 0, and 9 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME5, respectively;
- 0, 2, and 12 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME6, respectively;
- 1, 0, and 13 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME7, RME20, RME21 and RME23, respectively;
- 1, 1, and 12 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME8, RME15, RME18, and RME19, respectively;
- 1, 4, and 9 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME9, respectively;
- 0, 3, and 11 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME10, respectively;
- 2, 4, and 8 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME12, respectively;
- 8, 0, and 6 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME13, respectively;
- 2, 3, and 9 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME17, respectively;
- 2, 5, and 7 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME24, respectively;
- 2, 3, and 9 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME25, respectively;

- 0, 1, and 13 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME26, respectively;
- 5, 1, and 8 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME27, respectively;
- 0, 12, and 2 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME28, respectively;
- 0, 5, and 9 reviewed models fully satisfy, can be viewed as partially satisfying, and do not consider RME29, respectively.

With respect to the reviewed models, none of them fully considers or can be viewed as partially considering all 29 requirements of modelling an MCI environment (Table A.1), whereas two [61, 70], one [75], three [64, 68, 72], one [65], one [62], one [73], and one [66] of the reviewed models fully consider two, three, four, five, six, nine, and fourteen of the requirements, respectively. Furthermore, four [67, 69, 71, 74] reviewed models do not fully consider any requirement. In contrast, two [66, 69], two [68, 74], four [62, 70, 71, 73], two [67, 75], three [61, 64, 72], and one [65] reviewed models can be viewed as partially satisfying one, two, three, four, seven, and nine of 29 requirements, respectively.

For the requirements of coordination decisions, Table A.1 shows that none of the three requirements is fully considered or partially considered by all 14 reviewed models. Furthermore, it shows that zero, one and thirteen vs. zero, nine and five vs. zero, six and eight reviewed model fully satisfy, can be viewed as partially satisfying, and do not consider RCD1, RCD2 and RCD3, respectively. In terms of reviewed models, none of the reviewed models fully satisfies or can be viewed as partially satisfying all requirements. Further, none of them can be viewed as partially considering all requirements (Table A.1). However, the models presented in [61, 62, 64, 67-75] and [65, 66] consider one and two of the requirements, respectively.

Table A.1 shows ample scope for a decision support model to coordinate the emergency response to MCIs. This leaves room for an original and significant contribution to knowledge by developing a model that satisfies all the requirements defined in Chapter 4, considering the limitation in the identified models discussed and reviewed in Chapter 5.

Appendix B: Terminating the neighbourhood search algorithm

This appendix defines a number of experiments that are applied to a large-scale problem, aiming to define when the Neighbourhood Search Algorithm (NSA), discussed in Chapter 8 (Section 8.2.3), should be terminated when no improvement in the current post-pre-determined attendance (PDA) response plan is found. The large-scale problem in a mass casualty incident (MCI) refer to an MCI event with an overwhelming number of casualties that may exceed the capacity of emergency services, such as emergency responders, equipment, and supplies. Furthermore, they may exceed the number of available medical personnel, hospital beds, and medical supplies. This can result in delays in care, inadequate treatment, and preventable deaths.

B.1 Case study area and experiments

In order to define the experiments, the case study area of central London was selected to simulate the coordinated emergency response due to the density of emergency services and hospitals. In the case study area of central London, four hypothetical incident was assumed to occur at the British Museum (BM), which is a public museum in the Bloomsbury area dedicated to human history, art, and culture. Another incident was assumed to occur at the Embankment underground station (EUS), a London Underground station on the Circle, District, Northern and Bakerloo lines in Westminster. A further hypothetical incident was assumed to occur at Hyde Park (HP), one of the eight Royal Parks in London, which hosts gardens, historic sites, and outdoor activities. An additional hypothetical incident site was assumed to occur at Oxford Circus (OC), a London Underground station on the Central, Bakerloo, and Victoria lines, located at the junction of Regent and Oxford Street.

The key locations considered in the affected geographical area of central London, in addition to the hypothetical incident sites, are listed below.

- Seven ambulance stations: Bloomsbury ambulance station (BAS), Fulham ambulance station (FAS), London ambulance station (LAS), Oval ambulance station (OAS), St John’s Wood ambulance station (SJWAS), Waterloo ambulance station (WAAS), and Westminster ambulance station (WEAS).

- Seven fire and rescue stations: Dowgate fire station (DFS), Euston fire station (EFS), Fulham fire station (FFS), Old Kent Road fire station (OKRFS), Paddington fire station (PAFS), Peckham fire station (PEFS), and Soho fire station (SFS).
- Six hospitals: Chelsea and Westminster Hospital (CWH), Guy's Hospital (GH), King's College Hospital (KCH), St Mary's Hospital (SMH), Royal London Hospital (RLH), and University College Hospital (UCH).

The locations of ambulance stations, fire and rescue stations, hospitals, and the hypothetical incident sites (green, black, red circles, and blue, respectively) with the road network denoted by grey lines in the defined MCI-affected geographical area of central London are shown in Figure B.1. The area can be identified from the map's scale in which the top right and bottom left easting and northing coordinates are 535624.8, 184321 and 523647.7, 176081.6, respectively.

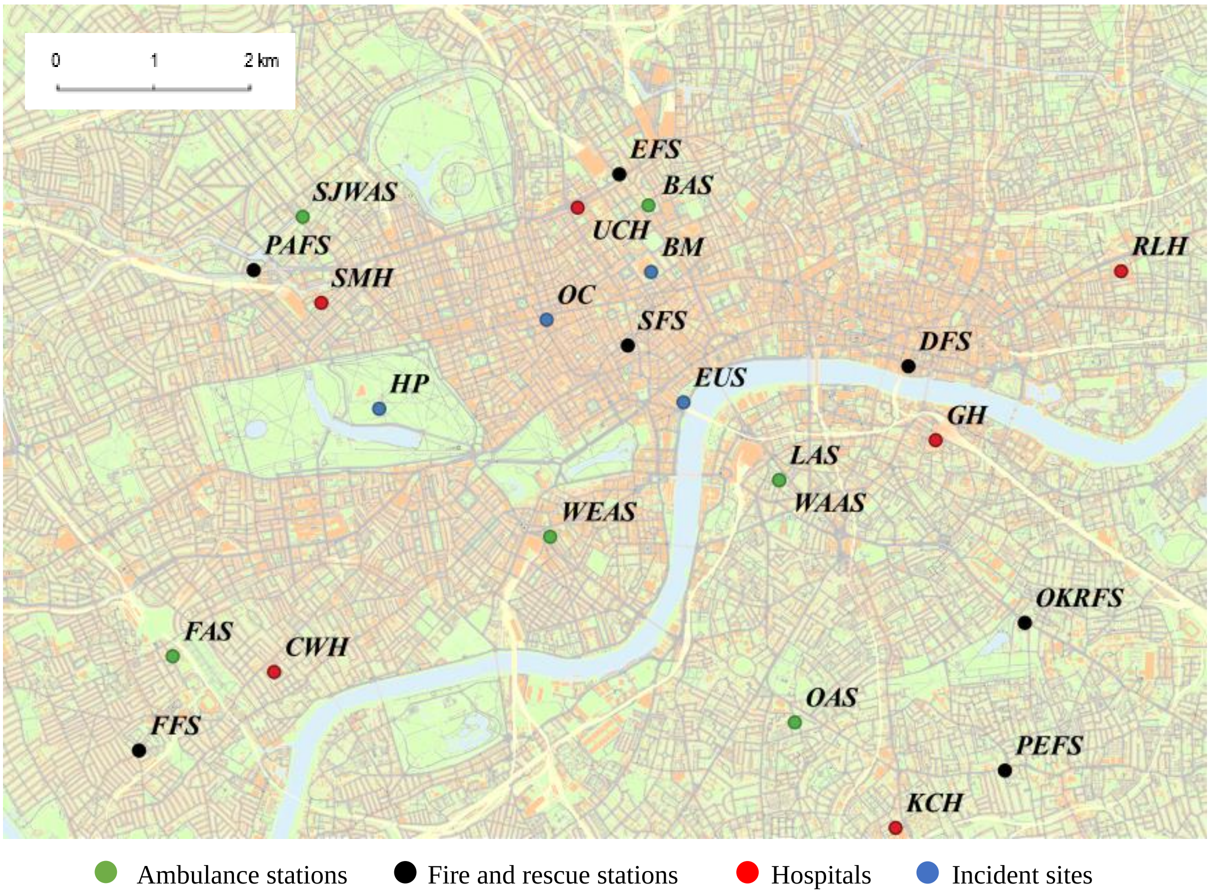


Figure B.1: Topography layer of the defined MCI-affected geographical area of central London.

Three experiments are defined in Table B.1. All experiments share the same location of the incident sites (l_{is}), the day (d_{is}), and the occurrence time of the incidents (t_{is}), the number of all casualties at incident sites ($n_{c,is}$), the percentage of trapped casualties ($n_{c^t_{is}}$), and the severity levels of casualties' health profiles, the number (n_{as}) and the location of ambulance stations (l_{as}), the number of paramedics ($n^{pa}_{er,as}$), HART responders ($n^{HART}_{er,as}$), HART ambulances ($n^{HART}_{ev,as}$), MERIT responders ($n^{MERIT}_{er,as}$) and MERIT ambulances ($n^{MERIT}_{ev,as}$) initially located at ambulance stations, the number (n_{fs}) and the location of the fire and rescue station (l_{fs}), the number of FAR ($n^{FAR}_{er,fs}$), fire engines ($n^{FE}_{ev,fs}$), SAR responders ($n^{SAR}_{er,fs}$), and incident support vehicles ($n^{ISV}_{ev,fs}$) initially located at fire and rescue stations, the number of emergency responders (n_{er}) and vehicles (n_{ev}), and the number (n_h) and the location of hospitals (l_h). However, they differed in relation to values associated with the number (n_{is}), and standard ambulances ($n^{SA}_{ev,as}$).

Table B.1: Design of experiments.

E	Incident sites			Casualties					Ambulance stations								Fire and rescue stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is} and t_{is}	$n_{c,is}$	$n_{c_{is}^t}$ (%)	Health profile (%)			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$			$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
1	4	BM	Sun 15:00:00	50	50	25	25	50	7	BAS	6	7	2	1	2	1	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	1	2	1		EFS	6	3	4	2				GH
		EUS		50	50	25	25	50		LAS	6	7	2	1	2	1		FFS	6	2	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	2	4	1				SMH
		HP		50	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	2	4	1				RLH
										WAAS	5	7	2	1	2	1		PEFS	5	2	5	2				UCH
		OC		50	50	25	25	50		WEAS	5	8	3	1	3	1		SFS	5	2	5	2				
				200							**40**	**50**	**15**	**7**	**15**	**7**			**40**	**16**	**30**	**12**	**140**	**92**		
2	4	BM	Sun 15:00:00	80	50	25	25	50	7	BAS	6	7	2	1	2	1	7	DFS	6	3	4	2			6	CWH
										FAS	6	7	2	1	2	1		EFS	6	3	4	2				GH
		EUS		60	50	25	25	50		LAS	6	7	2	1	2	1		FFS	6	2	4	2				KCH
										OAS	6	7	2	1	2	1		OKRFS	6	2	4	1				SMH
		HP		40	50	25	25	50		SJWAS	6	7	2	1	2	1		PAFS	6	2	4	1				RLH
										WAAS	5	7	2	1	2	1		PEFS	5	2	5	2				UCH
		OC		20	50	25	25	50		WEAS	5	8	3	1	3	1		SFS	5	2	5	2				
				200							**40**	**50**	**15**	**7**	**15**	**7**			**40**	**16**	**30**	**12**	**140**	**92**		

E, experiment; BM, British Museum; EUS, Embankment underground; HP, Hyde Park; OC, Oxford Circus; BAS, Bloomsbury ambulance station; FAS, Fulham ambulance station; LAS, London ambulance station; OAS, Oval ambulance station; SJWAS, St John's Wood ambulance station; WAAS, Waterloo ambulance station; WEAS, Westminster ambulance station; DFS, Dowgate fire station; EFS, Euston fire station; FFS, Fulham fire station; OKRFS, Old Kent Road fire station; PAFS, Paddington fire station; PEFS, Peckham fire station; SFS, Soho fire station, CWH, Chelsea and Westminster Hospital; GH, Guy's Hospital; KCH, King's College Hospital, SMH, St Mary's Hospital; RLH, Royal London Hospital; UCH, University College Hospital;n_{is}, the number of incident sites; l_{is}, location of incident sites; d_{is} and t_{is}, day and time of the occurrence of incident sites, respectively; $n_{c,is}$, number of casualties at incident sites; $n_{c_{is}^t}$, number of trapped casualties at incident sites; n_{as}, number of ambulance stations; l_{as}, location of ambulance stations; $n_{er,as}^{pa}$ and $n_{ev,as}^{SA}$, number of paramedics and standard ambulances located at ambulance stations, respectively; $n_{er,as}^{HART}$ and $n_{ev,as}^{HART}$, number of HART responders and ambulances located at ambulance stations, respectively; $n_{er,as}^{MERIT}$ and $n_{ev,as}^{MERIT}$, number of HART responders and ambulances located at ambulance stations, respectively; n_{fs}, number of fire and rescue stations; l_{fs}, location of fire and rescue stations; $n_{er,fs}^{FAR}$ and $n_{ev,fs}^{FE}$, number of FAR and fire engines located at fire and rescue stations, respectively; $n_{er,fs}^{SAR}$ and $n_{ev,fs}^{ISV}$, number of SAR responders and incident support vehicles located at fire and rescue stations, respectively; n_{er} and n_{ev}, number of emergency responders and vehicles, respectively; n_h, number of hospitals; l_h, location of hospitals.

Table B.1: Design of experiments (cont.).

E	Incident sites			Casualties					Ambulance stations								Fire and rescue stations						n_{er}	n_{ev}	Hospitals	
	n_{is}	l_{is}	d_{is} and t_{is}	$n_{c,is}$	$n_{c_{is}^{t}}$ (%)	Health profile (%)			n_{as}	l_{as}	Emergency responders and vehicles						n_{fs}	l_{fs}	Emergency responders and vehicles							
						Severe	moderate	mild			$n_{er,as}^{pa}$	$n_{ev,as}^{SA}$	$n_{er,as}^{HART}$	$n_{ev,as}^{HART}$	$n_{er,as}^{MERIT}$	$n_{ev,as}^{MERIT}$			$n_{er,fs}^{FAR}$	$n_{ev,fs}^{FE}$	$n_{er,fs}^{SAR}$	$n_{ev,fs}^{ISV}$			n_h	l_h
3	4	BM	Sun 15:00:00	50	50	50	50	50	7	BAS	6	9	2	1	2	1	7	DFS	6	3	4	2			6	CWH
										FAS	6	9	2	1	2	1		EFS	6	3	4	2				GH
		EUS		50	50	50	50	50		LAS	6	9	2	1	2	1		FFS	6	2	4	2				KCH
										OAS	6	9	2	1	2	1		OKRFS	6	2	4	1				SMH
		HP		50	50	50	50	50		SJWAS	6	9	2	1	2	1		PAFS	6	2	4	1				RLH
										WAAS	5	9	2	1	2	1		PEFS	5	2	5	2				UCH
		OC		50	50	50	50	50		WEAS	5	9	3	1	3	1		SFS	5	2	5	2				
				200							**40**	**63**	**15**	**7**	**15**	**7**			**40**	**16**	**30**	**12**	**140**	**92**		

The three experiments have been defined to examine when the NSA should be terminated when no improvement in the post-PDA response plan is found. Each of the three experiment was executed 10 times, in the first time, the number of non-improved feasible post-PDA response plans was set at 10, and in the tenth time, it was set at 100.

B.2 Results

The mean response times, $f_4(\mathrm{x})$ in hours, generated from the simulations of the three experiments defined in Table A.1 in the case study areas of central London is presented in Figure B.2. The emergency response time, defined as the time from when the PDA response plan is executed, to when the final casualty of any health classification type across all incident sites is delivered to the assigned hospital.

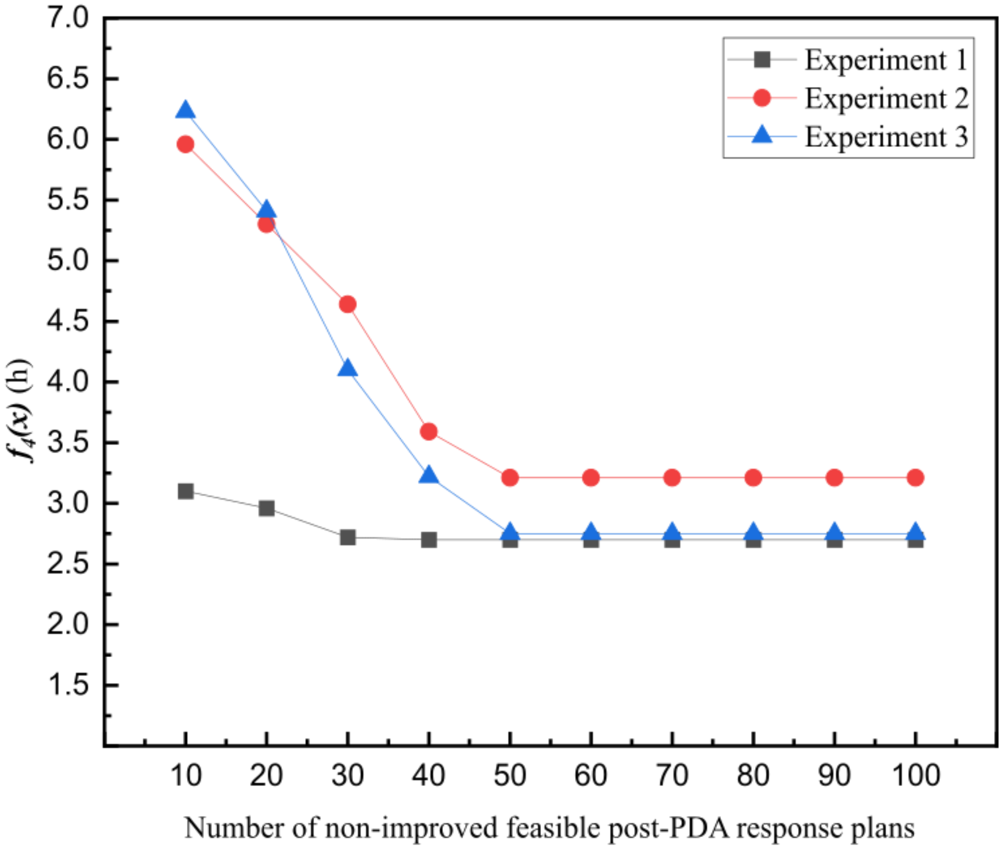


Figure B.2: Line chart presenting mean time in hours from objective function $f_4(\mathrm{x})$ for experiments 1 to 3 (based on 50 runs).

The results presented in Figure B.2 highlighted that the NSA failed to find an improvement in the current post-PDA response plan when the number of the non-improved feasible post-PDA response plans was equal to or greater than 40 for experiment 1 and equal to or greater than 50 for experiments 2 and 3. Thus, in this research, fifty non-improved feasible post-PDA response plans is chosen to terminate the NSA.

Appendix C: Setting up the case study areas

This appendix aims to provide an overview of the set-up of the two case study areas of two cities in the UK, namely central London and Birmingham city centre, as defined in Chapter 10 (Section 10.2). It starts by defining the geographical area involved in each case study to determine the key locations according to the road network of that area. Texts or figures presented in this appendix may have appeared previously in Chapter 10; however, they are presented again here for ease of access. In Section C.1, the definition of the MCI-affected geographical area of each case study is discussed. In Section C.2, the actual key locations in an affected geographical area are specified. In Section C.3, the visual representation of an affected geographical area is discussed. In Section C.4, the extraction of the road network in an affected geographical area is explained. In Section C.5, the key locations in an affected geographical area are determined. Finally, a summary of the appendix is provided in Section C.6.

C.1 Definition of an MCI-affected geographical area

The MCI-affected area of each case study has been defined based on the densities of ambulance and fire and rescue stations and hospitals in 100 km^2 of that area, which is the size limit of an area offered by DigiMap per a single request [89]. In other words, a geographical area has been defined in such a position that covered the locations of all hypothetical incident sites and maximised the number of ambulance stations, fire and rescue stations, and hospitals located in that 100 km^2 of the area. Thus, the geographical area of central London affected has been identified from the map's scale in which the top right and bottom left easting and northing coordinates are 535624.8, 184321 and 523647.7, 176081.6, and 409099, 289887 and 395739, 282417, respectively. Ambulance and fire and rescue stations and hospitals located outside the defined geographical area would not be involved in response to MCIs.

C.2 Specification of the actual key locations in an affected geographical area

The actual key locations, including ambulance and fire and rescue stations, and hospitals, should be specified based on the MCI-affected geographical area in each case study. Hospitals selected in the defined affected geographical area must have Major Trauma Centres in which acute, surgical, and rehabilitative services are available for casualties in all health classifications and/or an Emergency and Accident Department [91]. This ensured that casualties would be delivered to hospitals where proper lifesaving and other interventions could be provided. However, the aim of this research is to coordinate the pre-hospital responses of emergency services' resources to multiple MCIs. Therefore, treatment services provided at hospitals have not been modelled as this relates to post-hospital responses, which are outside the scope of this study.

Table C.1 presents the actual locations considered in the case study areas of central London and Birmingham city centre. In particular, it presents the four hypothetical incident sites, seven ambulance stations, seven fire and rescue stations, and six hospitals in the case study area of central London and the four hypothetical incident sites, two ambulance stations, four fire and rescue stations, and two hospitals in the case study area of Birmingham city centre. Details given include the postcodes of the identified locations converted using the Grid Reference Finder website into the easting and northing coordinates necessary to accurately represent these key locations visually on the maps of the affected geographical areas in central London and Birmingham city centre. Furthermore, the key locations can be accurately pinpointed in the road network, so that precise distances between any two locations can be obtained.

Table C.1: Key locations identified in the defined MCI-affected geographical areas of London and Birmingham.

Case study area	Key locations		Postcode	Grid reference	
				Easting	Northing
Central London	Hypothetical incident sites	British Museum	WC1B 3DG	530086	181669
		Embankment underground stations	WC2N 6NS	530406	180380
		Hyde Park	W2 2UH	527398	180317
		Oxford Circus	W1B 3AG	529053	181196
	Hospitals	Bloomsbury ambulance station	WC1N 1HP	530060	182327
		Fulham ambulance station	SW6 1RX	525356	177870
		London ambulance station	SE1 8SD	531352	179611
		Oval ambulance station	SW9 6ES	531507	177217
		St John’s Wood Ambulance station	NW8 8NL	526642	182214
		Waterloo Ambulance station	SE1 7BG	531352	179610
		Westminster Ambulance station	SW1V	529088	179051
	Fire and rescue stations	Dowgate fire station	EC4R 3UE	532630	180737
		Euston fire station	WC1N 1HP	530060	182327
		Fulham fire station	SW6 5UJ	525023	176939
		Old Kent Road fire station	SE1 5AA	533781	178201
		Paddington fire station	W2 6NL	526157	181687
		Peckham fire station	SE5 8PR	533584	176741
		Soho fire station	W1D 5ET	529856	180942
	Ambulance stations	Chelsea and Westminster hospital	SW10 9NH	526359	177715
		Guy’s hospital	SE1 9RT	532899	180006
		King’s College hospital	SE5 9RS	532503	176174
		St Mary’s hospital	W2 1NY	526826	181364
		Royal London hospital	E1 1BB	534733	181676
		University College hospital	NW1 2BU	529360	182305
Birmingham city centre	Hypothetical incident sites	Birmingham Arena	B1 2AA	405871	286880
		Birmingham New Street	B2 4QA	406922	286594
		Cannon Hill Park	B13 8RD	406905	283662
		Sunset Park	B15 2AF	406437	285719
	Ambulance stations	West Bromwich ambulance station	B71 IPD	399114	289336
		West Midlands ambulance station	B69 4LH	398961	288836
	Fire and rescue stations	Billesley fire station	B7 4HW	408489	287480
		Hay Mills fire station	B16 0RE	404880	286807
		Highgate fire station	B12 0DP	407981	285018
		West Bromwich fire station	B32 3AG	401504	283019
	Hospitals	Birmingham City hospital	B18 7QH	404780	287949
		Queen Elizabeth hospital	B15 2TJ	404427	283926

C.3 Visualising an affected geographical area

Having collected data concerning the affected geographical areas in central London and Birmingham city centre from DigiMap, QGIS software has been used to visualise the map of each area, particularly the topography and road network layers. QGIS software is a free, open-source geographic information system that enables the visualisation, editing, exploration, analysis, and publishing of geospatial data. Once the topography layer has been loaded into QGIS software, it appears in a monochrome colour, as shown in Figure C.1.

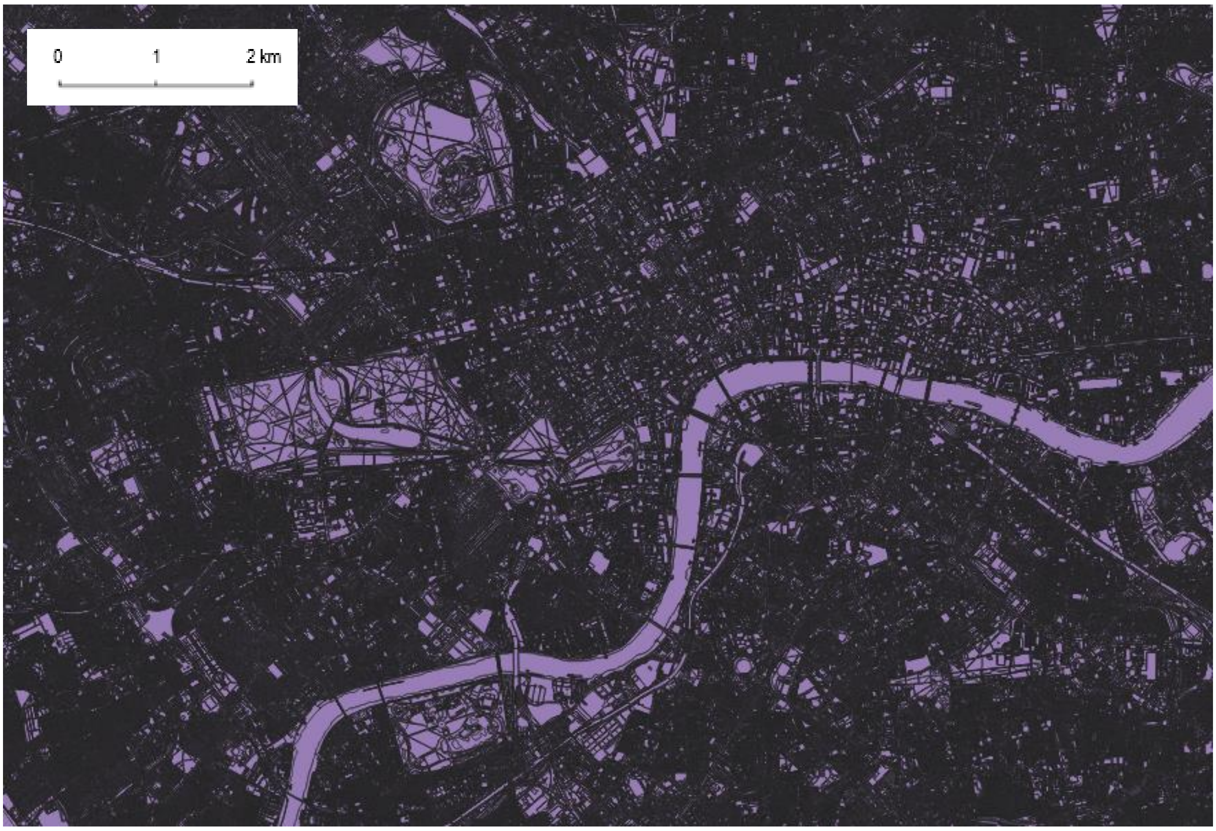


Figure C.1: Topography layer of the defined MCI-affected geographical area of London before the geographic features have been identified.

The geographical features of a topography layer, including water, land masses, and roads, cannot be distinguished. In this research, the colour code described in Table C.2 used to identify geographical features has been applied to the maps presented in this appendix and in Chapter 10. The topography layers of the areas considered in central London and Birmingham city centre after the application of the colour code are shown in Figure C.2 and Figure C.3.

Table C.2: Description of the geographical features and their colour on the map.

Geographical features	Description	Hex (r,g,b)
Water	A feature that contains water, such as rivers and lakes	DCF0FA (190,255,255)
Land	Describes the surface of a man-made, such as slopes and cliffs or natural polygons, such as parks and woodlands	DCFFBE (220,255,190)
Roads, Tracks, and Paths	A road is a made way for vehicles, whereas a track is an unmade road but clearly marked to be used by vehicles. The term path is used for any established way that is not a road or track	D7D7D7 (215,215,215)
Rail	A feature related to travel by railway or tramway. It provides information about permanent railways that connect two points, such as railway stations	FFFFCC (255,255,204)
Buildings	Man-made roofed constructions include private, public, residential, commercial, and industrial buildings, such as houses and schools	FFDCAF (255,220,175)
Heritage and Antiquities	Historical man-made features, such as standing stones and ruined buildings	DCDCBE (220,220,190)
Structures	Man-made constructions (not buildings) such as bridges, tunnels, and fountains	FFD7C3 (255,215,195)

Figure C.2: Topography layer of the defined MCI-affected geographical area of London after the geographic features have been identified.

Figure C.3: Topography layer of the defined MCI-affected geographical area of Birmingham after the geographic features have been identified.

C.4 Extraction of the road network in an affected geographical area

An external piece of code has been written in Java to extract the road network data of each case study area from the road network layer from DigiMap. The road network layer is formatted as a Graph Modelling Language which could be visualised using QGIS software. However, QGIS does not enable the extraction of road network data as a single readable file for the decision support model defined in Chapters 6 to 8. There might be other approaches to the extraction of road network data, but to the best of my knowledge, an external piece of code has been required. The extracted road network data must be cleaned up by removing redundant data or incomplete information associated with arcs on the edges of the road network of the defined MCI-affected geographical area with no ending nodes.

C.5 Determination of key locations in the road network in an affected geographical area

The locations of the hypothetical incident sites, ambulance and fire and rescue stations, and hospitals in a case study area could be specified in the road network and presented in the topography layer. This has been done by determining the nearest vertex in the road network layer to the easting and nothing coordinates of each key location. Accordingly, the appropriate vertices have been selected to represent the key locations in the road network, and accurate distances between any locations could then be determined. Table C.3 lists the key locations defined in the geographical areas affected in central London and Birmingham city centre, which are represented in Figure C.4 and Figure C.5, respectively. The topography layer presented in Figure C.4 contains 735,741 geographical features highlighted using the colour coding shown in Table C.2. Furthermore, the road network denoted by grey lines in Figure C.4 consists of 501,357 unique nodes connected by 606,297 arcs. In Figure C.5, the topography layer presented contains 387,448 geographical features, and the road network, denoted in grey, consists of 183,294 unique nodes connected by 207,286 arcs.

Table C.3: Locations of the hypothetical incident sites, ambulance and fire and rescue stations, and hospitals located in the MCI-affected areas considered.

Case study area	Key location		Nearest vertex in the road network	Distance from the actual location (meters)	Label on the map
Central London	Hypothetical Incident sites	British Museum	osgb4000000029971320	82.51	BM
		Embankment underground station	osgb4000000029970387	22.03	EUS
		Hyde Park	osgb4000000031114498	110.2	HP
		Oxford Circus	osgb5000005100387931	61.57	OC
	Ambulance stations	Bloomsbury ambulance station	osgb4000000029971511	34.1	BAS
		Fulham ambulance station	osgb5000005229027329	20.75	FAS
		London ambulance station	osgb4000000029968971	51.5	LAS
		Oval ambulance station	osgb5000005152002809	19.5	OAS
		St John's Wood ambulance station	osgb4000000029912439	14.01	SJWAS
		Waterloo ambulance station	osgb4000000029969141	36.9	WAAS
		Westminster ambulance station	osgb4000000029967727	36.8	WEAS
	Fire and rescue stations	Dowgate fire station	osgb5000005180358837	38.4	DFS
		Euston fire station	osgb4000000029971464	33.4	EFS
		Fulham fire station	osgb5000005141092362	16.09	FFS
		Old Kent Road fire station	osgb4000000029973202	40.7	OKRFS
		Paddington fire station	osgb4000000030871407	28.7	PAFS
		Peckham fire station	osgb5000005103173553	39.9	PEFS
		Soho fire station	osgb4000000029970514	28.9	SFS
	Hospitals	Chelsea and Westminster hospital	osgb5000005133929290	53.7	CWH
		Guy's hospital	osgb5000005239310322	74.57	GH
		King's College hospital	osgb4000000031247397	8.4	KCH
		St Mary's hospital	osgb4000000029911869	36.4	SMH
		Royal London hospital	osgb4000000029976219	98.56	RLH
		University College hospital	osgb4000000031032394	18.3	UCH
Birmingham city centre	Hypothetical incident sites	Birmingham Arena	osgb5000005207231054	65.90	BA
		Birmingham New Street	osgb5000005165830536	66.6	BNS
		Cannon Hill Park	osgb4000000019787887	40.01	CHP
		Sunset Park	osgb4000000019645409	47.40	SP
	Ambulance stations	West Bromwich ambulance station	osgb4000000017805715	28.32	WBAS
		West Midlands Ambulance Service	osgb4000000017805669	80.25	WMAS
	Fire and rescue stations	Billesley fire station	osgb4000000019132129	37.19	BFS
		Hay Mills fire station	osgb4000000019065145	42.78	HMFS
		Highgate fire station	osgb4000000019130380	29.64	HFS
		West Bromwich fire station	osgb5000005106685316	44.95	WBFS
	Hospitals	Birmingham City hospital	osgb5000005138858535	139.01	BCH
		Queen Elizabeth hospital	osgb4000000019781277	65.27	QEH

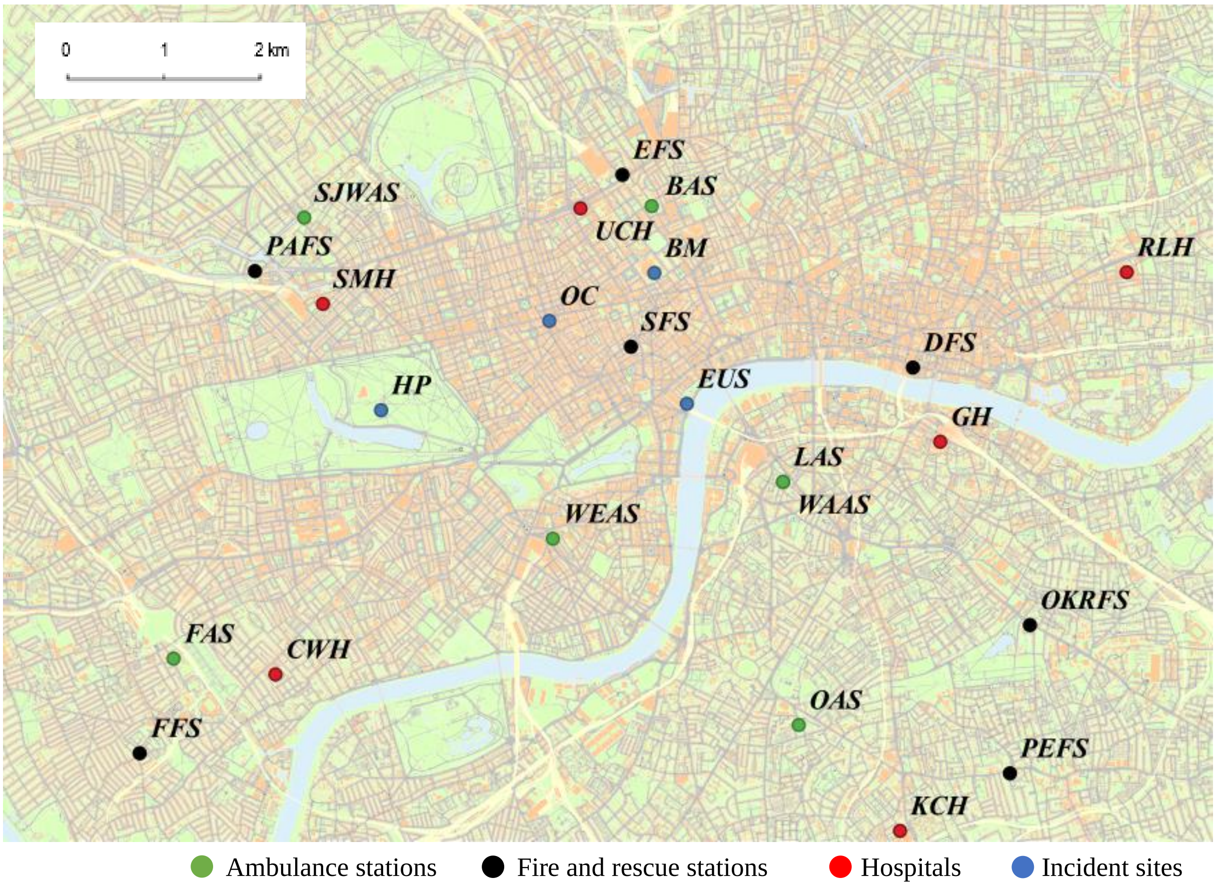


Figure C.4: Topography layer of the defined MCI-affected geographical area of London containing all locations considered with the road network denoted by grey lines.

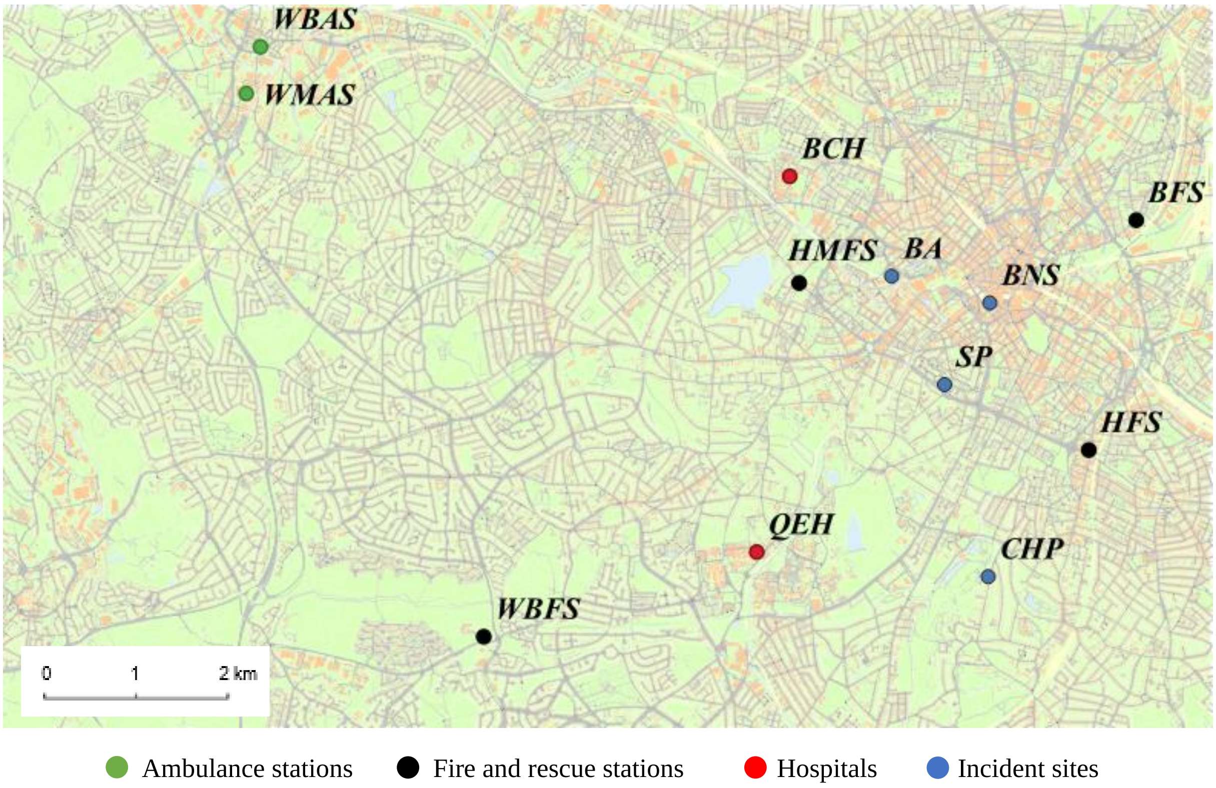


Figure C.5: Topography layer of the defined MCI-affected geographical area of Birmingham containing all key locations considered, with the road network denoted by grey lines.

C.6 Summary

This appendix has discussed the set-up of the two case study areas in central London and Birmingham city centre as defined in Chapter 10, including the definition and specification of key locations, the visualisation of maps, and the extraction of road networks and the positions of key locations in them.

Appendix D: Outlier

An outlier is a data point that is significantly different from the majority of the data points in the dataset. The outlier in Chapter 11, Figure 11.8(A) represents the value of the objective function $f_4(x)$ of an emergency plan that lies outside the overall distribution pattern of the values of the same function from other emergency plans. This outlier indicates the best (lowest) overall response time over the other emergency plans, given that Figure 11.8(A) shows the values of four objective functions of 50 plans, which are the output of 50 runs. There are several reasons that could cause this, including:

- the emergency responders who have been involved in the PDA response were assigned tasks associated with a number of the most critical casualties who need immediate life-saving interventions. Therefore, there has been no or less deterioration in the casualties' health, and the current optimised post-PDA response plan has not been updated multiple times;
- when the health of any casualty deteriorates, there is always an emergency responder available to be allocated a task associated with that casualty. Therefore, casualties receive life-saving and medical intervention on time;
- most of the emergency responders who were required to be allocated to the other incident sites when they occurred were available, which means earlier arrival at the other incident site;
- most of the casualties were less critical or non-critical and could be transferred to hospitals in pairs, which means that fewer movements between incident sites and hospitals were made by emergency vehicles;
- casualties to hospital allocation can also affect the overall response time.

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