QATAR UNIVERSITY

COLLEGE OF ENGINEERING

INDEX-BASED EMERGENCY RESPONSE MANAGEMENT SYSTEM (IERMS): A FRAMEWORK FOR THE PETROCHEMICAL INDUSTRIAL CITIES IN QATAR

BY

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A Dissertation Submitted to
the Faculty of the College of
Engineering
in Partial Fulfillment
of the Requirements
for the Degree of
Doctorate of Philosophy in Engineering Management

June 2018

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ABSTRACT

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Doctorate of Philosophy in Engineering Management

Title: INDEX-BASED EMERGENCY RESPONSE MANAGEMENT SYSTEM (IERMS): A FRAMEWORK FOR THE PETROCHEMICAL INDUSTRIAL CITIES IN QATAR

Supervisors of Dissertation: Prof. Shaligram Pokharel, Prof. Abdelmagid Hammuda, Dr. Galal Abdella

Emergency response operations are very important activities in the industrial areas. An incident in the industrial area can have considerable economic and social impact, response decisions to mitigate the impact of the incident are critical and have to be made in a very short time. Such decisions should consider the allocation of available resources in and around the industrial area.

The resources to be dispatched to an incident location should also consider factors such as metrological conditions and the nature of incident location such as wind speed, wind direction, population, chemicals and materials handled, and the characteristics of surrounding industrial facilities. In this thesis, some of the factors related to the incident in the industrial areas have been studied and they are considered for the development of a location-based hazard index (LHI). A higher index value for an incident location means a higher level of response resources required to mitigate the impact of the incident.

Therefore, the index provides information on the level of hazard of a particular industrial installation and its surroundings. The index is a new concept in the planning and management of response system in incident location.

In order to effectively analyze the dispatch the resources, a framework called Index-based emergency response management system (IERMS) is also proposed. In the framework, data related to the incident location is used to derive the hazard index. A clustering method is used to obtain the maximum value of the index such that enough resources can be dispatched to the incident location.

Two mathematical models are developed for the application of the framework, which results in time and resources required for the location and the allocation of different type of resources to the incident location. The application of the framework is demonstrated through a case study of the industrial area with petrochemical facilities. The results of the analysis show that the use of LHI and the framework helps in developing a better response to varied incident conditions. It is expected that the index, framework, and the mathematical models presented in the thesis can help the decision makers in making informed decisions on efficient allocation of resources in order to mitigate the impact of the incidence.

DEDICATION

I dedicate this thesis to the people who work in the industrial cities and oil and gas sector in order to support the country's economy.

Yousuf Rebeeh.

Place: Doha, Qatar

Date: May 2018

ACKNOWLEDGMENTS

I wish to sincerely thank all those who have contributed in one way or another to this study. Words can only inadequately express my deep gratitude to my supervisor Dr. Shaligram Pokharel and my co-supervisors Dr. Abdelmagid Hammuda, and Dr. Galal Abdella, for their meticulous care, kindness, and generosity. Their fruitful comments and insightful suggestions have been a crucial formative influence on the present study.

I would also like to thank individuals and management of Qatar Petroleum, the management of Industrial Cities, and staff at the HSE Departments of those industrial cities for their continuous support and cooperation to facilitate this research work.

I would like to thank my wife, my children Abdulla, Aisha, Rebeeh, Mohanna, Fahad, my mother, brothers, and sisters for their great support and understanding during the period that I spent on focusing on research and completing the thesis. I want to mention of special dedication to the sole of my father and my role model. My father used to inspire me to do the best my life.

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CHAPTER 1: INTRODUCTION

Qatar’s oil and gas sector is very vital to Qatar economy. Over the past 40 years, more than 75 large and medium size companies have been established in Qatar to process or support oil and gas exploration, development, downstream products. As a policy of the government, most of these companies and their subsidiaries are located in specified industrial areas, called industrial cities. Such locations help to orient the facilities of transportation, processing, maintenance management, and emergency incident management in the predefined area. These industries require processing plants, pipelines, and storage facilities, connectivity of the locations through road network and facilities for people working in those areas. Clustering of many industries in such areas also results in an inherent risk of triggering disaster situations. There are effort on the part of the industries and the government to preconceive the type of risks and put in place control measures to tackle emergency’ situations.

The emergency management and emergency response systems are defined as the science of managing complex systems and multidisciplinary personnel to address extreme events, across all hazards, and through the phases of mitigation, preparedness, response, and recovery. The emergency response and management systems concept have been evolved and expanded to a comprehensive emergency management system.

The concept of an emergency management system for industrial facilities is constantly linked with disasters prevention, as the first priority of such a system is to minimize the undesirable consequences of disastrous events. The industrial disaster, that is the risky incidents happening in the industrial cities, is termed as the technical disaster by Zio and Aven (2001). The term "disaster" is defined by the Asian Disaster Reduction Center (2003), as the "serious disruption of the function of society, causing widespread human, material, or environmental losses which exceed the ability of affected society to cope using only its own resources." Industrial disasters have always been associated with modern life and civilized growth of the societies (Granot, 1998). The use of reactive resources has been the main cause of several disasters in industrial areas (Hao-wei et al., 2011).

Industrial disaster is attributed to the loss of control of inherent business risk and malfunction of risk mitigation barriers within manufacturing and industrial systems. Therefore, in order to prevent disasters from happening, the inherent risk within each industrial system shall be indemnified and controlled at different stages and at different levels. However, the emergency response system needs to be available at all times to address any needs to mitigate, contain, and preplan the resources.

In the State of Qatar, large industrial cities can be taken as an example of industrial cities. These industrial cities contain largest inventories of the liquefied natural gas (LNG). Qatar has one of the largest gas processing and exporting hubs to supply LNG to the international market. According to Oil and Gas Journal, as of January 1, 2011, reserves of natural gas in Qatar were measured at about 25.4 trillion cubic meters, which is considered to be about

14% of all known natural-gas reserves around the world and this volume of reserve the third largest in the world (Chen et al., 2011).

1.1 Problem Statement

If disaster incident occurs in an industrial city, there would be inherent risks of loss of containment, fire, explosions, or activities that can be hazardous to operation and maintenance of the facility, to the people working within the facility and the vicinity and to the ecological environment surrounding the facility. The impact of such a risk can also reach beyond the industrial cities.

This is to be noted that most of the processing and handling facilities are built and designed considering state of the art monitoring and control systems to reduce inherent risk, there can be a residual risk or resulting risks (due to the incident in another location) that need to be considered. Any risk can trigger disaster and that would not only be a disaster to the physical assets, but it can have a significant impact on human lives. Any unscheduled shutdown or destruction of facilities can also be detrimental to the country because most of the national revenues are being generated by this sector. As the country is aiming to expand the processing facilities to meet the increasing LNG demand, it would mean that more volumes of processing materials and LNG would have to be stored in the future, and this will add to the need for a more effective emergency response mechanism. Therefore, designing and developing a good emergency response management system becomes important. In order to develop a better emergency response system, an understanding of four main circles becomes important.

1) The first risk circle arises within a single facility or any of its assets at which single unit is subjected to risk result from its activities or failure of unit protection layers and barriers. In this case, the effect is limited, controlled, and required limited intervention and emergency response normally within local emergency capacities at the site.
2) The second risk circle is developed when the extent of the hazard exceeds the unit and crosses the boundaries to adjacent units within the same facility. The magnitude of the expected risk, damage, consequences, and required intervention level are relatively higher in this circle.
3) The third risk circle affects the nearby facilities and results in a larger impact diameter. This may result in to the initiation of the second emergency case in the adjacent facility but within the boundaries or geographical limits of the industrial city.
4) The fourth risk circle affects not only the facilities within the industrial city but goes beyond the boundary and affect the nearby communities and public-use facilities such as residential areas, schools, or any other facility. The nature of effect and its magnitude, the effect of risk vary in nature due to a potential combination of higher risk due to fire, explosion, lethal gas release, heat, shock wave, spillage, noise, or any type environmental pollutions. The scale of risk occurrence also varies from simple incident to accidents or to major disaster or catastrophe.

The management and the facility owners in industrial cities require balancing between increasing demand for enhancing the level of readiness, availability of emergency response systems to mitigate the risk, and the relatively high cost for readiness at the distribution facilities in their premises. The conventional emergency management and responses management system used in these cities are based on models that are heavily dependent on human skills and manual intervention for information input, gathering information, analyzing the situation and developing a decision on response. The visit to the industrial cities in Qatar shows that the procedures are on the focus and the resources are not of concern in these cities. However, although the resources stocked for the emergency situations may not be of concern compared to the impact that it can mitigate, the suitability of resources and the sizing of resources can still be improved by considering and analyzing the physical/chemical characteristics of the materials and processes and the human involvement in the facilities. In this thesis, it is proposed to obtain hazard index of a particular facility (location) and its surroundings in order to understand the intensity of hazard and then use this feature to plan for the required resources for each of the locations in the industrial city. An integrated index based emergency response management system (IERMS) is proposed in order to plan and respond to emergency situations in industrial facilities. The proposed IERMS is expected to support the emergency response decision making in the industrial cities by providing a tool that supports planning and response of risk situation on an integrated manner, through optimal allocation and consumption of resources. The system shall provide the following advantages:

- Integrated source of emergency and risk-related information.
- Integrated emergency response.
- Adaptive to emergency situations escalation and reduction (minor to major).
- Integrated resources optimization at different levels

- Local to full emergency response team on a national level.

1.2 Objectives

The two main objectives of this thesis are given below:

1. Develop emergency response mechanism that will minimize the response time. Response time is a very crucial element of the emergency responses management system. The quicker the response time, the better would be the control of disaster impact and its propagation to critical levels, and minimization of injuries and causalities.
2. Develop the emergency response mechanism that provides the best possible resources to mitigate the impact of the disaster. The resource size for emergency response is usually determined based on risk impact, risk probability, and the likelihood of events. An isolated risk response planning system may require high redundancy of resources. Therefore, the objective is to develop a model that will provide a tool for economical and efficient emergency response planning system.

1.3 Contribution

As a contribution, in this research, the following concepts have been considered for emergency planning.

1. A new framework of index-based emergency planning and response model is proposed by combining common process used in both emergency response operations as well as the planning process for the emergency operations.
2. Location Hazard Index (LHI) is proposed for quick hazard calculation as a unique way to

determine the hazard level of incidence (emergency) locations and quantify it by consideration of the location-based characteristics.

3. Indexed based time optimization model is proposed based on LHI for optimal resources allocation or planning for resources allocation in industrial cities.

1.4 Scope

In order to implement the proposed IERMS, a framework called IERMS framework has been proposed. The framework consists of eight general interconnected modules that act as processing units, as shown in Figure 1.1, is described below.

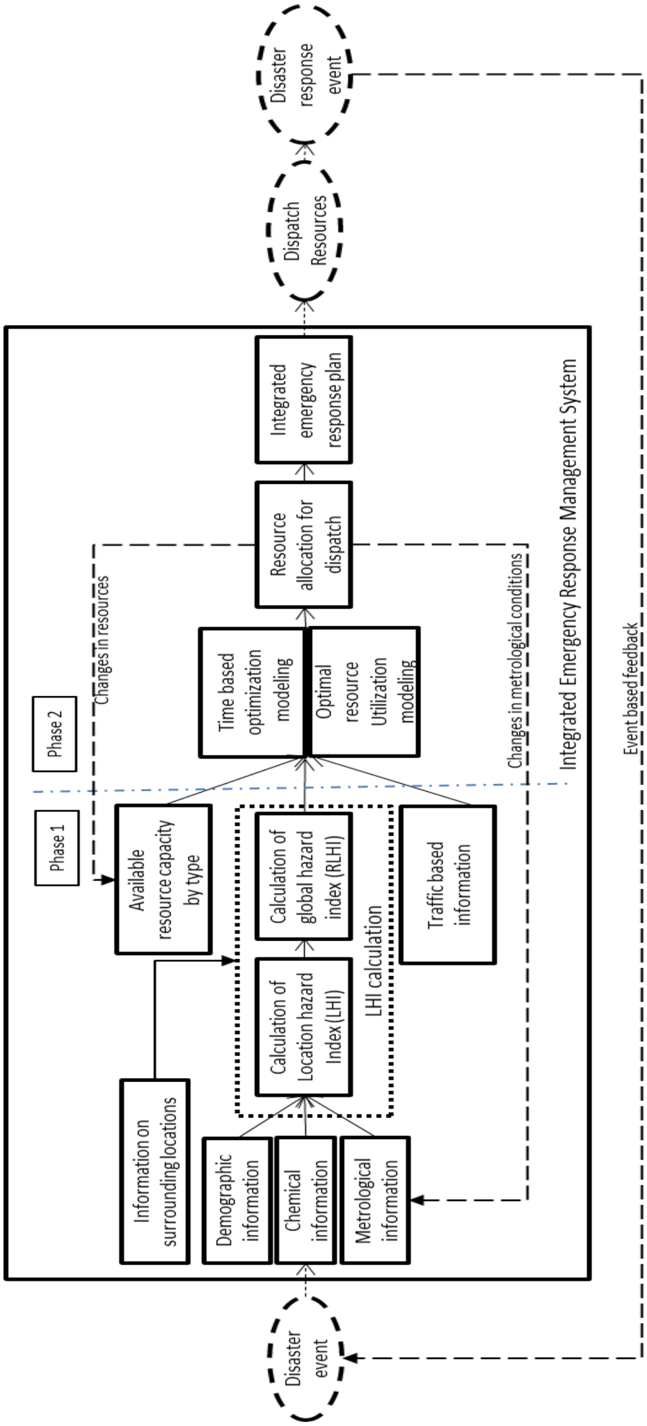


Figure 1.1 Proposed IERMS framework

The IERMS consist of two main phases:

- **Phase 1**: This phase is basically related to risk assessment and evaluation for the overall situation before dispatching any resources. At this phase, all inputs information are collected from different sources will be cleaned and transformed into a unified database. The cleaned data is analyzed, classified, and stored in the system database. The data ontology function is utilized at this stage as part of data analysis and classification.

- **Demographic information:** This information would include the headcount or population and distribution among different areas and cluster of the industrial city.
- **Chemical information**: This is relatively comprehensive data related to different types of chemicals, quantities, properties and its distribution in the industrial city locations.
- Metrological information :
- **Calculation of LHI**: The input from previous module is used to assess the level of emergency situation and potential of escalation (i.e., from minor situation classification to medium situation classification or from medium situation classification to major situation classification) based on other parameters (such as headcount available at the location, wind direction, and facilities or assets in proximity to incident/ accident situation) related to the incident. This classification is very important to assess the course of actions, resources, and communications based on the severity and significance of the emergency situation.
- **Calculation of Global LHI**: At this stage, the LHI will be adjusted based on nearby and surrounding condition to reflect the actual risk condition of the site, which will help to accurately set priority for resource allocation and dispatch.
- **Traffic based information**: related to roads and emergency routes availability and travel

  time between depot and incidents locations. This will be used to feed the resource optimization and dispatch model

  - **Available resource capacities:** contains an updated inventory of all available emergency resources in all depots. This will be providing information resources allocation and dispatch model in phase 2.

- **Phase 2**: In this phase, an overall view of the location and its situation with respect to emergency or near emergency situations, emergency procedures and regulations, acceptable risk thresholds, and general instructions are provided. The incident situation is analyzed to decide if it should be escalated to the emergency situation.

  - **Optimal Resources time modeling:** In this module, the status of emergency resources' availability, distribution, location, and its readiness are used as the inputs. Accordingly, based on the classification of the incident, and required resources and their availability, a dispatch order is issued to move emergency rescue units to the selected incident locations. The main objective here is to minimize the response time to incident or accident location by assigning the response task to the closest available resources and utilizing short and clear route from resource location to incident/ accident location.

  - **Resource allocation for dispatch**: In this module, continuous assessment of the situation in incident location is to be conducted to assess if extra resources are required. The focus in this module is on the management of the main activities required for site emergency management such as rescue of affected location, facilitate communication and information exchange with all stakeholders, and manage evacuation activities if required.

  - **Integrated emergency response plan**: In this module, post-event or incident analysis and actions such as site work normalization, and restoration to the normal and safe situation as well as clearing out all emergency and rescue measures on site are to be carried out. It also triggers the restoration of emergency and rescue resources to its original condition and ensures its readiness for the next emergency event. In this module, root-cause analysis for the accident/ incident is also conducted to identify any actions for improvement (corrective and preventive) and they are recorded as part of the post-event analysis and actions.
- **Feedback**: The feedback links the integrated stage of the IERMS framework. In this module, feedback, information, data, and actions from related modules are captured and circulated as part of the feedback loop in the system. It also provides a link to capture and report the closeout of individual incidents and report it into input pre-processing module for analysis. From the framework, we can observe three links of feedback:
  - Resource allocation feedback to resources database to reflect the utilization and availability of resources.
  - Resource allocation feedback to change in metrological information to reflect the change in risk rank or level due to change in wind speed or direction.
  - Event-based feedback to update disaster status based on site conditions and feedback to reevaluate the situation and dispatch additional resource or allocate them based on updated LHI and RLHI.

Figure 1.2 below shows the three main aspects of emergency logistics: the facilities, the resources, and the support services system. In an emergency response system, these aspects need to be clearly understood and analyzed. The following gives the details of the elements:

The facilities

1) Distribution of facilities location related to the expected site as well as the overall distribution of all service facilities in the area or the region.
2) The function of the facilities, which is required to cope with the emergency such as medical centers, hospitals, shelters, supply warehouse.
3) The cCapacity of each of the facilities (based on its function) to accommodate expected outcomes of emergency.

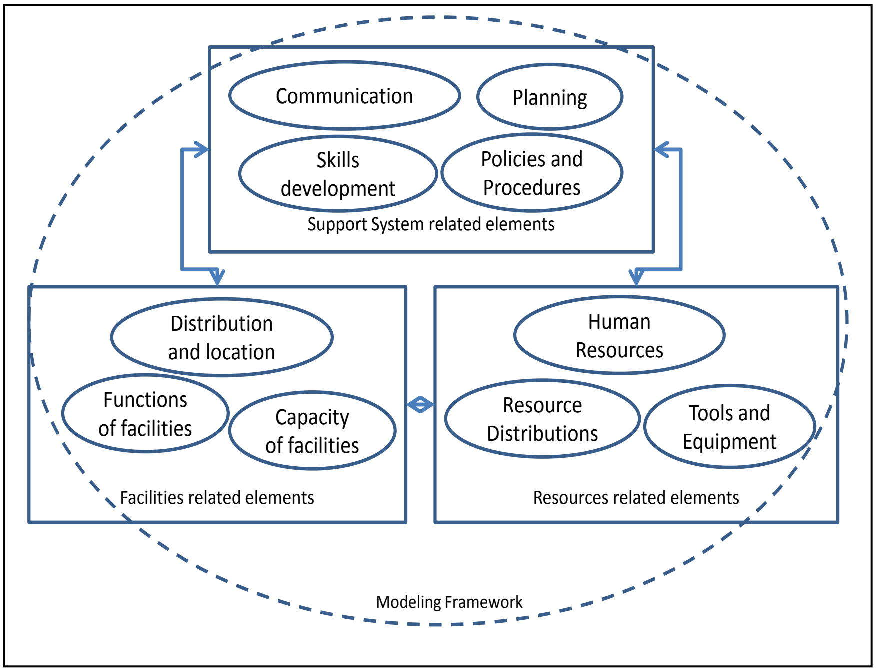


Figure 1.2: Elements of emergency response system

Resources

1) Human resources, which basically include all manpower required to support the emergency system for first intervention and support individuals in all discipline such as rescue team, firefighting, safety, security, and medical teams
2) Tools and equipment, which include all tools and equipment required by emergency management system and emergency response plan such as, fire trucks, ambulance cars, rescue tools, and transportation, and; 3) distribution of the resources (human, tools, and equipment) to fulfill the requirements of the emergency management system in all stages in central location or distributed across the region/area.

Support systems/services

1) Communication, which is an important element in the emergency management system which links all the components and provides required information on time (communication covers the establishment of dedicated means or using publicly available communication means based on availability in each stage, such as GSM network, satellite mobiles, and other special networks.
2) Policies and procedures, which is referred to all documents used to control, regulate, and standardize the emergency management system (normally it shall be ready, available with all team members in a convenient format such as paper, and electronic.
3) Planning, which is used in order to integrate all elements of the emergency management system and add a time element to it to make sure that all actions and plans are clearly evaluated and are fit for the given purpose

4) Training and skills development, which is required to develop essential skills, master utilization of tools, resources coordination as per the prepared plans in line with procedures and policies.

1.5 Methodology

In this research, the following methodology is adopted

1. Problem assessment and needs verification by visiting the relevant industrial cities.
2. Review of literature to understand the importance of emergency response system and to understand various types of models that are available for the use in emergency response system elsewhere.
3. Develop a preliminary framework for risk assessment and response analysis for optimal emergency resource use.
4. Develop optimization models in order to implement the IERMS framework.
5. Collect the data from a case industrial city, optimize the response time for a simulated incident location, and optimize the resources required.
6. Develop a preliminary understanding of the resource allocations and insights for the particular location being studied in this thesis.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The concept of an emergency management system for industrial facilities is linked with the reduction of undesirable consequences of disastrous events. Disaster refers to the event of serious interruption that leads to extensive losses of human lives and deterioration of the environment and physical facilities (Zio and Aven, 2013). The disasters in industrial facilities are classified as technological disasters, which essentially are man-induced disasters (Granot, 1998). Shaluf et al (2002) mention that the lack of an emergency response system could be disastrous in the industrial areas.

The causes of the industrial disasters are attributed to the inherent business operation risk and loss of control and functionality of risk mitigation. Therefore, in order to prevent the occurrence of disasters, an inherent risk based management system need to be developed and implemented within each of the industrial facilities. As the system should be implemented at different stages and at different levels, appropriate control mechanisms should also be designed and implemented.

Chen et al. (2012) provided concepts on the lifecycle of emergency management system in which response are classified into pre-incident, during incident and post-incident stages. During pre-incident, the focus is more on prediction, identification, and assessment. During the incident, the focus is on the effective response, coping with the situation and fast recovery, and during post-incident the focus is on complete recovery. In this research work, we have proposed the response mechanisms for these three stages in most of the modern industrial facilities are designated as proactive, reactive, and corrective as described below (Figure 2.1).

- Preventive (prediction) phase is an early stage management of emergency, which focuses on response planning for avoiding or minimizing the impact of the disaster. This phase requires planners to simulate various disaster scenarios by considering intensity and spread of the impact in and around the industrial facilities. Therefore, this type of system needs to support quick data access, communication, selection of locations to stock the resources for mitigation of disaster impact, and deployment of resources at the quickest possible time. The focus here is on the preparedness for all disaster situations.
- Reactive (response) phase is focused on emergency relief during or immediately after the occurrence of the disaster event. A good response system should activate immediately when a trigger for disaster is identified so that the impact can be contained as quickly as possible. The focus in this phase is to continuously monitor, control, and provide all possible services as needed. Therefore, facilities and support developed for preventive phase become very important to deploy reactive phase activities.
- Corrective (recovery) phase is focused on recovery after the occurrence of the disaster event. The main activities during this phase are the recovery centered to restore the situation to the equilibrium through rehabilitation and reconstruction. Lesson learned from the disaster becomes a key to update preventive measures so that response system becomes more effective.

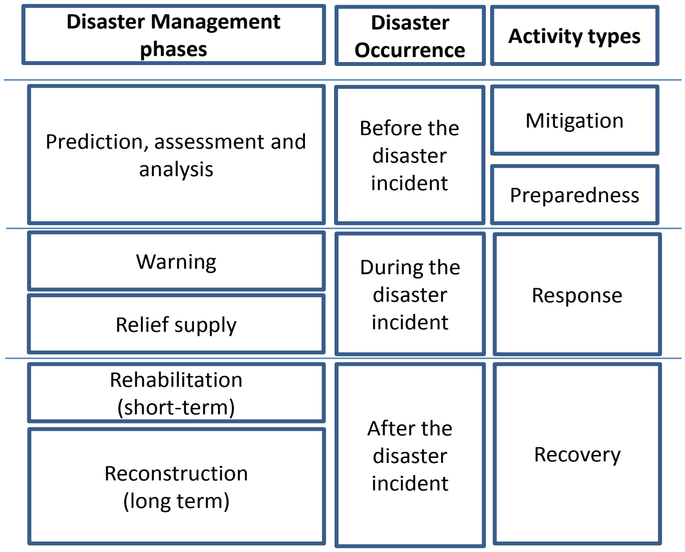


Figure 2.1: Emergency systems response types and classifications.

In this thesis, literature related to emergency response planning arising from disaster events are reviewed. The focus on the review is on theoretical models and applications published in journals from 2002. The literature on industrial disasters is searched from the vast physical and electronic database available at the university by using keywords such as decision support system (DSS), emergency logistics, emergency management systems, industrial accidents, and emergency communication. Content analysis is used to extract the focus presented in the literature. Caunhye et al (2012) have shown that content analysis helps in identifying the relevance of literature on the focus of the study. The literature used in this study is given in the reference list. The analysis shows that about 60% of the collected literature focused on the theoretical part while the rest focused on the applications and cases. Based on the analysis, the emergency situation phases are further categorized, for each phase, in terms of facilities, resources, and support systems/support services (as shown in Figure 1.2). The modeling framework available in the literature and are potentially applicable to each of these phases are also reviewed.

2.2 Literature Analysis

The analysis of literature presented here is based on the grouping in terms of the phases of emergency management and the categories of these phases mentioned above. The frameworks and models used in different phases are also described in brief in the review.

2.2.1 Preventive phase

Most of the literature in emergency management refers to the preventive phase. Planning of safety and security of industrial facilities is very important. Preventive phase planning can be very important specifically for the man-made disasters as incubation of the disaster may be eminent. Shaluf et al (2002) mention that incubation period can be from a very short period to very long period. The complacency of assuming everything to be in working condition, especially in the technological projects, can push away the need for planning for prevention. The authors give examples of short and long incubation periods causing major disasters in industries. This is to note that in the review presented here, the focus is on the provisions of measures to avoid or mitigate the disaster and not on the technological aspects like detection system or operational aspects. The review below focuses on sub-categories considered for the preventive phase.

Facilities

Facilities design, location determination, and its function are very important parameters for assessment of overall risk in the industrial facilities. For the preventive measures, the location should include capacity, type, and accessibility to the disaster sites. Therefore, the identification on the chances of incidence occurring in a location becomes a prerequisite for facility planning. Not only that, the design of industrial facilities and its contents (like materials storage) are also important considerations. Various techniques such as analytical hierarchical process (ANP) or analytical hierarchical process (AHP) can be used for risk assessment resulting from the storage of hazardous chemicals or installations handling hazardous materials. The industries are prone to chemical spill and fire and therefore, hazard assessment of such facilities become important.

Zhao et al. (2008) used AHP and geographical information system (GIS) to assess the risk of facilities that use hazardous materials. They defined the facility based risk assessment in terms of intrinsic risk (such as property of substance and quantity of storage), derivative accident (such as impact on water pollution and traffic disruption), impact on surrounding environment (such as economic condition and population density) and rescue force (such as medical and fire forces). Impact on water pollution focuses on surface and ground water pollution due to the mixing of the chemicals. Traffic disruption refers to the ease in accessing the site. Te economic condition here refers to the economic impact due to the disaster event and population density refers to the number of people who get affected in a particular area due to the disaster event. Medical rescue force refers to the readiness and capacity of local healthcare facilities and the fire force refers to the capacity, readiness, skills, and the equipment available in the nearby fire stations. The authors also use poison index (reflect the level of poisonous chemicals available on site), fire and explosion index (reflects chemicals substance nature from fire and explosion behavior) and erosion index (reflects chemicals substance nature from corrosion and erosion behavior) for their assessment. Erosion index can be very important as they can happen without being noticed for a long time but causing a disastrous effect. The system was developed by the author based on the requirements of emergency management agency in Kunshan city in China, and their study shows that GIS can be used to establish criteria for analysis in AHP. The AHP can be used for classifying and assessing risk factors so that overall priority of alternatives can be obtained for ranking hazardous installation based on their susceptibility to disaster. GIS was shown to be useful to show the interaction of the installation to the surroundings. This approach differs from standard risk assessments such as "Dow Fire" and "explosion index and ICI Mond index" as it adopts to the local inner details related to production, storing and transportations. The method provided by Zhao et al (2008) is static, as it does not consider changes in the parameters that are considered for decision-making. The model does not include important factors like wind speed and wind direction. Although the method is shown to be applicable to one particular area, portability of the model is not mentioned in the research.

Shen et al. (2015) studied chemical industrial parks in China. They mention that evacuation of people and location of shelters are important and they need to be addressed simultaneously when we consider the emergency management situations. These two aspects are closely related as the location of shelter determines the routing and vice versa. The model assumes a situation of a chemical spill, where time to affect the individuals and time to affect sheltered places are considered. Therefore, individual vulnerability (harm caused by the spill on individuals) and social vulnerability (harm caused to the population in an area and the location of the source of the spill) are considered by the authors as two objectives. However, these two objectives are combined with appropriates weights in order to solve it through a three stage linear programming method. In the first stage, the best locations of shelter areas are considered. In the second stage, factors on human vulnerability, time taken to reach the shelters and probability in terms of availability of each route for evacuation to the shelter areas are considered. Each of the factors mentioned in the second stage is expanded in stage 3. For example, human vulnerability is considered in terms of the number of disaster sources, social indicators and the probability of individual vulnerability.

For the outcome of the model, the obtained solution on the choice of the route and shelter depends on the weights assigned by the decision makers on vulnerabilities and usability of a particular route. The model provides a joint solution on the location of shelter areas and the routes for evacuating people to those shelter areas.

The authors applied their model in an evacuation network that considers 36 nodes, of which only three are in the upwind area, one of which can be selected as the shelter area. The model also helps to categorize the affected (or shelter) areas in a priority hierarchy so that the best shelter area could be chosen for location decision.

Shen et al (2015) did not consider traffic conditions during the disaster incident and only considers the passable probability due to the distance and the risk. The proposed model is developed for a specific case of a chemical spill and therefore, it is useful for applications in industrial cities where chemical spills of individual companies need to be considered. The model has limitations in terms of its use based on the wind speed, wind direction and air dispersion effect as these factors can have different impacts in terms of vulnerability of an individual and the shelter areas. Although the authors have mentioned two objectives and three stages, the objectives are complementary as both of them are intended to reduce the impact of the disaster.

Khayal et al (2015) have mentioned that when there is a disaster related situation at a large scale, then it would be necessary to develop temporary facilities in order to meet the immediate demand for relief supplies. Although the authors have used situation of a hurricane, at which the onset of the event is known, and the scale of the disaster is not known. This study helps in understanding that, when a disaster in a large industrial cities needs to be analyzed, urban planners should be able to understand that defining the location of temporary facilities like distribution centers or medical support centers becomes very important.

Inventory planning for prepositioning of relief supplies in different warehouses is considered by Davis et al (2013) for humanitarian logistics situation. The author developed a two-stage stochastic linear programming model in which the first stage is used for the prepositioning of supplies based on the forecasted impact of the disaster event. The authors consider the initial inventory at a location, the capacity of the facility, penalty cost for damaged supplies in the facility, distance from one supply point to another supply point, the time allowed for prepositioning and the congestion in the traffic in term of reduced speed of the supply to the affected location. The authors use various scenarios to identify the worst case demand (maximum demand) and worst case supply scenario (with the lowest level of available supply due to supply damage or loss of supply).

By studying the US Gulf coast region, Li et al (2011) developed a disaster preparedness model for shelter networks. They studied the locations and capacities of each of these shelters. In addition, they also consider different scenarios to analyze the situations with the evacuee and the relief supplies in the shelters. Li et al. (2011) used a dual-step stochastic program to analyze temporary shelters locations planning and its operations during disaster preparation phase and reactive arrangement preparation. The decision on building additional shelters and their location and capacity is complicated due to two aspects: the stochastic nature of the accident and the compromise among evacuation needs and evacuation available cost. The proposed solution can help rescue and evacuation agencies to decide on the allocation of budget to construct permanent emergency shelters. The authors proposed a sheltering network planning and operation model for a two-stage optimization by considering available resources, surplus or shortage of resources after evacuation in a particular shelter. The optimization uses the fixed cost of shelters and inventory cost of supplies in the shelters in the first stage. In the second stage, the cost for transportation for evacuation and transportation of supplies, and the cost of surplus or shortage of supplies are minimized.

From the reviewed literature in this subsection, it can be mentioned that for the reduction of disaster impact, the routes, location of shelters, impact on traffic due to disaster, the location of industrial facilities, the interaction of the facilities with the surroundings based on the type of chemical and the environmental factors are important considerations. Further, it also shows that mathematical models such as single objective (or multi-objective) programming or analytical hierarchical programming in combination with other models can be used for decisions on facilities.

Resources

Seok et al. (2012) have proposed a sustainability based DSS using collaborative control theory (CCT) to develop and recommend effective sustainability plans for the industry. The authors have used three key factors, called protocols, for consideration in the DSS: disruption analysis – to help in predicting and managing disruption based on the historical information or the simulated situation; negotiation management—an essential part of decision making where the stakeholders objectives need to be understood, analyzed, and negotiations should be carried out accordingly, and; knowledge management—provide relevant data and information for decision making and to maintain updated databases. The database in the DSS could refer to the case studies for each decision maker, or the case study related to sustainability issue, the database on strategy based framework or mathematical models, and database on the regulations and policies, and information on sustainability aspects on the environment, social, and economic matters related to the industry. The focus of the paper is on collaborative decision making for the operation of the industry. The authors have proposed that in order to develop this type of decision-making tool, researchers or practitioners have to focus on methods like fuzzy logic, available stochastic methods, genetic algorithm, artificial neural network, and case based reasoning methods. The authors showed a simple example of applying this method for resource scheduling. The authors mentioned that while considering the disruption analysis part in this case, one has to look at demand fluctuations. While considering negotiation part, one has to look at the options to get the supply from different manufacturers (or supplies) and any additional constraint needs to be considered. In knowledge management part, one has to consider the information on the requested amount, available capacity for transportation of the requested quantities, information on the location of manufacturers and the related costs. The authors have developed extensive mathematical models to analyze the decision situation. This research shows resources such as the proposed DSS would be useful when decisions are to be made in an industry environment. The focus in this type of environment is on collaborative decision making in order to develop a compromised solution that tackles the given situation in the most logical manner.

Improvement of safety in an industrial area is also studied by Reniers et al (2009) by considering the cluster of chemical plants. The authors mention that compared to a plant level safety standards, for cluster level safety, cooperation, joint workforce planning, joint risks and hazard analysis, and joint planning for emergency response planning are required. This kind of a situation invites information exchanges more formal safety documentation, and feedback based safety enhancement process. Therefore, development of a framework for cooperation on the safety of the clusters by considering human resources, production, maintenance, management, and safety support becomes important. This type of cooperation can create maximum synergy on risk analysis across the companies. This framework can also help in adequately defining and monitoring the responsibilities within the plant safety and cluster safety units for safety management. What is important here is that a framework as suggested in Reniers et al (2009) can support a better safety management in the industrial cities. This kind of framework can be helpful in preventing, mitigating, monitoring accidents, and quickly following up with the corrective actions. The authors also provide a list of 11 safety items that need to be considered in clusters. The authors believe in a win-win situation for all in this framework based system implementation.

The use of information systems has also been mentioned by Zhao et al (2008), who recommended using GIS based system and AHP to aid in the planning of disaster management. Similarly, Yoon et al (2008) mention of a computer based DSS, and Shaluf et al (2012) develop a framework for technological disaster.

Support Systems

Continuous training and skills development are the important elements emergency management support system. These elements in the pre-disaster phase (preventive) are centered on readiness for handling emergency and urgent situation as per the organizational emergency response plan. Shaluf et al (2002) and Yoon et al (2008) mention communication as one of the important aspects that can help in the running the support system for emergency management smoothly.

Shaluf et al. (2002) focused on disaster incubation and provided a list of causes that can lead to eventual disaster. Their study is focused on four technological disasters in Malaysia. The authors mention that the level of awareness of hazard and the emergency preparedness through the understanding of different causes of hazards are important in emergency management. The causes identified by Shaluf et al (2002) are:

- Social errors (such as people's low morale, awareness and personality, experience; lack of safety culture; continuity of people, and; top level commitment),
- Technical errors (such as due to equipment failure, the design of processes and equipment and failure to detect deviations),
- Organizational errors (such as a lack of operating procedure, occupational health and safety regulations, poor communication and ambiguity in procedures on various aspect of changes in the installation),

- Operating errors (operator/maintenance errors, testing errors for material and equipment and storage related errors),
- Warning system (such as lack of communication on early warning signals or blocking such a signal from being communicated),
- Triggering event (that makes disaster unavoidable such as due to operational errors and component failure), and
- Defense (lack of the last line of defense such as insufficient facilities for containing the disaster impact or inadequate detection system).

Shaluf et al. (2002) used the seven categories to develop an "Ibrahim-Razi model". The model starts in different phases: generation of error (phase 1), accumulation of error (phase 2), warning (phase 3), correction (phase 4), unsafe conditions (phase 5), triggering event (phase 6), defenses (phase 7) and finally end with the disaster (phase 8). In each of these phases, the progress heavily depends on the effectiveness of human resources. The authors mention that longer the incubation period of disaster, larger is the impact of the disaster. Therefore, consideration of the factors can help in considerably reducing the disaster impact in industrial installations.

Yoon et al. (2008) identified communication as one of the challenges for building and sustaining good emergency response system. Throughout disaster situation, emergency logistics services managers need to evaluate the situation and arrange for fast actions such as emergency information broadcast, blockages of streets, availability of diversion roads, and clearance of accidents wreckage. In emergencies, making a decision is very difficult, as they are usually not supported by normal emergency plans. Therefore, a computerized model for group DSS (GDSS) has been suggested by the authors as an efficient solution method to integrate and interlink information on resources and planning. The system uses real time information about available resources, communication contacts, maps, weather, plans, and procedures, which can simulate real situations, and it can be used for mock drills among all departments involved in real life emergency situation. This framework can be used to develop system for communication in emergency management situation to improve online data availability among all parties involved in the emergency situation.

Policies and procedures are the third elements of emergency management support system. It is relatively a broad area, which covers all important processes and sub processes in the emergency response system. Generally, these procedures and communications protocols provide guidelines for groups and individuals on how to react, and whom to contact in case of emergency. As per literature, two methods have been used to improve the procedures and communication. The first one is related to the implementation of best international practice and the second approach is to completely create a new system.

Calixto and Larouvere (2009) reviewed emergency response plans in Australia, Canada, Japan, United Kingdom, and the United States of America in order to develop such a plan for Brazil. The authors mention that, depending on the criticality of the disaster and the damages that it brings, the emergency plan includes industry, society and the government with various levels of responsibilities. These plans can be categorized in terms of individual level or site level, that focus on serious impact to individuals and the surrounding environment in a specific area, regional level, coordinated effort of multiple organizations, when an individual plan is not sufficient to cater to the needs for response, and national level, coordination of response and cooperation from multiple organizations in a larger scale. The response mechanism at the national level should also include the coordination of resources to be deployed from different organizations. National level emergency plans require taking multiple decisions at a very short period also called blitz. In order to develop response plans, various scenarios can be developed to simulate the multi-organization coordination and at the same time to devise a response framework, that suits a disaster situation. The authors carried out a sensitivity analysis to identify all the risks involved including technological and natural risk in order to develop sensitivity map and index by considering environmental, social, and economic factors. The sensitivity map shows criticality of a specific location and determines the location of critical resources needed for emergency response. The authors mention that although the government has asked the oil and gas industry to follow certain guidelines for emergency response; those responses are focused on an individual level. Some of the industries involve more stakeholders such as local government and different other companies, scaling up the response plan to regional level but it requires a good coordination. The preliminary regional framework developed by the authors before the oil spill in 2001 in Brazil was reviewed after the incident and a new response framework was developed to respond to such incidents. The framework emphasizes not only on the support needed, safety and environment, and an assessment system but also on the communication and coordination. The coordination of planning, logistics, and finance are considered as important for such an index-based emergency framework system.

Modeling framework for preventive emergency response

The researchers have used various mathematical or procedural frameworks in order to analyze the preventive aspects of the emergency management system. The authors have mostly considered a single objective programming based on mixed integer programming in order to arrive at either the location or location-allocation or location routing decisions. The authors have used either a single stage solution methodology or multilevel solution methodologies. The decision on the prioritization can be done through the weight-based system elicited from the decision makers or through the analytical hierarchical programming. The authors have also proposed that systems, like geographical information systems, computer based simple information system, framework based response system or individual response system become important to develop a holistic emergency response system. Table 2.1 below provides a snapshot of different mathematical models and systems that are used by different authors for the prevention based emergency management system.

Table 2.1: Modeling frameworks for preventive measures

Authors	Context	Objectives used	Single or multiple objective function	Data types Deterministic/ Stochastic	Solution Method	Information system/ Remarks
Calixto and Larouvere (2009)	Chemical disasters	--	--	Deterministic	Framework	Cluster based coordinated emergency response plan
Davis et al. (2013)	Hurricane	Prepositioning cost	Single	Stochastic	Single objective programming in two stages	--
Khayal et al (2015)	Generic disasters	Logistics and deprivation costs	Single	Stochastic scenarios	Single objective programming, multiperiod solution	--
Li et al. (2011)	Hurricane	Cost of capacity and cost of transportation	Single	Stochastic scenarios	Stochastic Single objective programming in two stages with L-shaped algorithm	--
Reniers et al (2009)	Chemical industrial areas	--	--	Deterministic	Framework-safety management	Development of cluster based safety management system
Shaluf et al (2002)	Fireworks, chemical and hazardous materials related industries	--	--	Deterministic	Framework	Development of a model for assessment of technological man-made disaster

Seok et al (2012)	Manufacturing entities	--	--	Deterministic	Collaborative control theory	Improvement in DSS with regard to sustainability on delivery scheduling and production planning
Shen et al (2015)	Chemical industrial parks	. Time satisfaction . Probability of using a route	Weight based single objective	Deterministic	Compromise programming for transportation and location	--
Yoon et al (2008)	Generic, but focus on transportation network	--	--	Deterministic	Framework	Development of Group DSS
Zhao et al (2008)	Chemical installations	--	--	Deterministic	AHP	Use of GIS

It can be seen from Table 2.1 that most of the models are developed on deterministic data, however, the focus is more on the development of the frameworks for decision making. Mathematical models are also developed using single objective programing method or analytical hierarchical programming, which ultimately supports the decision making process. The focus in the reviewed papers is mainly on the routing, location of facilities, evacuation, and developing a cluster (or group) based emergency response system.

2.2.2 Reactive (Response) phase

Most of the literature that focus on reactive phase explore resources, mainly tools and techniques used or to be used in the disaster event. Some models also discuss the temporary location for the purpose of redistribution of supplies. Some other models recognize the changing demand situations and needing inter facility transfer of supplies.

Facilities

Location of facilities and distribution of the medical supplies have been considered by Wei et al. (2012) by using rough set theory. In order to apply the rough set theory for reduction of possibilities in a particular disaster area, the authors consider various conditions, expert requirement (or situation of disaster), and the feasibility of constructing the distribution facilities in various sites within the disaster area. The authors develop a decision Table by considering different decision-making conditions and use that to reduce the subsets of possibilities for the location of facilities and distribution of supplies. The paper is applied for a case of an earthquake with 10 different scenarios (or decision-making inference), five different decision making conditions, and three levels possibility to construct a facility in a chosen location. The five conditions are the difficulty in construction of facility (by considering the availability of labor, materials, costs and other factors), conditions of roads and communication for contact from outside the disaster area, contacts (through communication and roads) within the disaster area, accessibility to medical supplies (quantity and type) in a nearby location, safety and security conditions (such as that can be caused by aftershocks). The feasibility levels are considered in terms of good, poor, and qualified. Through the set reduction rules, they find that those locations with poor conditions of external contact and contact within the disaster area are not suitable for the construction of distribution facilities although other conditions may be favorable. What is important here is that, where there are multiple situations, it is important to prioritize the conditions swiftly for decision making to supply relief materials as soon as possible. However, it should be understood that this type of situation is faced by the decision makers when preplanning or preventive measures have not been implemented.

Khayal et al. (2015) show that both preplanning and positioning of resources can be done if we are able to anticipate the onset of the disaster. This means that in the industrial cities, a good planning by developing various disaster scenarios can help in prepositioning the supplies in different places. However, during the event, not all areas may need all the supplies positioned at a particular place. Also, demand for such supplies can change from one decision period to another depending on the scale of the disaster. The authors, as mentioned earlier has used a mathematical model to develop facilities with a possibility of inter transfer of the supplies between different facilities to meet the demand of all areas covered by the set of facilities.

Providing supplies from the prepositioned facilities during the immediately after the disaster is considered by Davis et al. (2013) in a two stage stochastic linear programming model. In the second stage of the model, the authors consider the cost of distribution of supplies to the affected areas. The authors also consider demand-changing factor to account for the increased distance between the distribution location and the affected area. Similarly, supply-changing factor is also used to account for supply severity due to damages and the proximity of supply location to the disaster area. However, authors use a bound of the total population of the affected area to consider the maximum demand. The authors also consider the unit cost of unmet demand, a minimum fraction of demand that must be satisfied, maximum allowed response time and congestion factor in terms of reduced speed of supply.

Resources

Peng et al. (2011) proposed an incident information management framework to support emergency response management. The authors mention that compilation of incident data, dividing them in to pre and post incident related information, and using a multi-criteria decision making system can help in assessing the incident situation. This is necessary for developing response solutions for the incident. The proposed information management is applied in a case to examine meteorological disasters on agriculture such as draughts, floods, and sandstorms. The authors develop disaster coverage area and disaster affected area as two indices for their analysis and developed an incident management framework. The outcome of the multicriteria decision-making provides a ranking of areas according to the losses due to the disaster. In the first stage of the model, incident data is standardized, analyzed, evaluated, and dissected. In the second stage, data mining is employed and appropriate multicriteria-based methods are used to select the most appropriate alternative for a response. In the third stage, decision makers can use the query-based process to interact with the developed model. Although the work presented here is specifically on the crops and area based losses due to disaster, the framework developed by looking at the incidents and the use of multiple criteria based decision making can be helpful for use in the industrial disasters as well.

Lee et al. (2012) proposed an unstructured information management system (UIMS) framework to manage large databases of the emergency situation. The authors mention that this type of information is in various forms, like data, reports, speeches, images and video, which need to be analyzed to extract the knowledge in order to make decisions for emergency response management. In order to find the required data and information rapidly and precisely from the enormous data and information based on the behavior, features, conditions, the proposed framework is composed of three tiers. The first is a feed-in layer, which is the information input to the proposed system. It includes the amorphous data of the business (like emails and official papers). The second tier is the information outside the business (like the websites of its associates and competitors), and the third one is the public thesaurus of the domain industry. This system is used to provide decision makers with dependence and degree coloration to make appropriate decisions in emergencies. The authors mention that linear search of the database can provide the knowledge but they are not able to provide associative information on the knowledge, which is an important aspect for emergency response management. Therefore, the authors use synthesis evaluation to find the precision, usability, comprehensibility, reasonability, and usability of data. This was necessary for developing dynamic knowledge flow from the unstructured data, communication channels used by the people, automated classification of data, development of concept relation model, and navigation of data for usability of data.

Ju et al. (2012) focused on emergency response capability of an organization such as ab emergency department. The authors mentioned that the emergency response capability refers to the processing capability of the department (for example capability to command, collaboration with urgency), forecasting capability (for example, monitoring, warning, information system development and use), support capability (reserve available, communication, and simulating emergency plan), and after disaster process capability (for example, social support and reconstruction). The evaluation of emergency capabilities is a very important element in the emergency management process to determine the readiness availability of emergency resources. Due to the shortage of time, the absence of knowledge and information, emergency response professionals frequently assess the significance and the rankings of qualitative principles in the form of language variable valuations other than precise mathematical numbers to define their view for assessing the disaster response capability. The proposed model is a very useful tool for efficiency, effectiveness, readiness evaluation of emergency response system for industrial cities. Regular assessment of capability for emergency response is an important aspect for continuous upgrade of the emergency management system. In that respect, the use of scenario based after disaster response system becomes important for an effective emergency response.

Chen et al. (2012) proposed conceptual during incident process assessment framework for emergency response in the response phase. The authors mentioned that such a framework considers three factors: possibility related, necessity related and other influence related. Possibility related factors should consider the disaster type, current state and the evolutionary tendency of disaster, affected victims and property, and ability in terms of resource availability and supply of resources to required areas. In terms of necessary, the authors focus on profit and value. We believe that using profit in these cases instead of efficiency is not a good parameter to consider. Similarly, for other factors, they considered the preference and tolerance of the decision making and emergency situations. The authors divided the during incident assessment strategy in to three parts: mitigability, rescuability, and recoverability. Mitigability measures the ability to reduce the impact of disaster through specific arrangements and precautions; rescuability measures the potential to save lives and properties, and; recoverability measures the potential and difficulties that may be encountered to bring the facilities to the normal or enhanced state of operation. The authors mention that if these can be assessed properly, then appropriate emergency response decision can be selected for the implementation.

Baldini et al. (2012) mentioned the use of radio frequency identification technology (RFID) to increase the efficiency of providing supplies in case of disaster. The authors mention that disaster incident in chemical installations have low predictability, medium impact and medium possibility of extension to different areas. Compared to this storm and hurricane have medium predictability, medium to high impact and covers a large geographical area (high). The authors proposed a cryptographic algorithm to develop a secured supply system to reach the global and local government suppliers and charity organizations, and then to transportation and distribution and to the distribution units. The authors believe that this type of model helps to understand the flows correctly so that supplies can be coordinated. What is important in this paper is that, when supplies are constrained in an emergency situation, they can be routed easily to the most needed area through a nicely integrated technological solution. The authors propose system architecture to create such ability for distribution. Tagging information like this in industrial cities undoubtedly helps to maintain the database on the quantity, type, and usability of the relief materials and tracing them for use in case of disaster.

Zhong et al. (2010) used Petri net-based emergency response system to analyze urban emergency response system (UERS). The authors have provided a procedural framework that is used for ab emergency response related to a major disaster event. However, the events like SARS are considered in order to identify event location and interface with the local urban and external (national or other urban centers). The focus here is mainly on the communication of the situation.

Support Services

Laakso and Palomäki (2013) mentioned that different usage of terminologies and languages on the emergency situation and emergency response can, in fact, increase the damage. In order to minimize this problem, the authors developed a theoretical framework. The authors mentioned that disasters cannot be managed by an organization alone, therefore, horizontal level communication across organization so that cultural assimilation or cultural autonomy can be avoided for the cultural transformation for a new way of functioning by the organizations. The authors also mentioned of the communication integration on the vertical levels so that the top level understand the technology, processes, and promote collaboration for the information regarding evidence, plan, and responsibilities. In order to come up with their proposal to enhance the learning on the emergency management, the authors conducted a Delphi study in order to identify problematic situation on information flow and the challenges in terms of disaster lifecycle stages. Their study finds six different domains of issues which are: the issues related to the awareness of the situation and information flow, local company based management which focused on local incident, communication flow at the time of disaster and immediately afterwards, communication at the event site, cooperation between the organization working in an event site and the use of different types of communication system. They mention that cooperation is particularly important in industrial cities to warn the neighboring installation if an installation is exposed to the disaster risk. Therefore, tackling the communication, integration, cooperation and technology issue among the installation can help to contain the disasters. This type of system requires a high level understanding of the disaster exposure, continuous update of information on the operation and any trigger, and collaboratively providing resources for the containment of the impact of the disaster. However, this level of commitment requires a high level body in industrial cities that can provide oversight on the emergency management, emergency readiness (through training and planning), and containment of disaster impact to the lowest possible level.

Modeling framework for reactive emergency measures

Table 2.2 below shows various modeling framework, from mathematical models to framework based models in order to develop the understanding of an emergency situation, response mechanism system, decision support and policy development for common understanding of the emergency related situations policy making for tackling the during-incident situations. The coverage of the research is from natural disasters, man-made disaster, urban related disaster and consideration of the generic type of disaster. The review shows that there has been recent work in analyzing the emergency response situation and most of them are based on the development and implementation of the framework for response phase.

Table 2.2: Modeling frameworks for reactive measures

Authors	**Context**	**Objectives used**	**Single or multiple objective function**	**Data types Deterministic / Stochastic**	**Solution Method**	**Information system/ Remarks**
Baldini et al (2012)	Generic	--	--	Deterministic	A technology based framework for efficient relief supplies	Decision making through prior understanding of the needs and development of supply system to meet the need in the

						disaster area.
Chen et al. (2012)	Generic	--	--	Deterministic	A framework based response strategy	Supporting decision making for developing an appropriate response plan
Davis et al. (2013)	Hurricane	Cost of distribution	--	Stochastic	Single objective programming. Post-incident distribution is analyzed in the second stage of the two stage model.	
Ju et al. (2012)	Generic	--	--	Stochastic	Fuzzy AHP and 2-tuple linguistic approach	Capability framework for an organization
Khayal et al. (2015)	General	Logistics and deprivation costs for both prepositioning and post disaster distribution	Single	Stochastic scenarios	Single objective programming, multi period solution	
Laakso and Palomäki (2013)	Generic	--	--	--	Collaborative framework by considering various common issues on disaster event	Policy development for high level collaboration
Lee et al. (2012)	Data on various emergency response or planning related document	--	--	Deterministic	Development of framework by synthesizing the data and extracting the knowledge for emergency response	A case based knowledge flow model for decision support.
Peng et al. (2011)	Disaster related to weather	--	--	Deterministic	Data mining and multiple criteria	Interactive information management

					method	framework
Wei et al. (2012)	Earthquake related and medical supplies	--	--	Deterministic but scenario based	Rough set theory by considering various site based conditions.	--
Zhong et al (2010)	Urban areas related events	--	--	Stochastic	Petri Net based system for analysis of the system	Integration of communication between local and external emergency agencies for effective emergency response

2.2.3 Corrective (recovery) Phase

Corrective actions are usually taken after the disaster in order to recover it as fast as possible. Chen et al (2012) mention that in the post-incident stage, the focus is on complete recovery and bringing the situation to normal or to an enhanced level of performance. This means all the impact of the disaster should have been mitigated and lesson learned would have been used to develop a better response system and the affected facilities should have been operating in at least the same level of performance as in the pre-incident normal phase. The focus here is to review literature that takes the post disaster situations and response mechanisms. It is to note that some of the literature mentioned in the corrective phase may overlap with the reactive phase mentioned above. An attempt has been made to focus on those activities, which help in recovery after the first line of supplies or activities performed immediately after the disaster and the long term planning adopted after the disaster.

Facilities

Considering the post-disaster situation, Holguin-Veras et al. (2012) mention that logistics related to humanitarian impact should be considered differently than the logistics used for commercial purposes. In humanitarian logistics, a vast collection of activities including distribution of medicinal material for normal sickness control, nutrition goods to control starvation, and essential materials required for the rescue after major accidents are to be considered and they have to be quickly supplied to the affected people in order to avoid any deprivation of supplies which can have detrimental impact on the affected people. Pradhananga et al (2016) mention that unlike in commercial logistics, the demand and supply situation can change with time, even if it has a very small time window. Therefore, the nature of supply, frequency of supply and the quantity of supply should be carefully analyzed for the fastest possible recovery. Holguin-Veras et al. (2012) and Pradhananga et al (2016) show that one of the important factors that need to be considered in humanitarian logistics is the deprivation cost. That means, larger the time required to wait for the relief supplies, more the suffering of the individual people impacted by the disaster. This forces the decision makers to look at quick service of supplies in the right quantity to the affected people. Holguin-Veras et al. (2012) additionally mention that when the logistics are not adequately prepositioned or prepared, and it is collected as received, a lot of materials can be received by the agencies working on relief supplies. These materials, however, may or may not be useful to the targeted victims. Therefore, the convergence of relief materials in the disaster locations and management of such materials can hamper complete recovery after the disaster. Therefore, the design of facilities should consider various aspects of humanitarian logistics.

Ben-Tal et al. (2011) considered demand uncertainty in relief supplies and propose robust optimization (RO) method to assign response and to manage traffic flow for evacuation. Their method considers demand uncertainty and dynamic traffic assignment through robust optimization (RO) and cell transmission model (CTM). The method provides dynamic assignment of crisis management and control of roads traffic movement with time based on undefined requirements. The proposed model is built for handling a multi-period transportation problem. The model uses a lowest and highest values principle and uses modified version of the RO method tuned to dynamic optimization problems, an affinity adjustable robust counterpart (AARC) method. The author mentions that compared to the other methods such as deterministic or sampling based stochastic method, AARC based solutions are better in the case discussed in the paper.

Tzeng et al. (2006) presented a relief-distribution structure in a multi multi-objective programming framework for relief supplies for a case in Taiwan. The authors consider minimizing the costs of transfer points, minimizing travel time and the maximizing satisfaction. The authors mention that compared to the general (or commercial logistics), in relief supplies fairness of supplies instead of profit maximization, the temporality of the facilities instead of regular facilities, and transfer points for relief supplies rather than distribution centers should be considered. Relief supplies decisions are urgent and are based on available information, and therefore they are very dynamic compared to regular logistics where the focus is mainly on long-term decisions. The authors used fuzzy multiple objective model and used simulated scenarios to demonstrate the applicability of the model. The methodology can be implemented to establish local operating system that can be integrated with external larger emergency management and allocation application.

Turgut et al. (2011) have presented a DSS for the location of disaster logistics center in Istanbul constructed by using analytic hierarchy/fuzzy analytic hierarchy process. Identification of the principles and sub-parameters needed for the suggested DSS was done by a survey completed by experts employed by Istanbul Center of Disaster Coordination (ICDC), consultations with specialists, and use of the research work of other researchers in the same field. The authors mention that for the choice of such a center, decision makers should consider costs related to investment, operation and maintenance, cost of transportation by mode (air, sea, or land), infrastructure available (IT, energy and water), location (closeness to the city and the disaster location), and the climatic conditions.

Resources

Human resource is a very important element of emergency management system response in the recovery phase as well. Nivolianitou and Synodinou (2011) analyzed emergency management system in Greece to identify factors influencing response to natural and critical accidents based on feedback from emergency system documents analysis, interview with experts, official organization, and volunteers. The study cuts across eight partners from three European countries and focusses on natural disasters. The study identified 15 factors influencing emergency management related to emergency organization and stakeholders. These factors are: role framing (executing activates similar to outline of the organizations and the capabilities of its employees), competence, availability, intervention type, means, guidelines, cooperation degree, coordination degree, early reaction time, timely information passage, role clearness (exact information of team's member is account Table for), number of people, deeper contextual knowledge (associated information about emergency situation attributes), organization identity (if the institute is simply identified), and cognitive lock-up (readiness of the staff to take care of limited kind of incidents). In addition, the study identified two main human factors which need to be considered during an emergency. The first is personal factor, which include the physical condition (fitness), team gender, good memory, stress, fear (as an emotion), perception capacity, constant attention, bad temper, character, motivation. The second is labor factors such as years of experience, time pressure, and workload. The study also identified a group of factors for suitable activities and effective involvement with emphasis on operation and logistic related parameters. One of the major findings is that the importance of human factors evaluation needs to be seriously considered starting from physical condition until workload and capacity. The quantification of these factors and the establishment of required minimum levels are very important elements for emergency response but they are not covered in this study.

Zhou et al. (2011) presented a tool or method to evaluate cause-and-effect relationship in emergency management especially related to the natural disasters. The authors used fuzzy decision-making trial and evaluation laboratory (DEMATEL) method to obtain five important critical success factors (CSFs) from a list of 20 interdependent factors. The CSFs consist of four cause elements and one effect element which are, respectively, ‘sensible organization arrangement and comprehensive knowledge of roles and accountabilities of each individuals, efficient emergency communication system to guarantee information transmitting, ‘unified governmental management to integrate design and execution, utilization of up-to-date transportation techniques, and continual enhancement of working arrangement of emergency management. The study mentions that in order to have an effective emergency management system, there should be a process to continuously improve its operational parts.

In the area of equipment mobilization, Chiu and Zheng (2007) proposed a cells transformation techniques (CTM) for concurrent tools and equipment mobilization destination, determination of best traffic route, and dispatch timing for multi-priority groups (SMDTS-MPG) for an instantaneous emergency response for no-notice disasters. The authors recommend an integrated and multi-dimension evacuation and relief supplies distribution system in order to deploy the resources, which depends on the type of incident and the environment/facilities surrounding the incident. The authors used a cell transmission model (CTM) based linear programming model to minimize the travel time of multi priority groups for over the planning horizon. The result of the model provides travel time, traffic assignment, and departure schedule for different groups.

Vescoukis et al. (2012) proposed an environment information management system (EIM) for crisis management and planning based on 3D modeling software. The model is based on the real-time and stored information. The proposed model focuses mainly on systems architecture to support environmental simulation on the geospatial information for disaster response and decision support.

Maio et al. (2011) proposed a DSS framework based on fuzzy cognitive map (FCM). The FCM helps in information processing and resources identification based on the emergency situation. The framework consists of several interactive components that are run by an emergency manager. The manager provides inputs and directives to the framework and receives system outputs and stimuli (such as message or phone calls). Stimuli signals either start of the DSS session or adaptation of a particular emergency plan that is already existing in the system. The framework also contains an interface manager, communication interface, service interface, people’s information interface, and geo-social interface. The information to these interfaces is queried, updated of populated through a semantic middleware component. In the fuzzy cognitive evaluation process, three parts need to be considered, features of the situation, types of actions that match the features and the type of resources required (or available) to provide the availability and response time in a particular emergency location. The authors have simulated scenarios by analyzing features, actions, and resources at different periods. The authors mention that the use of FCM and simulation supports decision making at a very short period and this can be a relief to the emergency manager.

In the area of human resources behavior and performance, Subramaniam et al. (2010) mention that emergency response is a collective team effort, therefore, team level analysis becomes important. Their research focuses on team member resources like members' ability and personality and characteristics of team members in the group that are: age, tenure, leadership, roles, and norms (acceptable behaviors). However, the authors did not validate their structure.

Yaming et al. (2011) proposed a DSS system that used GIS. The focus is on the chemical gas dispersion and blowouts that happens in petrochemical industries. The authors have proposed the need to develop a gas dispersion simulation model by considering wind speed and direction, production capacity, the content of the gas, surface roughness, and reference atmospheric pressure. Based on the simulated scenario, a simple static heuristics is used to identify a route for quick evacuation. The authors proposed an emergency response DSS by considering stakeholders, risks, simulation models, knowledge database, analytical modeling database.

In the area of resources and equipment allocations, Chen et al. (2011) presented a GIS based structure to allocate equipment required to respond to disasters. The proposed structure consists of three components: emergency resource repository portal (E2RP), mobile resource request client (MR2C), and automate resource management system

(ARMS). The authors recognize the need for a repository model in the form of database in the DSS. The MR2C is a portable application interacts with E2RP and offers onsite information on equipment to emergency team. The use of GIS in ARMS helps to provide routes that take minimum time from a set of location to the disaster site. The focus in the paper is on the automation of trivial matters and database on resource availability so that emergency response can be made more effective.

In the field of resources (tool, equipment, and distribution), de la Torre et al. (2012) provided analysis on selected models used in disaster relief routing in order to assist relief organization and research in this field. The disaster relief review covers a wide span of research areas starting from policies, demand assessment, uncertainty in supply and demand, vehicles routing, modeling vehicle depot, specialized models, commodities delivery and location, vehicle fleet type and technology, and finally uncertainty in the vehicle fleet.

Support systems and services

Park et al. (2013) conducted analysis on Japanese companies that got affected by Tsunami and the restoration of business. The study mentions four distinct crisis processes in order to recover from such disasters: crisis detection, assessment of damages and required responses, preparation to resume duties, and reexamination of crisis management activities. The authors mention two concepts for re-initiation of supply chain system. The first is the emergency supplies delivery systems attributes that include concentration, complication, and connection-points importance and significance. The second is the emergency supplies network adaptability and contingency features that include threats signal detection and recovery. Subsequently, the authors extended the basic model and represent it as the supply chain design information (SCDI) by integrating production info system, imaginary data collection, and cooperative databank substructure and supply chain information flows for portability of supply chain information.

In the area of policies and procedures, Reniers et al. (2011) have examined the chemical plant shut down policies through a survey. They examined six chemical plants in which there are both fast shutdowns and slow shutdowns as a means to respond to the fire induced risks from a nearby installation. The slow shutdown time in the surveyed companies varies from 15 minutes to 36 hours whereas that for fast shutdown time varied between 15 minutes to about 3 hours. However, although fast shutdowns can help in disaster situations, authors show that it can cost a lot to the company and the start-up time would take much longer. Cumulative daily loss due to fast shut down could be to the tune of € 190,000. The authors mentioned that although the tendency in many companies is to shut down the plant as soon as the fire hazard is noticed in the nearby installation, the use of data and the real option theory could provide different scenario based solutions, which make the installations safe and economically justified. Therefore, proper procedures need to be developed to implement such options.

The interaction between the organizational policies and work practices that happens in the installations are discussed by Taber et al (2008). The authors conducted an empirical study by interviewing emergency response workers (such as firefighters, and paramedics) to explore the areas for improvements. The analysis of information showed that organizational policies support in experience gain and collaborative activities with the colleagues in the workplace enhances the learning process beyond the initial training. The collaboration between the paramedics and firefighters indicated that they are now better prepared for the work and to respond to the emergency situation faster.

There are examples of long term impacts and capabilities analyzed for better emergency response. For example, Nagarajan et al. (2012) focusses on communicating warning messages for evacuation and Paton (1999) focusses on business continuity by examining staff vulnerability, training, recovery management method, risk hazard and assessment, and organizational system. Parlak et al. (2012) studied the behavior of victims in a radioactive disaster situation. The authors use multi-criteria analysis to prioritize the initiatives for different behaviors. Simpson (2008) studied disaster preparedness and response capability for better emergency response in a city by considering factors like public safety, hazard exposure, city's financial state, developed disaster preparedness measurement methodology driven from existing system for readiness assessment. The study used numerous information bases, like interview of important facility executives in two different societies, two town's complete policies, financial plan, and the crisis operation procedures, emergency medical services response capability, and fire protection measures. Kusumasari (2010) also emphasize on the capability of local governments to manage the pre--, during—

and post—emergency situations. The researchers mention that in the post—incident situation expertise on damage assessment, and skills for disaster related assistance would be of high value to the local government.

The need for a sound communication infrastructure to reduce the impact of disaster situation has been studied by Yang and Hsieh (2012). Their study on Asian Tsunami in 2004 shows that a sound IT based crisis management system as adopted by the Tsunami Crisis Coordination Center helped in monitoring the available stocks and requirements for emergency materials and assessing and best method for material delivery. The success in response was due to several reasons such as key resources deployment during crisis response (such as leadership, IT resources availability, effort of cooperative system of numerous community and private division), capabilities deployed (such as gathering resources rapidly, using merchant assistance, and operational creativeness), capability to make information system quick (such as software recycle strategy and IT improvisation), and skill to produce effective info movement (such as exploiting robust links and info operational creativeness). In addition to communication infrastructure, Oh et al. (2010) mention that other infrastructure and industry service also needs to be analyzed to develop an emergency response system.

The review of literature in corrective phase is mostly related to flow assignments, planning in anticipation of next disaster, supporting database development, and DSS. The study reviewed here also focus on infrastructure, behavior of victims, structure of the team, and the policy formulation as well. Therefore, holistic view becomes important in the corrective phase as the lessons learned in the previous incident can help in developing a better response mechanism for the future.

Modeling framework for corrective emergency measures

Table 2.3 below shows various modeling frameworks and DSS based framework in order to support corrective measures or to develop future capabilities to manage emergency responses. The research covers not only the disaster events but also simulated scenarios and collaborative initiatives among different disciplines related to emergency management. Although various mathematical models can be used to support decision making, the main focus in the corrective phase should be related to the development of policies, training, collaborative joint efforts for emergency management as a culture, a ramped up geo-spatial database system, and the development of wide range of computer model based disaster scenarios for active interaction by the emergency response units.

Table 2.3: Models and framework for corrective measures

Authors	Context	Objectives used	Single or multiple objective function	Data types Deterministic/ Stochastic	Solution Method	Information system/ Remarks
Ben-Tal et al. (2011)	Generic	Time space dependent cost for traffic flow assignment	Single	Both Deterministic and stochastic	Robust optimization, cell transmission model and	--

					affinely adjusted	
Chen et al. (2011)	Civil engineering related response for emergency	--	--	Deterministic	Database analysis and information protocol for request and dispatch of equipment	Uses GIS for developing fastest route to the site (from multiple locations)
Chiu and Zheng (2007)	Urban based no-notice disaster	Minimization of travel time	Single	Stochastic	Cell transmission based Linear programming	Information on possible routes and disaster location, but this is not explicitly shown.
Maio et al. (2011)	Generic	--	--	Deterministic	Framework, fuzzy cognitive mapping and simulation modeling	DSS with GIS based data
Reniers et al. (2011)	Chemical plants	--	--	Deterministic and scenario based	Use of real option theory	Obtain economically justified shutdown time for each installation
Subramaniam et al. (2010)	Generic	--	--	Deterministic/behavioral	A team based decision for emergency response	Team structure is presented
Taber et al (2008)	Paramedics and fire fighter	--	--	--	Survey based study for collaborative work	--
Turkut et al (2011)	Earthquake	--	--	Deterministic	AHP and fuzzy AHP for location of the disaster	Decision support to help choice of a location.

					relief supply center	
Tzeng et al. (2007)	Earthquake	Minimization of fixed cost, minimization of travel time, maximization of satisfaction	Multi-objective	Deterministic	Scenario based and fully multiple objective modeling	Electronic location map for supply routes
Vescoukis et al. (2012)	Generic, fire hazard discussed	--	--	Deterministic	Systems architecture for planning and simulation modeling	Expected as a decision support system with integration of geospatial data system
Yaming et al. (2011)	Petrochemical industry	--	--	Deterministic	Simulation of gas dispersion and heuristics for routing	GDSS based on GIS
Zhou et al. (2011)	Natural disasters	--	--	Stochastic	Fuzzy DEMATEL method	Focus is on finding the critical success factors for emergency management

2.3 Summary of the literature review

The review presented in this chapter shows that considerable work has been done in understanding, planning, and preparing for the disaster situation. The impact of a disaster depends on the nature of disaster (natural-like floods, hurricanes or earthquake, or man-made disasters like technology or process induced) and the geo-spatial condition of the disaster area. What is clear from the literature is that there are varieties of disaster related situations, which needs to be tackled mostly based on the local conditions. Some of the literature also focused on the development of better decision support system, having a good database, strong data mining and associative rule capability and good communication infrastructure.

Literature also shows that in some companies economic value of incident like shutdown time may have to be considered to develop a response mechanism. This might require preemptive inspections and increased periodic maintenance with minimal or staggered shut down to avoid economic value. Some of the models in the literature consider evacuation time, evacuation need and routing of evacuation, sheltering the evacuated people, protecting the installation and its neighborhood. From the review it can be concluded that localization of response depending on the nature of the area (spatial and technical), and the capability of the response mechanism are the most important factors to decrease the impact on social, business and infrastructural aspects.

The review shows that the current research on emergency management is usually focused on the individual plant level and is scaled up to the industrial city level. This is not necessarily right because of the interaction of one industry with the other, in terms of triggering the disaster situation. For example, if the fire is started in one-location moves to the next location, the damage in the neighboring location can be much more than the place where the primary incident occurred. This means that the nature of the environment, the types of installations and the content of the materials handled, stored and processed in the installation becomes important. This requires developing new hazard index considering the chemical and physical nature of the chemicals handled in a particular location. Such a hazard index should consider the incident impact on a location due to the surrounding facilities. It should also consider the impact of the incident location to the surrounding facilities. Multi-enterprise collaboration therefore, becomes important for emergency response (Nof et al., 2006). This part of emergency response considering the characteristic of the incident location is the focus of this thesis.

CHAPTER 3: RESEARCH METHODOLOGY

3.1 Introduction

The research design techniques have been applied to explore the proposed index-based emergency response management System (IERMS) framework and location hazard index (LHI) methodology. In this section, the methodology used to develop and examine the IERMS Model and location hazard index (LHI) are presented. A case study with sensitivity analysis is provided to examine the model and its behavior under different real life scenarios.

3.2 Research design

The research design is divided into two parts: the development of the location hazard index, and; the development of a framework for index-based emergency response system (IERMS). First, The Location hazard index is developed based on the information obtained from a database that exists in the industrial city. This information is tabulated and used to calculate the location hazard index of a specific location based on neighboring and nearby locations (called clusters here). The calculation is verified via conceptual simulation, which is highlighted in chapter 4. The concept verification will be done via three different scenarios simulation to examine the behavior of the model in different emergency situations. The model is examined under S1(single incident with 3 potential location scenario), S2 (Multiple incidents with 4 potential locations scenario) and S3 (Multiple incidents with 10 potential locations scenario).

Second, the development of the proposed index-based emergency response system (IERMS), as mentioned earlier, is shown through to minimize the emergency response time. The mathematical model is developed and solved with given constraint ts based on real life situation. The model is tested by simulating several real life incidents in the case study industrial city.

3.3 Data collection

Data for the model analysis were obtained from the HSE department in different industrial cities. Of particular interest is the data on oil and facilities. The location specific data are also required in the proposed framework. Typical data used for typical emergency response systems are:

- Weather Conditions / Stations
- Local emergency resources
- Traffic Data
- Monitoring and warning system
- Plant Critical Process Data
- Gas detection and Monitoring / Network
- Incident / Accidents Reports by individuals
- Topographic Data (Typical)
- GIS information
- Head Count/ Human distribution

- Volunteers data base/availability
- Regional Emergency resources
- National medical capacity
- Data reported by Public (website Social Medial)
- Demographic information
- Warehouse and Sheltering
- Update from site team (during / normal operations and events)
- Manual Inputs by the emergency team.

This information is collected from different source and input into the module, charts, and tables which are used for calculation of different indexes and factors of LHI and optimization process.

The next stage is using analytical techniques to analyze the tabulated date, to figure out the overall pattern and apply prediction and forecasting functions from available historical information obtained from the HSE units as mentioned above.

3.4 Selection of the study area

For this research work, one industrial city with major oil and gas processing facilities is selected. For the State of Qatar, this industrial city contains largest inventories of LNG.

The risks that are being considered for emergency response are the loss of containment, fire, explosions or activities that can be hazardous to operation and maintenance of the facility, to the people working within the facility and the vicinity and to the ecological environment surrounding the facility. The impact of such a risk can reach beyond the industrial cities themselves.

Most of the processing and handling facilities are built and designed considering state-of-the-art monitoring and control systems to reduce inherent risk due to loss of containment, fire or explosions accidents, or any activity within the facilities, there is residual risk that needs to be considered and prepared for in case of any failure of any of the control or monitoring system requires an emergency response management system. The current emergency response system is based on the stocking of maximum response resources. There has not been any assessment/analysis on the optimal response time and resource allocations to a particular incident location. All types of facilities are treated equal, and therefore, there is less understanding in terms of analysis based on the propensity of incidence in a particular location.

3.5 Preliminary data analysis

A simple analysis is used to demonstrate the capability of framework and LHI calculations. For this analysis, the risk and optimization of existing resources required for emergency services to reach different sites of the industrial area at the different time of the day such as normal working hours and rush hours. For superior results, A GPS based model can be utilized to use a real time traffic monitoring application that can provide estimated travel time based on actual traffic conditions (the application is excluded from this scope). The used time in the case study simulation is listed in Table 4.8 in chapter 4. The time used for simulation represent a typical rush hour travel movement time which has been used to test the model and conduct simulation. In normal working hours, the travel time is assumed to be shorter, but proportional to rush hour which might not have an impact on the overall results of optimization and resources allocation.

3.6 The variables for analysis

In emergency response system, as explained earlier, many important variables need to be considered. For example, variables referring to hazardous chemicals refer to its availability in the incident location, its nature (flammability, toxicity, and reactivity) and its quantities. The variable referring to population should consider total population and its distribution on site. The variable referring to metrological condition should consider wind speed and wind direction. The variable referring to the site should consider the incident location configuration, proximity of emergency resources, and their location to incident location, the location and distribution of emergency centers, and the location of accident incident in each site. Finally, time refers to the time it requires to respond based on the proximity and the availability of resources for mitigating the impact. In the study area, there are five emergency centers or depots scattered in five different locations, and there are ten work locations where incidents might occur requiring emergency response services. The location hazard index (LHI) is calculated for each of these locations. This index is then used in the optimization process. More details on the setup and assumption used in the model and case study will be explained in next chapters.

3.7 Field research

The field research work was carried over a period of 3 months. Several visits to the industrial city were conducted. This helped to gather information, understand the need for the integrated system and the current procedures used by the HSE experts in the industrial city for emergency response.

3.8 Research limitation

The thesis is based on the data provided by the case study industrial city. The research is focused on a single incident operation and is focused on fire-fighting service. The priority setting used for the location and allocation of resources is based on the currently available location and resource capacity in the industrial city. The conclusions of the analysis are, therefore, methodologically correct, and are related to the specific case study industrial city.

CHAPTER 4: MODEL DEVELOPMENT

In this chapter, the development of the location hazard index, optimization models have been discussed. The model is used to show the implementations in a test case. The model would be fully implemented and tested for different emergency response scenarios in Chapter 5.

4.1 Location hazard index

When materials and processes are reactive and their interaction can lead to an emergency situation. In such a case it is necessary to understand the characteristics of the location. That means the reactivity of the materials to create a hazard in a particular location is to be established. This reactivity is characterized as location hazard index (LHI) here. The evaluation of LHI helps to understand as to which locations are more critical and which are less critical in terms of hazard incidence requiring an emergency response. The index will help the decision makers for hazard identification to support the decision for resource allocations. This index is obtained based on the following. Further elaborations are given in Appendix A.

- Materials have chemical properties such as toxicity, flammability, and reactivity. The classification and rank for each property per substance in each location are taken from international classification system such as NFPA 704 “Hazard Rating system. The overall hazard rating depends on the type and volume of each chemical substance.
- Metrological effect: In each location, wind direction, wind speed, and pattern have an effect

on spreading the impact of the incident. International classification of wind “Beaufort Wind Scale” is used here to quantify wind and wind effect on the incident location.

- People exposure to risk is directly related to their presence and their distribution in the incident location. Population in the location can be categorized between the location without population and the location with high population. In addition, the location of the population with respect to the incident location or cluster is very important to determine the overall hazard of the location.
- The potential hazard of adjacent location (or cluster) is also important and therefore, the hazard potential of such clusters (around the location) should also be considered.

Various variables and indices to be used for the calculation of the local hazard index and the resultant hazard index (effect of the clusters) are given below in Table 4.1.

Table 4.1: The indices and variables for the development of the LHI model.

Notation	Description
I	Emergency incident location, $i = \{1, 2, \dots\dots, I\}$
LHI_i	Location hazard index for each incident location i.
m	Emergency's location clusters, m=1…9, for each location i.
c	Chemical type c, c=(1……C)
LHI_{im}	Cluster's hazard index for location i cluster m.
R_{im}	Risk-based location index ($0 \leq R_{im} \leq 1$) for location i and cluster m.
R_{imcv}	Risk factor ($0 \leq R_{imcv} \leq 1$) based on each chemical volume index (v) of chemical (c) substance in each cluster m.
T_c	Toxicity rank ($0 \leq T_c \leq 4$) of chemical c , as per NFPA 704.
F_c	Flammability rank ($0 \leq F_c \leq 4$) of chemical c, as per NFPA 704.
R_c	Reactivity rank ($0 \leq R_c \leq 4$) of chemical c, as per NFPA 704.
W_f	Wind effect factor based on Beaufort Wind Scale
S	Wind Speed/ Pattern based on "Beaufort Wind Scale".
D	Wind direction relative to the incident center.
H	Headcount factor of the population in the incident location. (Table 4.2)
P	Population's location factor for cluster m in location i. (Table 4.3)
W_d	Wind direction relative to the incident location. The values range from 0 to 1 based on the cluster's location relevant to the incident cluster. (Table 4.3)

Table 4.2: location headcount factor (H)

No	No of staff	population	factor H
1	0	No population	0.001
2	1	low populated	0.5
3	2 to 5	Medium populated	0.8
4	more than 5	heavly pouplated	1

Table 4.3: Wind-related factor (D)

Location of population	factor P	factor W_d
Center	1	1
Down	0.8	0.8
Side	0.5	0.5
Up	0.1	0.1

Model for the calculation of the location hazard index (LHI)

For the development of the LHI model, location-specific index, R_{im}, volume index, and Rimcv need to be considered. They create a multiplier effect with the chemical substance characteristics given as toxicity, reactivity, and flammability. The incident location is divided into a number of clusters within the location and LHI is calculated for each cluster as given below. If there are multiple locations (i), LHI has to be calculated for each location.

$$LHI_m = \sum_{c=1}^{C} R_{im} * R_{imcv} * (T_c + F_c + R_c), \quad \forall\, m \tag{4.1}$$

Eq (4.1) is for calculating LHI_m for each cluster for a given location i. The highest LHI_m in each location is selected as the LHI_i for that location. Hence, the LHI_i for a particular location is obtained as follows:

$$LHI_i = \max_{\forall\, m} \{LHI_1, LHI_2, \ldots, LHI_m\} \tag{4.2}$$

For the chemical substances, the Council of Major Accidents Hazards regulations 2015 (COMAH) provides lower and upper limits of toxicity, flammability, and reactivity for each hazardous chemicals. These limits are volume based and provides the safe limits for dealing with these chemicals in case of accidents. All chemicals with volume below the lower tier will not require special precautions (low risk).if the chemicals' volume exceeds the lower tier level, then special precautions need to be taken. If the volume exceeded the upper tier limits, then the additional precisions need to be taken. The type and level of precaution taken are mainly dependent on types of chemicals available on site of the accident, and are proposed by the facilities owner and approved by COMAH.

For wind speed/pattern (S), "Beaufort Wind Scale" as explained in Table 4.4 is used. The wind speed/patter Beaufort Wind Scale was developed in 1805 by Sir Francis Beaufort, U.K. Royal Navy. For wind direction (D), sideways, upwind and downwind are considered.

Table 4.4: Effect of wind and location factor W_f on LHI_i and $RLHI_i$.

Wind (Knots)	m/s	Km/Hour		WMO Classification	S	W_f Direction and speed effect			
						Center	downwind	Side	up-wind
Less than 1		1.9		Calm	0.5	1	0.75	0.5	0.1
1 to 3	0.5	1.9	5.7	Light Air	0.5	1	0.8	0.55	0.15
4 to 6	2.1	7.6	11.4	Light Breeze	0.5	1	0.85	0.6	0.2
7 to 10	3.7	13.3	19	Gentle Breeze	0.5	1	0.9	0.65	0.25
11 to 16	5.8	20.9	30.4	Moderate Breeze	0.85	1	0.95	0.7	0.3
17-21	9.0	32.3	39.9	Fresh Breeze	0.85	1	1	0.75	0.35
22-27	11.6	41.8	51.3	Strong Breeze	0.85	1	1	0.8	0.4
28-33	14.8	53.2	62.7	Near Gale	0.85	1	1	0.85	0.45
34-40	17.9	64.6	76	Gale	0.85	1	1	0.9	0.5
41-47	21.6	77.9	89.3	Strong Gale	0.85	1	1	0.95	0.55
48-55	25.3	91.2	104.5	Storm	0.3	1	1	1	0.6
56-63	29.6	106.4	119.7	Violent Storm	0.3	1	1	1	0.65
64+	33.8	121.6		Hurricane	0.3	1	1	1	0.7

Resultant Location Hazard Index (RLHI)

When the incident conditions such as gas cloud size, concentration, wind speed, and wind direction have a potential to transfer hazard to a different location, the LHI needs to be converted into RLHI. This requires incorporation effect of location and wind effect, wind factor, W_f as shown below:

$$RLHI_i = LHI_i \times W_f \qquad (4.3)$$

Table 4.4 shows the values for W_f to account for wind and location. In the incident location, the RLHI= LHI as $W_f = 1$, while in a location where the incident has no impact or potential effect, the RLHI = LHI*W_f = 0 as $W_f = 0$. The purpose of utilization for this factor is to consider the impact of incident locations on adjacent locations (clusters). Therefore, omission of W_f is not representative of hazard intensity of a location.

When more than one incident location are involved (multiple incidents) the RLHIi for any affected location should be calculated based on the highest RLHIi. Let z be the number of nearby incidents, then the $RLHI_i$ is as follows:

$$RLHI_i = \max_{\forall I} \{RHI_{i-1}, RLHI_{i-2}, \ldots, RLHI_{i-z}\} \qquad (4.4)$$

4.2 Hazard and time optimization model

The optimization models considering the LHI should consider the service delivery time and resources (trucks here) setup time.

- **Service delivery time**:

  The response time is related to many parameters such as accident/incident location, roads conditions, availability of alternatives, traffic conditions, as well as parameters related to management response team setups such as the type of tools used and resources, the number of resources and their distribution.

- **Trucks setup time:**

  For emergency response and planning purpose the situation is different as cost optimization is presented in terms of setup time in minutes and then used as a criteria to improve response to multiple emergency situations by utilizing the available resources In practice, resources are sized and selected based on preset emergency scenarios, these scenarios are built based on assumed size, location, and distribution of expected emergency resources. Therefore, if a major disaster occurs, then the resource requirements vary from one location to another. Therefore, hazard index becomes necessary as an indirect measure to identify the resources requirements.

  For the purpose of the demonstration a square area of 500m x 500m inside a hypothetical industrial area is assumed (as shown in Figure 5.2). Each square is identified by a unique number, which could be an alphabetic letter, a number, or a combination of both example of the matrix and numbering is attached in Appendix F.

4.3 The emergency resources optimization based on time and the location hazard index

In order to develop the optimization model for resource optimization, the following assumptions are made.

- The emergency incident will be evaluated and ranked based on LHI for emergency as explained in the above part.
- For simplicity, only one type of emergency supports vehicles is assumed (firefighting trucks, here).

- The total number of emergency vehicles is assumed as CT.
- The incident location or site is divided based on clustered areas and the incident is in the center of each cluster, for example, “Ai”, where 1 = 1…… m.
- Each route used for emergency response has a defined travel time (for simplicity it is assumed as fixed) to the incident location.
- The emergency support is dispatched from the existing stations called depots, b = 1….n.
- Emergency response time shall not exceed 15 min.

The objective is then to minimize the emergency response time for incidents based on given priority of LHI:

Let G = (O, P) to be the service area (industrial city), with $O = A \cup B$, and $P = T_{kl}$

T_{ji} is the time for travel from location i to location j , $i,j, \in O$, $i \neq j$.

Each incident location ai has a demand di, $0<di< D$, for the resources.

ui is the maximum capacity of each vehicles at location i.

hi the maximum traveling distance of each vehicles leaving location i.

4.3.1 Time based minimization (TBM)

The proposed model for response time minimization model is given below.

Objective function:

$$Min\ (ERT) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} \frac{x_{ijk}}{RLHI_i} \left(T_k + t_{ijk}\right) \qquad (Ob.1)$$

Subject to:

1- Incident location demand constraint t

$$\sum_{j=1}^{m} \sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \qquad (1)$$

2- Emergency resource availability constraint t

$$\sum_{i=1}^{n} \mathrm{C}_k \ * \ x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (2)$$

3- Resource usage constraint t

$$\sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} (\mathrm{C}_k * x_{ijk}) - \sum_{i=1}^{\mathrm{n}} \mathrm{D}_i \leq \lambda^* * \sum_{i=1}^{\mathrm{n}} \mathrm{D}_i \qquad (3)$$

4- Quick response vehicles “K1” dispatch:

$$\mathrm{x}_{ij1} \geq 1 \qquad \forall i \in I;\ \forall j \in J; \qquad (4)$$

5- Non-negativity constraint t

$$x_{ijk}\ are\ postive\ integr\ variables\ and\ x_{ijk} \in (0,1) \quad \forall i \in \mathrm{I};\ \forall j \in \mathrm{J};\quad \forall k \in \mathrm{K} \qquad (5)$$

Variables Description:

"j" is the emergency response / Firefighting center or depot, $j = \{1, 2, \dots \dots m\}$; where m is the number of centers

"i" is emergency incident location, $i = \{1,2, \dots \dots, n\}$, where n is the number locations

"k" is the resource type, $j = \{1,2, \dots \dots, w\}$, where w is the number resource types/classes

"T_k" is the setup time of resource k

"t_{ijk}"= travel time from emergency response center "i" to location "j " for resource type "k".

"x_{ijk}" are binary variable that will have value 1 if resources k, has been dispatched from emergency response center i to location j, other with = 0

LHI_i = Location Hazard Index for location "i"

"$\mathrm{D_i}$"= is firefighting material demand for incident location i,

"$\mathrm{R_{jk}}$"= is emergency resource type k located in emergency center j.

"$\mathrm{C_k}$"= total hold up capacity of material volume for emergency truck type k.

"λ" = resources optimum utilization factor %. Normally range of $0 \leq \lambda \leq 100$ %.

"Ck sys" = Dispatched capacity by the model.

"ΔCk " = Difference between the total capacity and dispatched capacities.

The objective of the model is to minimize the overall emergency response time by utilization of location hazard index (LHI). LHI acts as weighing factor . The objective function considers the total time travel time t_{ijk} and setup time T_k, for each resource to be used in the emergency response operation

The constraint (1) ensures that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (C_k) equal or more than the required demand for each incident location (D_i).

The constraint (2) ensures that the number of allocated resources for each incident location (i) and from each emergency center/depot (j) will not exceed the total available resources available in each center (j). This to make sure that it does not overbook the resources and assign fire trucks which does not exist or assigned resources that have already been assigned to a different incident location.

The constraint (3) restricts the over usage of resources to $\lambda * \sum_{i=1}^{n} D_i$; where the constant λ represents maximum allowed limits for the % difference between the demand and supply. This condition is based on the structural difference between the demand and supply due to used trucks capacities and expected demand scenarios. The value of λ is usually specified based on each emergency response system for the specific industrial city as per their policy and advice by the emergency response team. A typical value would be in the range of $0 \leq \lambda \leq 100$ %, but in some cases, it might exceed 100% if the structural difference between the supply and demand might get significantly more than the demand due to lack of availability of smaller trucks' capacities.

The constraint (4) ensures that each emergency response to each incident is including K1 type of resources as a minimum. This is to consider the real life scenario as commander van/ vehicle are normally dispatched to site for initial quick control and arrangement for the required resources.

The constraint (5) are non negativity constraints.

4.4 Numerical study

To test the mathematical model tentative locations of the facilities and the emergency incidence have been developed. Different scenarios have been developed to show the changes in output due to the scenario in terms of incident locations.

The test site consist of 25 locations in a typical oil and gas industrial city. The type of installations are given in Table 4.5. These sites are randomly located on the plot plan as shown in Figure 4.4. The LHI calculated for each of the locations are also given in Table 4.5 and in Figure 4.4.

Table 4.5: Description of the simulation test case locations.

No	Location	Description	LHI	Di
1	A	Petrochemical plant	12	10,000.00
2	B	Utilities facilities	5	6,000.00
3	C	administrative Area	0.1	100.00
4	D	Workshop	0.2	250.00
5	E	Labors camp	0.1	150.00

6	F	Warehouse	0.5	1,000.00
7	G	Chemicals storage	5	6,500.00
8	H	Plant area	4	4,800.00
9	I	Plant area	3	3,700.00
10	J	workshop	0.8	900.00
11	K	empty land	0	-
12	L	chemicals storage	4.5	4,900.00
13	M	Petrochemical plant	8	8,000.00
14	N	Petrochemical plant	6	7,000.00
15	O	Hazards waste area	8	8,000.00
16	P	empty land	0	-
17	Q	workshop	0.5	1,000.00
18	R	Utilities facilities	2	2,200.00
19	S	logistic Area	1	1,000.00
20	T	chemicals storage	3.5	3,900.00
21	U	empty land	0	-
22	V	administrative Area	0.2	250.00
23	W	Utilities facilities	3	3,500.00
24	X	Petrochemical plant	5.5	5,200.00
25	Y	Petrochemical plant	4	4,400.00

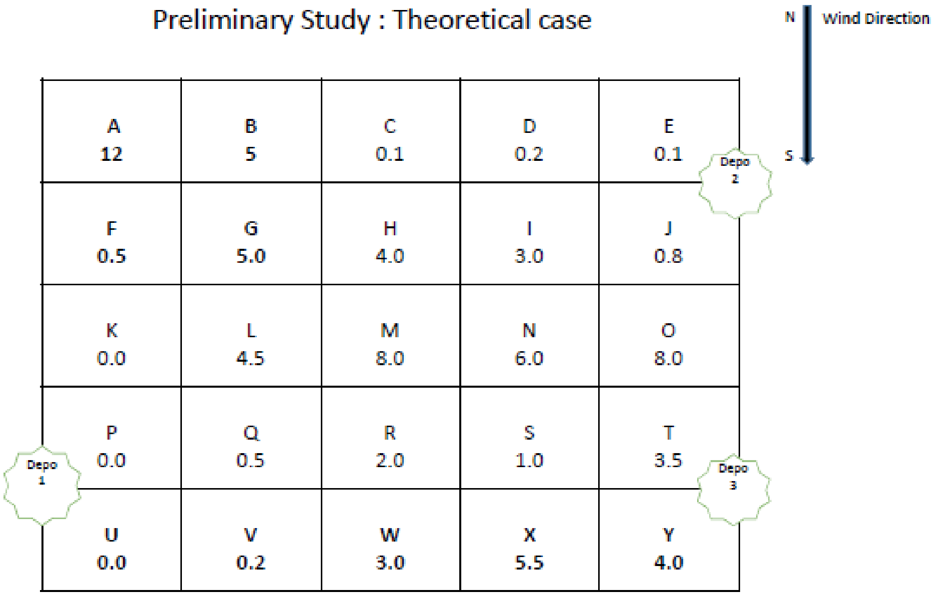


Figure 4.1: Industrial city plot plan.

Three emergency response centers (depots) are considered as shown in Figure 4.1. Their geographic location are given in Table 4.6. Each depot contains different type of resources such as commander vehicles (K_1), different size trucks (K_2 and K_3) and tankers (K_4). Each truck or resource type has different carrying capacity of the firefighting supplies, speed factors, and setup time as shown in Table 4.7. These parameters are used in the model for optimization purpose.

Table 4.6: Fire Depot location

Emergency Response center/ Depot location / Description	No J
South West between Location P and U	1
North East between location E and J	2
South East between location T and Y	3

Table 4.7*: Fire Trucks capacity, types, speed factor and setup time.*

Fire trucks capcity/ gallon	Type	capacity Ck,	time/ speed factor	Operation setup cost (setup time) min/ trip
Command truck	k1	400	1	500
Covintional FF truck	k2	1000	1.05	1000
Heavy FF Truck	k3	4000	1.2	1200
Tanker Truck	k4	6000	1.5	800

It is assumed that each depot has 5 trucks of K_1 type, 2 of K_2 types, 5 of K_3 types and 6 of K_4 types. The total number of trucks in each depot is 18, a total of 54 trucks are available to support emergency calls as shown in Table 4.8.

Table 4.8: Emergency resources availability in each depot.

Depot location	J	K1	K2	K3	K4	Total	Ck
South West between Location P and U	1	5	2	5	6	18	60,000
North East between location E and J	2	5	2	5	6	18	60,000
South East between location T and Y	3	5	2	5	6	18	60,000
Total		15	6	15	18	54	180,000

For truck capacity, the smallest K_1 has a holding capacity of 400 gallons, K_2 with 1000 gallons, K_3 with 4000 gallons and K_4 with 6000 gallons as shown in Table 4.9. Each depot has a maximum capacity of 60,000 gallons for use.

Table 4.9: No of available emergency response resources for each type.

Emergecny reource	No	Ck	∑Ck
k1	15	400	6000
k2	6	1000	6000
k3	15	4000	60000
k4	18	6000	108000
Total	54		**180,000**

For LHI and RLHI calculation, location A is considered. The location has chemical storage for highly flammable substances such as Trinitrobenzene (highly flammable and explosive material), liquefied natural gas (methane), propane, butane, Diesel fuel, methanol, and ethane.

Each incident location in Figure 4.1 is divided into nine clusters as mentioned in Figure

A.2 in Appendix A. The hazard index value for each cluster is calculated based on its chemical properties, and then adjusted as per the volume available in each location. For A1 (center of the cluster) the volume effect index is very high (1 or 100%) as all chemicals volumes and classifications are of the upper tier and the headcount and wind are considered as having the maximum effect. Accordingly, the overall impact of each chemical in that situation is calculated by by applying eqs. (4.1), (4.2), (4.3), and (4.4). The results of the calculations are shown in Appendix I. The highest value among the group of substances in each cluster is selected to reflect the overall LHI, which is 12 points (out of 12 point). For this example, the highest LHI value is obtained for A1 due to the contents there: Trinitrobenzene (highly flammable and explosive material). Subsequently, LHI for other clusters are calculated in the same way, but the location impact changes based on the wind direction and population in each cluster. The overall Site 1 calculations including the 9 clusters are shown in Appendix I. The maximum LHI for all clusters is for A1 = 12 points. Therefore, this value is selected as the LHI for Location A.

Theoretical Test Scenarios*:*

To examine the model, three test scenarios have been assumed. The overall test scenarios are shown in Table 4.10. Each scenario has combinations of main event (F, fire location is assumed), potentially affected locations (P, potential affected) which might be affected in different degrees based on its location and wind direction and finally, the ideal locations (G, no impact) which does not get impacted by the event (as shown in Figure 4.2, 4.3 and 4.4). For each location, the RLHI is calculated as explained with more details in for each scenario.

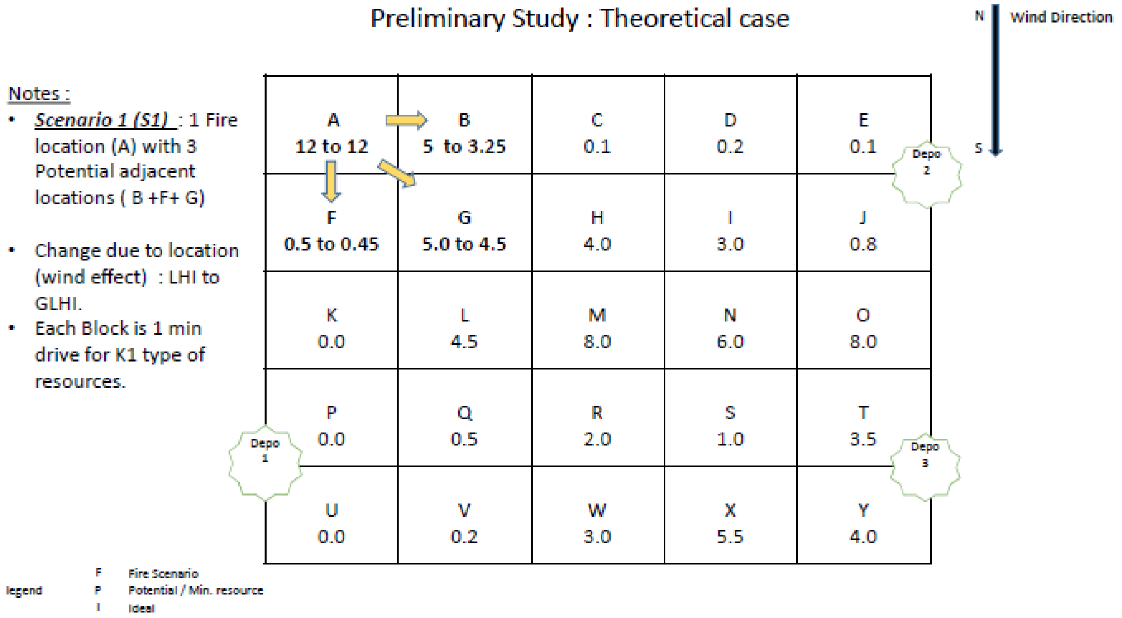
Table 4.10: The test scenarios for proposed locations.

					Preliminary Study : Theoretical scenarios								
					Scenarios								
No	Location	Description	LHI	Di	Wf1	RLHI 1	1	Wf2	RLHI 2	2	Wf3	RLHI3	3
1	A	Petrochemical plant	12	10,000	1	12	F	0	0	I	0	0	I
2	B	Utilities facilities	5	6,000	0.65	3.25	P	0	0	I	0	0	I
3	C	administrative Area	0.1	100	0	0	I	0	0	I	0	0	I
4	D	Workshop	0.2	250	0	0	I	0	0	I	0	0	I
5	E	Labors camp	0.1	150	0	0	I	0	0	I	0	0	I
6	F	Warehouse	0.5	1,000	0.9	0.45	P	0	0	I	0	0	I
7	G	Chemicals storage	5	6,500	0.9	4.5	P	0	0	I	0.25	1.25	P
8	H	Plant area	4	4,800	0	0	I	0	0	I	0.25	1	P
9	I	Plant area	3	3,700	0	0	I	0	0	I	0.25	0.75	P
10	J	workshop	0.8	900	0	0	I	0	0	I	0.25	0.2	P
11	K	empty land	0	-	0	0	I	0	0	I	0	0	I
12	L	chemicals storage	4.5	4,900	0	0	I	0	0	I	0.65	2.925	P
13	M	Petrochemical plant	8	8,000	0	0	I	0	0	I	1	8	F
14	N	Petrochemical plant	6	7,000	0	0	I	0	0	I	1	6	F
15	O	Hazards waste area	8	8,000	0	0	I	0	0	I	0.65	5.2	P
16	P	empty land	0	-	0	0	I	0	0	I	0	0	I
17	Q	workshop	0.5	1,000	0	0	I	0	0	I	0.9	0.45	P
18	R	Utilities facilities	2	2,200	0	0	I	0.25	0.5	P	0.9	1.8	P
19	S	logistic Area	1	1,000	0	0	I	0.25	0.25	P	0.9	0.9	P
20	T	chemicals storage	3.5	3,900	0	0	I	0.25	0.875	P	0.9	3.15	P
21	U	empty land	0	-	0	0	I	0	0	I	0	0	I
22	V	administrative Area	0.2	250	0	0	I	0	0	I	0	0	I
23	W	Utilities facilities	3	3,500	0	0	I	0.65	1.95	P	0	0	I
24	X	Petrochemical plant	5.5	5,200	0	0	I	1	5.5	F	0	0	I
25	Y	Petrochemical plant	4	4,400	0	0	I	1	4	F	0	0	I

Single Fire location with three potential locations (Scenarios 1):

It is assumed that the fire accident occurs at petrochemical manufacturing facilities located in location "A" as shown in Figure 4.2. Location A has three adjacent sites which can be affected by fire incidents in location A, site nature (LHI), and the weather conditions. Location B is in the east side (industrial utility facilities), location G is on south-east side (a chemicals storage area), and Location F is on the south side (general warehouse). Others sites are assumed not to be affected by the incident on location A, and are, therefore, classified as ideal locations.

For this scenario, it is assumed that the wind is blowing from the North with a velocity between 13 to 19 Km/hr (Gentle Breeze). This information are used to calculate the correction factor W_f in order to obtain RLHI for the affected locations. The W_f factors are shown in Table 4.4.



Notes :
- *Scenario 1 (S1)* : 1 Fire location (A) with 3 Potential adjacent locations (B +F+ G)
- Change due to location (wind effect) : LHI to GLHI.
- Each Block is 1 min drive for K1 type of resources.

A 12 to 12	B 5 to 3.25	C 0.1	D 0.2	E 0.1
F 0.5 to 0.45	G 5.0 to 4.5	H 4.0	I 3.0	J 0.8
K 0.0	L 4.5	M 8.0	N 6.0	O 8.0
P 0.0	Q 0.5	R 2.0	S 1.0	T 3.5
U 0.0	V 0.2	W 3.0	X 5.5	Y 4.0

Figure 4.2: Test scenario 1 for Conceptual Simulation.

Based on equations in Section 4.3.1 and the parameters given in Section 4.4 the LHI for site A, B, G, and F are obtained as 12, 5, 5, and 0.5, respectively. These values are used in equation eq. (4.4.) to get the RLHI. The values of RLHI are obtained as 12, 3.25, 4.5, and 0.45 as shown in Table 4.7 and Figure 4.2.

This information with other necessary information related to travel time between location and depots as (Table 4.15), setup time, vehicles capacities, are used as input to the optimization model.

Table 4.11: Wind speed and Direction effect.

					W_f for different wind speed and direction			
Wind (Knots)	Speed range in m/s		WMO Classification	Speed (S)	Center	Downwin	Side wind	Upwind
Less than 1	<0.51		Calm	0.50	1	0.75	0.5	0.10
1 to 3	0.51	1.56	Light Air	0.50	1	0.80	0.55	0.15
4 to 6	2.05	3.08	Light Breeze	0.50	1	0.85	0.6	0.20
7 to 10	3.60	5.14	Gentle Breeze	0.50	1	0.90	0.65	0.25
11 to 16	5.65	8.23	Moderate Breeze	0.85	1	0.95	0.7	0.30
17-21	8.74	10.80	Fresh Breeze	0.85	1	1.00	0.75	0.35
22-27	11.31	13.89	Strong Breeze	0.85	1	1.00	0.8	0.40
28-33	14.40	16.97	Near Gale	0.85	1	1.00	0.85	0.45
34-40	17.49	20.57	Gale	0.85	1	1.00	0.9	0.50
41-47	21.09	24.17	Strong Gale	0.85	1	1.00	0.95	0.55
48-55	24.69	28.29	Storm	0.30	1	0.55	0.3	0.00
56-63	28.80	32.41	Violent Storm	0.30	1	0.55	0.3	0.00
64+	32.90		Hurricane	0.30	1	0.55	0.3	0.00

Output of Scenario 1:

The results obtained for resource allocations for Scenario 1 are given in Table 4.12. The results are obtained through the optimization model, which shows the following.

- For incident location A, Three trucks are dispatched due to high demand for mitigating fire. One K_1 type truck, one K_3 type truck, and one K_4 type truck from Depot 1 are needed.
- For Potential incident location B, one K_1 and one K_4 type trucks from Depot 2 are needed.
- For Potential incident location F, one K_1 and one K_2 type trucks from Depot 1 are needed.
- For Potential incident location G, oneK_1 type truck is needed from Depot 2 and one K_1 and one K_3 type trucks from Depot 1 are needed.

Table 4.12: Output results of Scenario 1 (Single Fire scenario with three potential locations).

					Theoretical case: S1					
				Depo						
Scenario 1	Location i	1	2	3	Location i	1	2	3	total	K1
	A	K1+K3+K4			A	14.8			14.8	4
	B		K1+K4		B		10		10	4
	F	K1+K2			F	6.15			6.15	3
	G	K1+K4	K1		G	10	4		14	4
									44.95	15

With this dispatching strategy, the following can be observed:

- The emergency response time was minimized with the following :
    - The resources requirements for location A is provided from Depot 1 due to the shortest travel time to site A. K_1 reaches the site in 4 min, while the total accumulated travel time for all trucks to site A is 14.8 min.
    - For location B, resources are dispatched from Depot 2, however, the travel time from Depot 1 to location B is similar to that of Depot 2. K_1 reaches the site in 4 min, while the total accumulated travel time for all trucks to site B is 10 min.
    - For location F, Depot 1 is the closest and accordingly all required resources are dispatched from this depot. K1 reaches to the site in 3 min, while the total accumulated travel time for all trucks to the site is 6.15 min.
    - For location G, Depot 1 and Depot 2 are similar. Therefore, resources are sent from both of the depots by considering the availability. K_1 reaches the site in 4 min, while the total accumulated travel time for all trucks to the site is 14.0 min.
    - The minimum response time for all of these sites is 44.95 min.

- **Demand requirements for each incident location**:
    - Through the analysis of allocated capacity (D_{if}) and required demand (D_i) for each site, it can be seen that the demand is fulfilled as shown in Table 4.13. The ΔDi value for each location is also positive. Generally, there is an excess supply of 300 to 400 gallons per location, due to the constraint that each location should receive K_1 type of trucks first.

- Capacity utilization for each depot: Each depot has a holdup capacity of 60,000 gallons. This capacity is more than the demand for all locations assumed in Scenario 1. Therefore, the ΔC_k value is positive in this case as shown in Table 4.13.
- LHI priority consideration: The consideration of LHI can be seen here. The higher the value of LHI, the lower is objective function value (TTT) and the overall response time. This happens as the location with higher LHI is given priority to provide the nearby available resources over other locations with lower LHI.

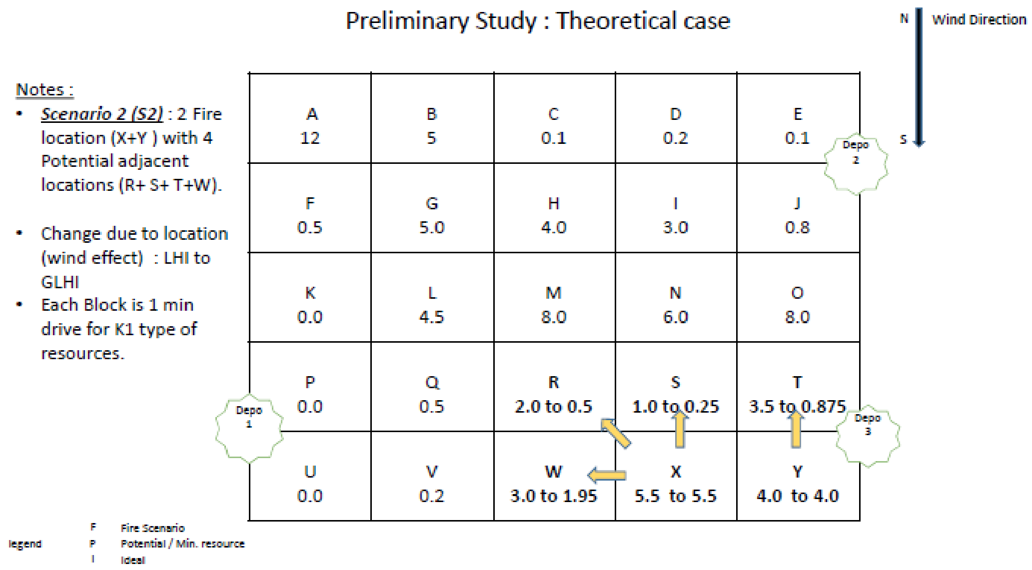
Table 4.13: Demand and Capacity analysis of theoretical Scenario 1.

	Depot						
Location i	1	2	3	Di_f	Di	ΔDi	%
A	10400			10,400	10,000	400	4
B		6400		6,400	6,000	400	7
F	1400			1,400	1,000	400	40
G	6400	400		6,800	6,500	300	5
	18200	6800	0	25,000	23,500	1,500	6
Ck_f	18,200	6,800	-	25,000			
Ck	60,000	60,000	60,000				
Δ Ck	41,800	53,200	60,000				
%	69.67	88.67	100.00				

Two Fire locations with four potential locations (Scenario 2):

For scenario 2, it is assumed that two fire accidents occur in location X and Y as shown in Figure 4.3. Both locations have 4 adjacent sites with the high potential to get affected due to its LHI. For the adjacent locations, it is assumed that R is the industrial utility facility, S is the logistics area and is chemical storage area. Site W is another utility facility. Other sites are assumed not to be affected by the incident on location X and Y.

For Scenario 2, it is assumed that wind direction is from the North, and the wind speed ranges between 13 to 19 Km/hr (Gentle Breeze). This information is used to calculate Wf and RLHI for the affected locations. The Wf factors are shown in Table 4.8.



Preliminary Study : Theoretical case

Notes :
- *Scenario 2 (S2)* : 2 Fire location (X+Y) with 4 Potential adjacent locations (R+ S+ T+W).
- Change due to location (wind effect) : LHI to GLHI
- Each Block is 1 min drive for K1 type of resources.

A 12	B 5	C 0.1	D 0.2	E 0.1
F 0.5	G 5.0	H 4.0	I 3.0	J 0.8
K 0.0	L 4.5	M 8.0	N 6.0	O 8.0
P 0.0	Q 0.5	R 2.0 to 0.5	S 1.0 to 0.25	T 3.5 to 0.875
U 0.0	V 0.2	W 3.0 to 1.95	X 5.5 to 5.5	Y 4.0 to 4.0

Figure 4.3: Test scenario 2 for Conceptual Simulation.

The results obtained for this scenario are given in Table 4.11. The results from the optimization model shows the following:

- For potential incident location R, K_1 and K_3 type trucks are dispatched from Depot 1.
- For potential incident location S, K_1 and K_2 type trucks are dispatched from Depot 2.
- For potential incident location T, K_1 and K_3 type trucks are dispatched from Depot 3.
- For potential incident location W, K_1 type truck is dispatched from Depot 3 and K_3 type truck is dispatched from Depot 3.
- For incident location X, K_1 and K_4 type trucks are dispatched from Depot 3.
- For incident location Y, K_1 and K_3 type trucks are dispatched from Depot 3.

Table 4.14: Output results of Scenario 2 (two Fire scenario with four potential locations).

	Theoretical case : S2									
				Depo						
Scenario 2	Location i	1	2	3	Location i	1	2	3	total	K1
	R	K1+ K3			R	6.6			6.6	3
	S			K1+K2	S			4.1	4.1	2
	T			K1+K3	T			2.2	2.2	1
	W	K3		K1	W	3.6		3	6.6	3
	X			K1+K4	X			5	5	2
	Y			K1+K3	Y			2.2	2.2	1
									26.7	12

With this dispatching strategy, the following can be observed.

- **The emergency response time was minimized with the following** :

- The location R is supported from Depot 1 due to the shortest travel time. Site R is located in the center from depots 1 and 2 due to the same travel time. K_1 reaches the site in 3 min, while the accumulated travel time for all trucks to site R is 6.6 min.
- For location S, resources are dispatched from Depot 3. K_1 reaches the site in 2 min, while the total accumulated travel time for all trucks to site S is 4.1 min.
- For location T, Depot 3 is the closest. K1 reaches the site in 1 min, while the total accumulated travel time for all trucks to site T is 2.2 min.
- Location W has similar travel time from both depots 1 and 3. The resources are sent from Depot 1, because of availability of resources in this depot. K_1 reaches the site in 3 min, while the total accumulated travel time for all trucks to site G is 6.6 min.
- For location X, Depot 3 is the closest one and therefore, the required resources are dispatched from this depot. K_1 reaches the site in 2 min, while the total accumulated travel time for all trucks to site T is 5.0 min.
- For location Y, Depot 3 is the closest one. Therefore, all required resources are dispatched from this depot. K_1 reaches the site in 1 min, while the total accumulated travel time for all trucks to site T is 2.2 min.
- The minimum response time for all locations is 26.7 min.

- **Demand requirements for each incident location:**

  Through the analysis of allocated capacity for each site (D_{if}) and required demand (D_i), it can be observed that all demand are fulfilled and there are enough supplies to cover all the demand (D_t). As shown in Table 4.15, the ΔD_i has a surplus except for location Y, where the supplied capacity is equal to the demand. Generally, there is an excess in supply in the range of 2200 to 400 gallons per location. In location R, 2200 more gallons were supplied due to the next available capacity (4000 gallons) to fulfil the demand (2200 – 400 = 1800, since K_2 is 1000 and K_3 is 4000 gallons, therefore, K_3 was selected).
- Capacity utilization for each depot: Each depot has a hold-up capacity of 60,000 gallons, which is more than demand for Scenario 2. Therefore, in this case also, ΔC_k is always positive as shown in Table 4.12.
- LHI priority consideration: The effect of LHI can be seen in the results as higher LHI location has been given priority to allocate nearby available resources over locations with lower LHI regardless of the travel distance.

Table 4.15: Demand and Capacity analysis in Scenario 2.

	Depot						
Location i	1	2	3	Dif	Di	ΔDi	%
R	4400			4,400	2,200	2,200	100
S			1400	1,400	1,000	400	40
T			4400	4,400	3,900	500	13
W	4000		400	4,400	3,500	900	26
X			6400	6,400	5,200	1,200	23
Y			4400	4,400	4,400	-	-
	8,400	-	17,000	25,400	20,200	5,200	26
Ckf	8400	0	17000	25,400			
Ck	60,000	60,000	60,000				
Δ Ck	51,600	60,000	43,000				
%	86.00	100.00	71.67				

Two Fire scenario with ten potential locations (Scenario 3):

For Scenario 3, it is assumed that there are two fire accidents in location M and N as shown in Figure 4.4. Both locations have 10 adjacent sites. For adjacent locations, sites H and I are industrial plants. Site J is the maintenance workshop. Site G is chemical storage and site O is hazards waste area. Site L is another chemicals storage area, site Q is workshop area, sites R and S are utilities and logistics facilities, respectively. Finally, Site T is another chemical storage. Others sites are assumed not to be affected by the incident in location M and N.

For the Scenario 3, it is also assumed that the wind is blowing from the North, and the wind speed is between 13 to 19 Km/hr (Gentle Breeze). This information is used to calculate W_f and RLHI for the affected locations. The Wf factors are shown in Table 4.4.

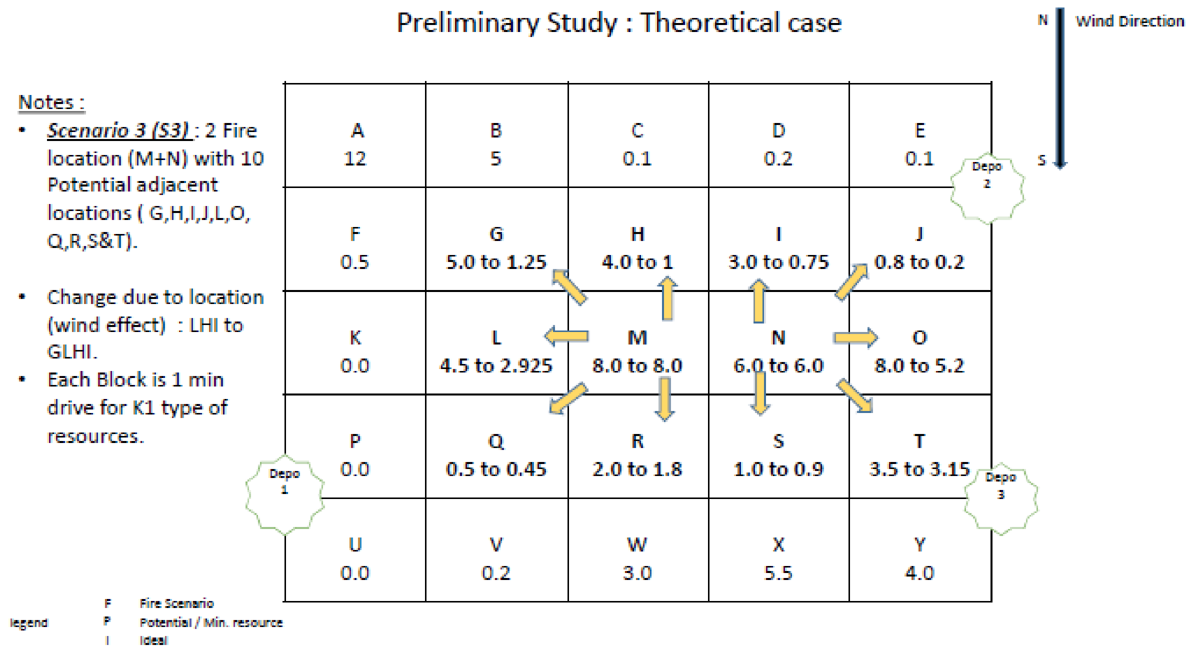


Figure 4.4: Test scenario 3 for Conceptual Simulation.

The results obtained for this scenario are given in Table 4.16. The results from the optimization model shows the following:

- For Potential incident location G, K_1 is dispatched from Depot 2 and K1 and K4 are dispatched from Depot 1.

- For Potential incident location H, K1 and K2 are dispatched from Depot 2.
- For Potential incident location I, K1 and K3 are dispatched from Depot 3.
- For Potential incident location J, K1 is dispatched from Depot 3 and K3 is dispatched from Depot 1.
- For Potential incident location L, K1 and K4 are dispatched from Depot 3.
- For incident location M, one K1 and two of K3 are dispatched from Depot 1.
- For incident location N, two of K3 are dispatched from Depot 2 and one K1 is dispatched from Depot 3.
- For Potential incident location O, K_1 is dispatched from Depot 3 and two K_3 are dispatched from Depot 2.
- For Potential incident location Q, K_1 and K_2 are dispatched from Depot 1.
- For Potential incident location R, K_1 and K_3 are dispatched from Depot 1 and 3, respectively.
- For Potential incident location S, K_1 is dispatched from Depot 3 and K_3 is dispatched from Depot 1.
- For Potential incident location T, K_1 and K_4 are dispatched from Depot 3.

Table 4.16: Output results of Scenario 3 (two Fire scenario with ten potential locations).

	Theoretical case: S3									
				Depot						
Scenario 3	Location i	1	2	3	Location i	1	2	3	total	K1
	G	K1+K4	K1		G	10	4		14	4
	H		K1+K4		H		7.5		7.5	3
	I		K1+K3		I		4.4		4.4	2
	J		K1+K2		J		2.05		2.05	1
	L	K1+K4			L	7.5			7.5	3
	M	K3	K3	K1	M	4.8	4.8	4	13.6	4
	N		K3	K1+K3	N		3.6	6.6	10.2	3
	O		K1+K3	K3	O		4.4	2.4	6.8	2
	Q	K1+K2			Q	4.1			4.1	2
	R			K1+K3	R			6.6	6.6	3
	S			K1+K2	S			4.1	4.1	2
	T			K1+K3	T			2.2	2.2	1
									83.05	30

Table 4.17 : Demand and Capacity analysis of theoretical Scenario 3.

	Depot						
Location i	1	2	3	Dif	Di	ΔDi	%
G	6400	400		6,800	6,500	300	5
H		6400		6,400	4,800	1,600	33
I		4400		4,400	3,700	700	19
J		1400		1,400	900	500	56
L	6400			6,400	4,900	1,500	31
M	4000	4000	400	8,400	8,000	400	5
N		4000	4400	8,400	7,000	1,400	20
O		4400	4000	8,400	8,000	400	5
Q	1400			1,400	1,000	400	40
R			4400	4,400	2,200	2,200	100
S			1400	1,400	1,000	400	40
T			4400	4,400	3,900	500	13
	18,200	25,000	19,000	28,400	23,100	5,300	23
Ck f	18,200	25,000	19,000	62,200			
Ck	23,000	12,800	12,800				
Δ Ck	4800	-12200	-6200				
%	20.87	(95.31)	(48.44)				

With this dispatching strategy, the following can be observed.

- The emergency response time was minimized as the following :
  - The responses for location G was supported from Depot 1 and 2. Both depots have the same travel time to site G. Site G is located in the center of depots 1 and 2. The initial time for K_1 to reach the site is 4 min, while the total accumulated travel time for all trucks delivered to site G is 14 min.

- For Location H, resources are dispatched from Depot 2. The initial time for K_1 to reach the site was 3 min, while the total accumulated travel time for all trucks to site H is 7.5 min.
- For Location I, Depot 2 is the closest one. The initial time for K_1 to reach the site is 2 min, while the total accumulated travel time for all trucks to the site I is 4.4 min.
- For Location J also, Depot 2 is the closest one. The initial time for K_1 to reach the site is 1 min, while the total accumulated travel time for all trucks to site J is 2.05 min.
- For Location L, Depot1 is the closest one. The initial time for K_1 to reach the site is 3 min, while the total accumulated travel time for all trucks to site L is 7.5 min.
- For Location M, Depot1 is the closest one. The initial time for K1 to reach the site is 4 min, while the total accumulated travel time for all trucks to site M is 13.6 min.
- Location N has similar travel time form both depots 2 and 3, therefore, resources are provided based on the availability in each depot. The initial time for K1 to reach the site is 3 min, while the total accumulated travel time for all trucks to site N is 10.2 min.
- Similarly, for Location O, it has similar travel time from both Depot 1 and Depot 3, therefore, resources are provided based on their availability. The initial time for K1 to reach the site is 2 min, while the total accumulated travel time for all trucks to site O is 6.8 min.
- For Location Q, Depot1 is the closest. The initial time for K1 to reach the site is 2 min while accumulated travel time for all trucks to site Q is 4.1 min.
- Location R has similar travel time from both Depot 1 and Depot 3. The initial time for K1 to reach the site is 3 min, while the total accumulated travel time for all trucks delivered to site R is 6.6 min.

  - For Location S, is Depot 3 is the closes and accordingly all required resources have been dispatched from it. The initial time for K1 to reach site was 2 min while accumulated travel time for all trucks to site S is 4.1 min.
  - For Location T, is Depot 3 is the closest one. The initial time for K1 to reach the site is 1 min, while the total accumulated travel time for all trucks delivered to site T is 2.2 min.
  - The minimum response time for all locations is 83.05 min.

- **Demand requirements for each incident location:**

  Through the analysis of allocated capacity for each site (D_{if}) and required demand (D_i), it can be observed that there are enough supplies to cover all the demand (D_t). As shown in Table 14, the ΔD_i value for each location is positive and for location Y, the supply is equal to the demand. Generally, there is an excess of supply, which ranges from 2200 to 300 gallons per locations due to the capacities that cannot be divided. In Location R, 2000 more gallons had to be supplied as the next available capacity is 4000 gallon to fulfil its demand of 2200 Gallon (2200 – 400 = 1800, since K2 is 1000 and K3 is 4000 gallons, K3 was selected).
- Capacity utilization for each depot: Each depot has a hold-up capacity of 60,000 gallons which is more than demand for Scenario 2. Therefore, in this case also, ΔC_k is always positive as shown in Table 4.17.
- LHI priority consideration: The effect of LHI can be seen in the results as higher LHI location has been given priority to allocate resources from the nearby depots over other locations with lower LHI as can be seen for location M and N.

Table 4.18 : Travel time between incident location and depots for Conceptual Simulation model.

Travel time Tijk from Depo J to Location i used in *theoretical test scenarios.*			**Response time in minutes**			
	j	I	K1	K2	K3	K4
h	**1**	A	4	4.2	4.8	6
h	**1**	B	5	5.25	6	7.5
h	**1**	C	6	6.3	7.2	9
h	**1**	D	7	7.35	8.4	10.5
h	**1**	E	8	8.4	9.6	12
h	**1**	F	3	3.15	3.6	4.5
h	**1**	G	4	4.2	4.8	6
h	**1**	H	5	5.25	6	7.5
h	**1**	I	6	6.3	7.2	9
h	**1**	J	7	7.35	8.4	10.5
h	**1**	K	2	2.1	2.4	3
h	**1**	L	3	3.15	3.6	4.5
h	**1**	M	4	4.2	4.8	6
h	**1**	N	5	5.25	6	7.5
h	**1**	O	6	6.3	7.2	9
h	**1**	P	1	1.05	1.2	1.5
h	**1**	Q	2	2.1	2.4	3
h	**1**	R	3	3.15	3.6	4.5
h	**1**	S	4	4.2	4.8	6
h	**1**	T	5	5.25	6	7.5
h	**1**	U	1	1.05	1.2	1.5
h	**1**	V	2	2.1	2.4	3
h	**1**	W	3	3.15	3.6	4.5
h	**1**	X	4	4.2	4.8	6
h	**1**	Y	5	5.25	6	7.5
h	**2**	A	5	5.25	6	7.5
h	**2**	B	4	4.2	4.8	6
h	**2**	C	3	3.15	3.6	4.5
h	**2**	D	2	2.1	2.4	3
h	**2**	E	1	1.05	1.2	1.5
h	**2**	F	5	5.25	6	7.5
h	**2**	G	4	4.2	4.8	6
h	**2**	H	3	3.15	3.6	4.5
h	**2**	I	2	2.1	2.4	3

h	**2**	J	1	1.05	1.2	1.5
h	**2**	K	6	6.3	7.2	9
h	**2**	L	5	5.25	6	7.5
h	**2**	M	4	4.2	4.8	6
h	**2**	N	3	3.15	3.6	4.5
h	**2**	O	2	2.1	2.4	3
h	**2**	P	7	7.35	8.4	10.5
h	**2**	Q	6	6.3	7.2	9
h	**2**	R	5	5.25	6	7.5
h	**2**	S	4	4.2	4.8	6
h	**2**	T	3	3.15	3.6	4.5
h	**2**	U	8	8.4	9.6	12
h	**2**	V	7	7.35	8.4	10.5
h	**2**	W	6	6.3	7.2	9
h	**2**	X	5	5.25	6	7.5
h	**2**	Y	4	4.2	4.8	6
h	**3**	A	8	8.4	9.6	12
h	**3**	B	7	7.35	8.4	10.5
h	**3**	C	6	6.3	7.2	9
h	**3**	D	5	5.25	6	7.5
h	**3**	E	4	4.2	4.8	6
h	**3**	F	7	7.35	8.4	10.5
h	**3**	G	6	6.3	7.2	9
h	**3**	H	5	5.25	6	7.5
h	**3**	I	4	4.2	4.8	6
h	**3**	J	3	3.15	3.6	4.5
h	**3**	K	6	6.3	7.2	9
h	**3**	L	5	5.25	6	7.5
h	**3**	M	4	4.2	4.8	6
h	**3**	N	3	3.15	3.6	4.5
h	**3**	O	2	2.1	2.4	3
h	**3**	P	5	5.25	6	7.5
h	**3**	Q	4	4.2	4.8	6
h	**3**	R	3	3.15	3.6	4.5
h	**3**	S	2	2.1	2.4	3
h	**3**	T	1	1.05	1.2	1.5
h	**3**	U	5	5.25	6	7.5
h	**3**	V	4	4.2	4.8	6
h	**3**	W	3	3.15	3.6	4.5
h	**3**	X	2	2.1	2.4	3
h	**3**	Y	1	1.05	1.2	1.5

Simulation summary and conclusion:

The summary of three scenarios is given in Table 4.19. The following are the main highlights:

- The LHI index calculations are proportional to hazard in each location based on its content of chemicals, population, and wind conditions. This can be clearly observed from the LHI value for each location and the content and effect of measured elements mentioned above. Furthermore, it highlights the interaction of LHI with nearby conditions as it might alter its value based on nearby hazards which is reflected in the final global LHI value after assessing the effect on surrounding conditions, as it can be seen in the three scenarios.
- The integration of LHI in the dispatched mathematical model is demonstrated to improve the emergency response time for high LHI locations. It is show that LHI acts as a weighing factor in the mathematical model as it give more weight for those locations and ensure minimizing the response time. This can be observed in the model outputs as higher LHI locations has been given priorities in fulfilling its demand over other (less LHI locations) which might be located very close to the depots.
- The final output of dispatch model of each scenario represents optimum time and capacity optimization.

Table 4.19: Summary of the three Theoretical scenarios.

Preliminary Study : Theoretical scenarios	Scenarios		
	1	2	3
TTT	557.626	615.89	1,479.01
Full response time, min	44.95	26.70	83.05
initial response time, min	15.00	9.00	30.00
No of Trucks	10.00	12.00	28.00
Total supplied capacity, Gallon	25,000	25,400	62,200

CHAPTER 5: MODEL IMPLEMENTATION

5.1 Introduction

In this chapter, the implementation of the Index-based Emergency Response Management model (IERMS) is discussed in the case industrial city. The proposed framework is presenting useful tools for decision support system by providing essential information to handle simultaneously multiple risky events with limited resources by evaluation of the potential hazard via calculation of location Hazard index (LHI) for each hazardous location then distribution or dispatching the resources based on criticality of each incident with overall objective to minimize the overall repose time. The IERMS model is implemented based on two steps. In the first step, LHI is calculated based on based on assumed 4 incidents or emergencies, then at the 2nd step, the LHI will be used to set priorities in the Mathematical model simulation. The AMPL program is written with the overall objective to minimize the delivery time of emergency response and support to the incident locations.

5.2 Implementation method

The IERMS Model testing and verifications will be done in two steps. The first part is the calculation of Location hazard index, which can be modulated with a spreadsheet using MS, excel. The spreadsheet features are used to create series of databases and tables, which will be linked and used to build the calculation sheet for the location hazard index based on location demographic information, chemicals substances databases and metrological information.

The Second part of the IERMS model is the mathematical model used for dispatching process of emergency resources based on LHI (calculated in part 1 by MS Excel) and target objective of minimizing the response time via allocation of required resources from nears emergency response center (Depot) based on LHI. AMPL programing language has been chosen to simulate the mathematical model due to its flexibility and ability to solve high-complexity problems for large-scale mathematical computing such as large-scale optimization and scheduling-type problems.

5.3 Cases Study: An Optimization model of Emergency response based on Location Hazard index for Oil and Gas industrial city in Qatar.

The case study city is located in the north and consists of major industries that process LNG. The case study city covers industrial facilities, logistics and administrative buildings with total area of about 230 sq. km and is adjacent to the sea. The basic model developed in Chapter 4 will be implemented first in the case study. Then seven addition models are developed as scenario models (TBO 2 to TBO 8) to show the impact of relaxing or restricting some of the features of the model. The type of models discussed here are given in Table 5.1

Table 5.1: The full model and scenarios for emergency incident management.

No	Model		Elements	Description
1	TBO1	Model 1 (Full model)	Time base+ LHI+K1+ΔDi	The full model developed in this case as time optimization with LHI, RLHI, early response (K1) and minimize the utilization constraint.
2	TBO 2	Model 2	Time base	Time optimization only
3	TBO 3	Model 3	Time base+ LHI	Time optimization with LHI, RLHI only
4	TBO 4	Model 4	Time base+K1	Time optimization with early response (K1) effect only.
5	TBO 5	Model 5	Time base+ ΔDi	Time optimization with minimize the utilization constraint only.
6	TBO 6	Model 6	Time base+ LHI+K1	Time optimization with LHI, RLHI, and early response (K1) only.
7	TBO 7	Model 7	Time base+K1+ΔDi	Time optimization with early response (K1) and minimize the utilization constraint only
8	TBO 8	Model 8	Time base+ LHI+ΔDi	Time optimization with LHI, RLHI, and minimize the utilization constraint only.

5.3.1 Location Hazard index for the full model

To test the location hazard index, four different locations in the industrial sites are

1. Cluster/ location 1: Terminal and LNG storage Area.
2. Cluster/ location 2: Ethylene Production facilities.
3. Cluster/ location 3: Support Services / camp.
4. Cluster/ location 4: Utilities and Services Area.

Each area or cluster contains different facilities which might vary from plant equipment, storage, office, workshop or accommodations. Each will have different inventories of dangerous substances, population, and other location parameters.

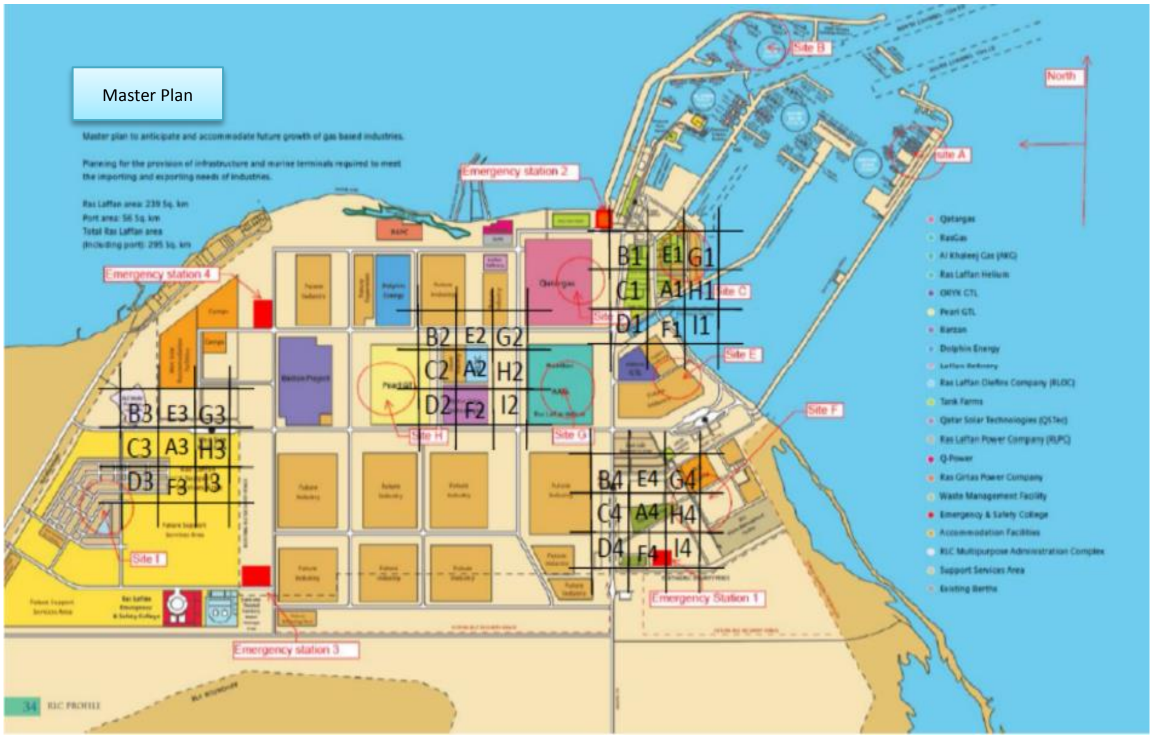


Figure 5.1: Overall site plan with cluster concept on locations.

5.3.1.1 Site Data analysis:

1. For location 1 (Terminal and LNG storage Area): the selected site (See Figure 5.1 and Table 5.2) is used for storage facilities and tanks of highly flammable substances such as liquefied natural gas (Methane), Propane, butane, Diesel fuel, Methanol, and Ethane. By applying the proposed methodology which was explained earlier and divide the incident location into 9 clusters. The hazard index is calculated for each cluster based on the chemical properties, and then the index is adjusted as per the volume available in each

location. For A1 (center of the cluster) the volume effect index was very high (1 or 100%) as all chemicals volumes and classifications were of upper tier and the headcount and wind were consider maximum as this is the central cluster (incident actual location). Accordingly, the overall impact of each chemical in that situation is obtained as shown in Table 5.3. The highest value among the group of substances in each cluster will be selected to reflect the overall LHI which is 6 points (out of 12 points). Accordingly, other clusters will be calculated in the same way, but the location impact will change based on the wind direction and population in each cluster accordingly. The overall site 1 calculations including the 9 clusters are shown in Appendix F. As the Maximum LHI for all clusters is for A1 = 6 points, it has been selected as the LHI for site 1 which is the Terminal and LNG storage site. The overall

Table 5.2: LHI calculation of cluster A1:

Description of Chemicals		Location Description				Input			Hazard Category for chemical		LHI
Chemical	Volume, MT	Wind Class	Adjacent Cell Location	R_{im}	Head Count	Toxicity, Tc	Flammability, Fc	Reactivity, Rc	Tier	Value, R_{imcv}	
LNG (Methane)	10,000	Gentle Breeze	Center		1	2	4	0	UU	1	6
Propane	6,000					1	4	0	UU	1	5
Butane	5,000					1	4	0	UU	1	5
Diesel	2,000			1		1	2	0	UU	1	3
Methanol	500					1	3	0	UU	1	4
Ethane	3,000					1	4	0	UU	1	5
								Max			6

2. Location 2: Ethylene Production facilities. This location is used for manufacturing and storage facilities for Ethylene, Ethane, propylene and other flammable and highly toxic substances such as Hydrogen sulfide, Ethylene, Ethane, Propane, Butane. By applying clusters division, the hazard index value for each cluster is obtained and adjusted as per the volume in each location. For A2 (center of the cluster) the volume effect index was very high (1 or 100%) as all chemicals volumes and classifications were of the upper tier and the headcount and wind were consider maximum as this is the central cluster (incident actual location). Accordingly, the overall impact of each chemical in that situation is obtained as shown in Figure 5.4. The highest value among the group of substances in each cluster is selected to reflect the overall LHI, which is 8 points (out of 12 points). Accordingly, LHI for other clusters are calculated and the maximum LHI for all clusters is obtained for A2 as 8. This value is been selected as LHI for site 2 which is the Ethylene production facilities.

Table 5.3: LHI calculation for A2.

Description of Chemicals		Location Description				Input			Hazard Category for chemical		LHI
Chemical	Volume, MT	Wind Class	Adjacent Cell Location	R_{im}	Head Count	Toxicity, Tc	Flammability, Fc	Reactivity, Rc	Tier	Value, R_{imcv}	
H2S	3,000	Gentle Breeze	Center		1	4	0	4	U U	1	8
Ethylene	8,000					1	4	2	U U	1	7
Propylene	700					1	4	0	U U	1	5
Propane	2,000			1		1	4	1	U U	1	6
Methane	500					1	4	0	U U	1	5
								Max			8

3. Location 3: Support Services/camp area (Fire in the trash and waste damp area). This location is used as support service and camps for contractors. Accordingly, this areas contains a very small amount of sulfide, Ethylene, and Methane which is used in very limited locations (cluster B3 only) for the purpose of domestic and training purposes. All other clusters are empty of chemicals, but they have a relatively very high number of population due to facilities such as labor camps and workshops (D3 area), training center (B3 Area), and officer buildings (F3 and H3). By applying clusters division, the hazard index value for each cluster is calculated and adjusted as per the volume, population and wind conditions in each location. For A3 (center of the cluster) the volume effect index was zero as no chemicals volumes were present in this location. But other clusters shower very high population such as D3 (1500 individuals), B3 (500 individuals), F3 (30

individuals) and H3 (20 individuals). Accordingly, the overall impact of each cluster is obtained as shown in Table 5.3. The highest value among site 3 clusters is B3 which is selected as the overall LHI for Site 3 which is 0.4 @ B3 (out of 12). Accordingly, LHI for other clusters are calculated in the same way and the maximum LHI for all clusters (B3 = 8) is selected as the LHI for the site.

Table 5.4: LHI for location 3.

	chemicles hazard input			Location info. Input			Out put						Volume indix				Location Indix				
	Hazr no	substance	Vc, voume, MT	type/ class	Adjacent cell location	head count	Tc, Toxisisty	c, flambilit	c, reactivity	Ii	Ivc	New LHI	substance	volume	Teir	Overall	type/ class	direction	Adjacent cell location	head count	Location Factor
: Support Services / camp																					
A3	1	NA	0	Gentle Breeze	center	0	0	0	0	1.00	0.00	0.0	NA	0	NA	0					
	2	NA	0				0	0	0	1.00	0.00	0.0	NA	0	NA	0					
	3	NA	0				0	0	0	1.00	0.00	0.0	NA	0	NA	0					
												0.0	0	0			Gentle Breeze	North	center	0	1
B3	1	H2s	1	Gentle Breeze	up-wind	500	3	4	0	0.20	0.25	0.4	H2s	1	LL	0.25					
	2	Etylene	1				1	4	2	0.20	0.25	0.4	Etylene	1	LL	0.25					
	3	MethANE	1				1	4	0	0.20	0.25	0.3	MethANE	1	LL	0.25					
												0.4	0	0			Gentle Bree	North	up-wind	500	0.2
C3	1	NA	0	Gentle Breeze	side	5	0	0	0	0.52	0.00	0.0	NA	0	NA	0			0		
	2	NA	0				0	0	0	0.52	0.00	0.0	NA	0	NA	0			0		
	3	NA	0				0	0	0	0.52	0.00	0.0	NA	0	NA	0			0		
												0.0	0	0			Gentle Breeze	North	side	5	0.52
D3	1	NA	0	Gentle Breeze	Down-wind	1500	0	0	0	0.72	0.00	0.0	NA	0	NA	0			0		
	2	NA	0				0	0	0	0.72	0.00	0.0	NA	0	NA	0			0		
	3	NA	0				0	0	0	0.72	0.00	0.0	NA	0	NA	0			0		
												0.0	0	0			Gentle Breeze	North	Down-wind	1500	0.72
E3	1	NA	0	Gentle Breeze	Up-wind	200	0	0	0	0.20	0.00	0.0	NA	0	NA	0			0		
	2	NA	0				0	0	0	0.20	0.00	0.0	NA	0	NA	0			0		
	3	NA	0				0	0	0	0.20	0.00	0.0	NA	0	NA	0			0		
												0.0	0	0		**0**	Gentle Breeze	North	Up-wind	200	0.2

Cont. Table 5.4: LHI for location 3.

F3	1	NA	0	Gentle Breeze	down-wind	30	0	0	0	0.72	0.00	0.0	NA	0	NA	0			0		
	2	NA	0				0	0	0	0.72	0.00	0.0	NA	0	NA	0			0		
	3	NA	0				0	0	0	0.72	0.00	0.0	NA	0	NA	0			0		
												0.0	0	0			Gentle Breeze	North	down-wind	30	0.72
G3	1	NA	0	Gentle Breeze	down-wind	0	0	0	0	0.63	0.00	0.0	NA	0	NA	0			0		
	2	NA	0				0	0	0	0.63	0.00	0.0	NA	0	NA	0			0		
	3	NA	0				0	0	0	0.63	0.00	0.0	NA	0	NA	0			0		
												0.0	0	0			Gentle Breeze	North	down-wind	0	0.63
H3	1	NA	0	Gentle Breeze	side	20	0	0	0	0.59	0.00	0.0	NA	0	NA	0			0		
	2	NA	0				0	0	0	0.59	0.00	0.0	NA	0	NA	0			0		
	3	NA	0				0	0	0	0.59	0.00	0.0	NA	0	NA	0			0		
												0.0	0	0		**0**	Gentle Breeze	North	side	20	0.585
I 3	1	NA	0	Gentle Breeze	Down-wind	0	0	0	0	0.00	0.63	0.0	NA	0	NA	0			0		
	2	NA	0				0	0	0	0.00	0.63	0.0	NA	0	NA	0			0		
	3	NA	0				0	0	0	0.00	0.63	0.0	NA	0	NA	0			0		
												0.0					Gentle Breeze	North	Down-wind	0	0.63
												0.4									
										0.12	**0.0**	**0.4**	**0**	**Out of 12**							
										Variance	**Average**	**MAX**	**Weighted**								

4. Location 4: Utilities and Services Area. This location is used for industrial utilities and service areas such as storage warehouse, petrol station and chemical logistic area. Accordingly, this area contains small to medium amount of Hydrocarbons and chemical substances such as gasoline, Diesel fuel, butane, propane, methanol, and methane which is stored or used in a very limited amount such as cluster B4 and E4. All other clusters are empty of chemicals, but they contain relatively medium to high number of population such as E4 (300 individuals) and G4 (500 individuals). By applying clusters division, the hazard index value for each cluster os obtained and adjusted for the volume, population and wind conditions available in each location. For A4 (center of the cluster) the volume effect index was zero as no chemicals volumes were present in this location. Accordingly the overall impact of each cluster was obtained as shown in Table 5.5. The highest value among the 4 clusters is E4, which is selected to reflect the overall LHI for Site 4 which is 1.0 @ E4 (out of 12 points).

Table 5.5: LHI calculation for location 4.

		chemicles hazard input		Location info. Input			Out put						Volume indix				Location Indix				
	Hazr no	substance	Vc, vuome, MT	type/ class	Adjacent cell location	head count	Tc, Toxisisty	c, flambilit	c, reactivity	Ii	Ivc	New LHI	substance	volume	Teir	Overall	type/ class	direction	Adjacent cell location	head count	Location Factor
Pixel/ location 4 : Utlities and Services Area																					
A4	1	NA	0	Gentle Breeze	center	3	0	0	0	1.00	0.00	0.0	NA	0	NA	0					
	2	NA	0				0	0	0	1.00	0.00	0.0	NA	0	NA	0					
	3	NA	0				0	0	0	1.00	0.00	0.0	NA	0	NA	0					
												0.0	0	0			Gentle Breeze	North	center	3	1
B4	1	Gasoline	500	Gentle Breeze	up-wind	15	1	3	0	0.20	1.00	0.8	Gasoline	500	UU	1					
	2	Buteane	2.00				1	4	0	0.20	0.25	0.3	Buteane	2	LL	0.25					
	3	Propane	1.50				1	4	0	0.20	0.25	0.3	Propane	1.5	LL	0.25					
												0.8	0	0			Gentle Breeze	North	up-wind	15	0.2
C4	1	NA	0	Gentle Breeze	side	60	0	0	0	0.59	0.00	0.0	NA	0	NA	0					
	2	NA	0				0	0	0	0.59	0.00	0.0	NA	0	NA	0					
	3	NA	0				0	0	0	0.59	0.00	0.0	NA	0	NA	0					
												0.0	0	0			Gentle Breeze	North	side	60	0.585
D4	1	NA	0	Gentle Breeze	down-wind	0	0	0	0	0.63	0.00	0.0	NA	0	NA	0					
	2	NA	0				0	0	0	0.63	0.00	0.0	NA	0	NA	0					
	3	NA	0				0	0	0	0.63	0.00	0.0	NA	0	NA	0					
												0.0	0	0			Gentle Breeze	North	down-wind	0	0.63
E4	1	Disel Fuel	1,000.00	Gentle Breeze	UP-wind	300	1	2	0	0.20	1.00	0.6	Disel Fuel	1000	UU	1					
	2	Buteane	500.00				1	4	0	0.20	1.00	1.0	Buteane	500	UU	1					
	3	Propane	900.00				1	4	0	0.20	1.00	1.0	Propane	900	UU	1					
	4	Methanol	10.00				1	3	0	0.20	0.50	0.4	Methanol	10	UL	0.5					
	5	MethANE	1,000.00				1	4	0	0.20	1.00	1.0	MethANE	1000	UU	1					
												1.0	0	0			Gentle Breeze	North	UP-wind	300	0.2

Cont. Table 5.5: LHI calculation for location 4.

F4	1	NA	0	Gentle Breeze	down-wind	0	0	0	0	0.63	0.00	0.0	NA	0	NA	0					
	2	NA	0				0	0	0	0.63	0.00	0.0	NA	0	NA	0					
	3	NA	0				0	0	0	0.63	0.00	0.0	NA	0	NA	0					
												0.0	0	0			Gentle Breeze	North	down-wind	0	0.63
G4	1	NA	0	Gentle Breeze	up-wind	500	0	0	0	0.20	0.00	0.0	NA	0	NA	0					
	2	NA	0				0	0	0	0.20	0.00	0.0	NA	0	NA	0					
	3	NA	0				0	0	0	0.20	0.00	0.0	NA	0	NA	0					
												0.0	0	0			Gentle Breeze	North	up-wind	500	0.2
H4	1	NA	0	Gentle Breeze	side	0	0	0	0	0.24	0.00	0.0	NA	0	NA	0					
	2	NA	0				0	0	0	0.24	0.00	0.0	NA	0	NA	0					
	3	NA	0				0	0	0	0.24	0.00	0.0	NA	0	NA	0					
												0.0	0	0			Gentle Breeze	North	side	0	0.235
I 4	1	NA	0	Gentle Breeze	down-wind	0	0	0	0	0.63	0.00	0.0	NA	0	NA	0					
	2	NA	0				0	0	0	0.63	0.00	0.0	NA	0	NA	0					
	3	NA	0				0	0	0	0.63	0.00	0.0	NA	0	NA	0					
												0.0					Gentle Breeze	North	down-wind	0	0.63
												1.0									
										0.40	0.2	1.0	0	**Out of 12**							
										Variance	Average	MAX	Weighted								

Table 5.6: LHI calculation from Cluster to Location level

0	Location 1	Location 2	Location 3	Location 4
Pixel/ location	6.0	8.0	0.0	0.0
A	5.0	7.0	0.0	0.0
	5.0	5.0	0.0	0.0
	3.0	6.0	0.0	0.0
	4.0	5.0	0.4	0.8
	5.0	8.0	0.4	0.3
	6.0	**0.1**	**0.3**	**0.3**
B	1.0	0.1	0.4	0.8
		0.0	0.0	0.0
		0.1	0.0	0.0
	1.0	**1.6**	**0.0**	**0.0**
C	1.0	2.6	0.0	0.0
	1.6	2.1	0.0	0.0
	1.6	2.6	0.0	0.0
	0.3	4.1	0.0	0.0
	1.6	4.1	0.0	0.0
	1.2		**0.0**	**0.6**
D	2.2	4.1	0.0	1.0
	0.0	0.4	0.0	1.0
	0.0	0.7	0.0	0.4
	2.2	**0.3**	**0.0**	**1.0**
E	0.8	0.7	0.0	1.0
	0.8	1.0	0.0	0.0
	0.0	1.0	0.0	0.0
	0.8	**0.7**	**0.0**	**0.0**
F	1.9	0.9	0.0	0.0
	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0
	1.9	**0.0**	**0.0**	**0.0**
G	3.2	0.0	0.0	0.0
	0.6	0.0	0.0	0.0
	0.0	0.0	0.0	0.0
	3.2	**0.0**	**0.0**	**0.0**
H	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0
	0.0	0.0	0.0	0.0

	0.0	**0.0**	**0.4**	**0.0**
I	0.0	0.0		0.0
	0.0		0.0	1.0
	0.0		0.0	
	0.0	**8.0**	**0.0**	**1.0**
	6.0	**8.0**	**0.4**	**1.0**
	MAX	**MAX**	**MAX**	**MAX**

The location hazard index of each location is a unique single-figure tool that can provide you with very comprehensive view of the hazard level in each location. It integrates important and significant site information such as site hazardous substance nature, the volume effect, wind effect, population effect and the effect of neighboring locations. The LHI for each site can be used very easily by the emergency response managers to make very quick decision related to priority, response and vital resource allocations for locations with highest LHI and then to the lowest LHI. Furthermore, the LHI can be used and input for the dispatch model as it will be demonstrated in next section.

5.4 Resources optimization in the full model (Model 1)

The resource optimization simulation will be done by using AMPL as explained earlier. For emergency scenarios and resources optimization, it is assumed that emergency incidents will occur in 10 different locations inside the industrial city in the same period of time. Each location will be having its location hazard index (LHI) and the available resources in each depot shall utilized to respond to these incidents considering minimizing the response time to attend and control the situation as early as possible. The Detailed information used in the model as the following:

5.4.1 Incident locations (i):

The 10 Incident locations (i: 1 to 10) has been selected on the map of industrial city to represent typical emergency scenarios in various locations with different operations nature, criticalities, hazardous materials content , and head in site map as shown in Appendix D. The diversity in the selected location has been considered as different, such as industrial plant facilities, hydrocarbon, and highly flammable materials terminal, chemicals storage, domestic warehouse, workshops, laydown areas labor camps, and administrative facilities. The description of the selected locations with description and LHI are shown in Table 5.7.

Table 5.7: Incident locations with LHI.

Descriptions	i	LHI
Location 1: Terminal and LNG storage Area.	1	6
Location 2: Ethylene Production facilities.	2	12
Location 3: Support Services / camp.	3	0.35
Location 4: Utilities and Services Area.	4	1
Location 5: Construction site 1	5	0.8
location 6: construction site 2	6	0.7
Location 7: lay down area.	7	0.6
Location 8: Empty car parking area.	8	0.5
Location 9: assembly point	9	0.4
Location 10: Open storage area.	10	0.1

5.4.2 Emergency response center / Depot (J):

The location of the emergency response centers or depots (j: 1 to 5) has been plot on the map based on actual location selected location in the case study location as shown in the map attached in Appendix D. List of location and depot numbers are shown in Table 5.7 below. Generally observed that emergency response centers are located in the north and North east part of case study location which is due to intensive location activates which is located in the north and north east area of the industrial city.

Table 5.8: Emergency centers / depot locations

Emergency Response center/ Depot location / Description	No J
North east / Perth and logistic Area.	1
North east / Support service area.	2
Mid North / Plant Area	3
North west / Future development / camps.	4
North east / Perth and shipyard area.	5

5.4.3 Emergency Types (k) and Resources capabilities (Ck):

To simulate real life scenarios, it is assumed that there are four types of resources available. These resources are command truck, conventional Firefighting truck, heavy duty firefighting trucks and tanker trucks. Each type of resources/ trucks has its own has its properties which will be utilizable to in the model to optimizer the emergency response model. From Table 5.10, it can be observed that each truck has different water holding capacity (Ck) and cost per trip as well as the response time factor. The holdup capacity will be used to determined number and type of trucks that would be required to respond to demand requirements of each incident location. The time factors will be used to determine the time required for each type of trucks to reach certain incident location. The reference time is measured for K1 type of resources and then it will be scaled up by multiplication with time factor to find the time required by the different type of trucks or resources. The cost of each type of truck will be used in a later stage to optimize the allocation process by considering relevant cost beside capacity and response time. The detailed information of each type of trucks is shown in Table 5.9.

Table 5.9: emergency Resources available on each site.

Resources available in Depot	J	K1	K2	K3	K4	Total
North east / Perth and logistic Area.	1	1	3	2	2	8
North east / Support service area.	2	1	2	1	1	5
Mid North / Plant Area	3	1	2	1	1	5
North west / Future development / camps.	4	1	1	0	1	3
North east / Perth and ship yard area.	5	1	1	0	1	3
Total		5	9	4	6	24

Furthermore, the available resources are distributed among different emergency response centers/depots as shown in Table 5.9.

Table 5.10 : Emergency trucks capacity

Fire trucks capacity/ gallon	Type	capacity Ck,	time/ speed factor	Operation setup time min/ trip
command truck	k1	400	1	5
Conventional FF truck	k2	1000	1.05	10
Heavy FF Truck	k3	4000	1.2	15
Tanker Truck	k4	6000	1.5	20

5.4.4 Demand capacity for incident locations (Di):

For each incident location, demand requirements of firefighting water are defined, which are proportional to the location hazard index of each location. The details of each incident location demand is shown in Table 5.11. The demand (Di) will be used to determine the required volume of water on each site, which will be converted into the number of trucks required for each site.

Table 5.11 : Fire water demand (Di) of each incident location.

Demand Table / gallon	i	Di	LHI
Location 1: Terminal and LNG storage Area.	1	1,500	6
Location 2: Ethylene Production facilities.	2	10,000	12
Location 3: Support Services / camp.	3	400	0.35
Location 4: Utilities and Services Area.	4	600	1
location 5: Construction site 1	5	500	0.8
location 6: construction site 2	6	400	0.7
Location 7: lay down area.	7	300	0.6
Location 8: Empty car parking area.	8	250	0.5
location 9: assembly point	9	200	0.4
Location 10: Open storage area.	10	100	0.1
Total Demand		**14,250.00**	

5.4.5 Travel time (t) :

For any assignment of emergency resource dispatched from emergency response center or depot (J) to incident location (i), there will be defined route (h) with specified travel time. The selection of the route will be based on optimization function or objective to minimize the response time. A database s prepared with all possible routes between the emergency centers and proposed incident locations has been prepared and feed into the mathematical model to select the most suitable route to minimize the response time. A list of all possible routes with estimated time for each vehicle type has been listed in Table 5.12. This list will be concerted in to AMPL Data file and used to solve the objective function.

Table 5.12: Estimated travel time for different type of resource.

Estimated travel time for selected route h for each Truck Type						
	From	**To**	**Response time in minutes**			
	j	**i**	**K1**	**K2**	**K3**	**K4**
h	**1**	1	2	2.1	2.4	3
h	**1**	2	5	5.25	6	7.5
h	**1**	3	15	15.75	18	22.5
h	**1**	4	10	10.5	12	15
h	**1**	5	13	13.65	15.6	19.5
h	**1**	6	15	15.75	18	22.5
h	**1**	7	10	10.5	12	15
h	**1**	8	20	21	24	30

h	**1**	9	3	3.15	3.6	4.5
h	**1**	10	12	12.6	14.4	18
h	2	1	4	4.2	4.8	6
h	2	2	6	6.3	7.2	9
h	2	3	10	10.5	12	15
h	2	4	2	2.1	2.4	3
h	2	5	4	4.2	4.8	6
h	2	6	8	8.4	9.6	12
h	2	7	10	10.5	12	15
h	2	8	15	15.75	18	22.5
h	2	9	6	6.3	7.2	9
h	2	10	8	8.4	9.6	12
h	**3**	1	4	4.2	4.8	6
h	**3**	2	2	2.1	2.4	3
h	**3**	3	6	6.3	7.2	9
h	**3**	4	5	5.25	6	7.5
h	**3**	5	3	3.15	3.6	4.5
h	**3**	6	5	5.25	6	7.5
h	**3**	7	3	3.15	3.6	4.5
h	**3**	8	10	10.5	12	15
h	**3**	9	3	3.15	3.6	4.5
h	**3**	10	3	3.15	3.6	4.5
h	4	1	10	10.5	12	15
h	4	2	6	6.3	7.2	9
h	4	3	2	2.1	2.4	3
h	4	4	10	10.5	12	15

h	4	5	6	6.3	7.2	9
h	4	6	4	4.2	4.8	6
h	4	7	3	3.15	3.6	4.5
h	4	8	6	6.3	7.2	9
h	4	9	6	6.3	7.2	9
h	4	10	2	2.1	2.4	3
h	**5**	1	10	10.5	12	15
h	**5**	2	15	15.75	18	22.5
h	**5**	3	18	18.9	21.6	27
h	**5**	4	6	6.3	7.2	9
h	**5**	5	7	7.35	8.4	10.5
h	**5**	6	9	9.45	10.8	13.5
h	**5**	7	10	10.5	12	15
h	**5**	8	20	21	24	30
h	**5**	9	10	10.5	12	15
h	**5**	10	13	13.65	15.6	19.5

5.4.6 Optimization model output:

By applying objective function and constraint s (1 to 5) for same conditions and assumptions used for the test case par 5.4 and the setup cost per trip values shown in Table 5.13, and the outputs are shown in Table 5.14, which can be explained as the following:

- For incident location 1, two truck of K1+ K3 type with 4400 Gallon of water capacity has been dispatched from Depot 1.

- For incident location 2, three truck of K1+K3+K4 type with a total capacity of 10,400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 4, two truck of K1+K2 type with 1400 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, two truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 2 and K2 type trucks with a capacity of 1000 Gallon from depot 3.
- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 5.
- For incident location 7, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 8, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- The TBO 1 case will be analyzed and compared vs other models in the Parametric Sensitivity analysis part.

Table 5.13: Output result of TBO 1 case.

	Depo				
Location i	1	2	3	4	5
1	K1+K3				
2			K3+K4		K1
3				K1	
4		K1+K2			
5		K1	K2		
6					K1
7			K1		
8			K1		
9	K1				

The response time can be divided two components. The first is the initial response time which measures travel time for the first units arrived to the emergency site before other back resources as required and, the second is the overall response time at which all the required resources will be available on location. For TBO 1 case, the initial time accumulated for all scenarios is 38.65 min, while the overall response time for all resources was 65.05 minutes.

For the top critical sites in this scenario, which has the highest LHI index (site 1 and site 2), it can be observed that early arrival time for initial resources is done within 2 and 2.4 minutes consecutively. The overall response time is 4.4 minutes for site 1 and 20.4 minutes for site 2 as site two required additional supplies. The longest early response time was for site 8 which is 10 minutes due to its location and low priority (low LHI = 0.5). The detailed results for all sites are highlighted in Table 5.14.

Table 5.14: Emergency response time for case TBO 1.

Location i	1	2	3	4	5	Total	Early
1	4.4					4.4	2
2			5.4		15	20.4	2.4
3				2		2	2
4		4.1				4.1	2.1
5		4	3.15			7.15	3.15
6					9	9	8
7			3			3	3
8			10			10	10
9	3					3	3
10				2		2	3
				Total time =		65.05	38.65

- For the demand analysis of each incident location used in case TBO 1, by analyzing the output of allocated capacity for each site (Di_f) vs required demand (Di), it can be observed that all demand is positively fulfilled for all incident location considering that there is enough water to cover all the demand (Dt). As shown in Table 5.14, the ΔDi value for each location is either zero (such as location 3 and 6) or positive such as (1, 2, 4, 5, 6, 7, 8, 9 and10). Generally, the demand analysis is very close to case 3 and identical to case 4 at which all the demand has been fulfilled positively.
- Results of capacity utilization for each depot is acceptable. Globally, it can be observed that all dispatched resources are within available capacities in each depot and no shortage case for all depots as the capacity of each depot has been respected and allocations are within each depot capacity as ΔCk value is always equal or more than zero as shown in Table 5.15.

Table 5.15: Supply and demand analyisis of emergency reponse of TBO1.

			Depo						
Location i	1	2	3	4	5	D sys	Di	∆ Di	%
1	4400					4,400	1,500	2,900	193
2			10000		400	10,400	10,000	400	4
3				400		400	400	-	-
4		1400				1,400	600	800	133
5		400	1000			1,400	500	900	180
6					400	400	400	-	-
7			400			400	300	100	33
8			400			400	250	150	60
9	400					400	200	200	100
10				400		400	100	300	300
						20,000	14,250	5,750	40
Ck sys	4800	1800	11800	800	800	20,000			
Ck	23,800.	12,800.	12,800.	7,800	7,800	65,000			
∆ Ck	19000	11000	1000	7000	7000	45,000			
%	79.83	85.94	7.81	89.74	-				

5.5 Parametric Sensitivity analysis of TBO model (change in objective function and constraint):

For the sensitivity analysis, some parameters that might have aa direct impact on emergency response time such as the LHI, resources dispatch structure (i.e., sending K1 type of trucks with each response), and capacity utilization can be considered.

5.5.1 Model 1 (Full model, TBO1):

For TBO 1 Case: time based optimization with LHI effect response vehicles structure (K1 constraint) & the supply optimization (Full case):

The proposed TBO 1 case has a very comprehensive view and coverage of important elements in the operations and management of emergency response operations. The objective function reflects the impact of LHI on the optimization function as the inverse of LHI has been used as a weight factor to reflect its importance in minimization function. Furthermore, five constraint equations have been introduced to improve the optimization. The details of used objective function and constraint in TBO1 are highlighted in Paragraph 4.31.

By applying objective function and constraints (1 to 5) for same conditions and assumptions used for the test case given in Section 5.4 and the setup cost per trip values are shown in Table 5.15, and is explained as the following :

- For incident location 1, two truck of K1+ K3 type with 4400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 2, three truck of K1+K3+K4 type with a total capacity of 10,400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.

- For incident location 4, two truck of K1+K2 type with 1400 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, two truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 2 and K2 type trucks with a capacity of 1000 Gallon from depot 3.
- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 5.
- For incident location 7, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 8, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- The TBO 1 case will be analyzed and compared vs other models in the Parametric Sensitivity analysis part.

Table 5.16: Output result of TBO 1 case.

	Depo				
Location i	1	2	3	4	5
1	K1+K3				
2			K3+K4		K1
3				K1	
4		K1+K2			
5		K1	K2		
6					K1
7			K1		
8			K1		
9	K1				

The response time can be divided in to two components. The first is the initial response time which measures travel time for the first units to arrive at the emergency site before other back resources as required and, the second is the overall response time at which all the required resources will be available on location. For TBO 1 case, the initial time accumulated for all scenarios is 38.65 min, while the overall response time for all resources was 65.05 minutes.

For the top critical sites in this scenario, which has the highest LHI index (site 1 and site 2), it is observed that early arrival time for initial resources is done within 2 and 2.4 minutes consecutively. The overall response time is 4.4 minutes for site 1 and 20.4 minutes for site 2 as site two required additional supplies. The longest early response time was for site 8 which is 10 minutes due to its location and low priority (low LHI = 0.5). The detailed results for all sites are highlighted in Table 5.16.

Table 5.17: Emergency response time for TBO 1.

Location i	1	2	3	4	5	Total	Early
1	4.4					4.4	2
2			5.4		15	20.4	2.4
3				2		2	2
4		4.1				4.1	2.1
5		4	3.15			7.15	3.15
6					9	9	8
7			3			3	3
8			10			10	10
9	3					3	3
10				2		2	3
				Total time =		65.05	38.65

- For the demand analysis of each incident location used in case TBO 1, it is observed by analyzing the output of allocated capacity for each site (Di_f) vs required demand (Di) that all demands has been positively fulfilled for all incident location considering we have enough water to cover all the demand (Dt). As shown in Table 5.30, the ΔDi value for each location is either zero (such as locations 3 and 6) or positive such as (1, 2, 4, 5, 6, 7, 8, 9 and 10). Generally, the demand analysis are very close to case 3 and identical to case 4 at which all the demand has been fulfilled positively.
- Results of Capacity utilization for each depot is acceptable. Globally, it can be observed that all dispatched resources are within available capacities in each depot and no shortage case for all depots as the capacity of each depot has been respected and allocations were within each depot capacity as ΔCk value is always equal or more than zero as shown in Table 5.18.

Table 5.18: Supply and demand analysis of emergency response of TBO 1.

	Depo								
Location i	1	2	3	4	5	D sys	Di	∆ Di	%
1	4400					4,400	1,500	2,900	193
2			10000		400	10,400	10,000	400	4
3				400		400	400	-	-
4		1400				1,400	600	800	133
5		400	1000			1,400	500	900	180
6					400	400	400	-	-
7			400			400	300	100	33
8			400			400	250	150	60
9	400					400	200	200	100
10				400		400	100	300	300
						20,000	14,250	5,750	40
Ck sys	4800	1800	11800	800	800	20,000			
Ck	23,800.	12,800.	12,800.	7,800	7,800	65,000			
∆ Ck	19000	11000	1000	7000	7000	45,000			
%	79.83	85.94	7.81	89.74	-				

5.5.2 Model 2 (time based optimization, TBO2):

The second case (TBO 2) is a simple time based optimization which will be used for comparison with other models to show the impact of each element on the overall emergency response time due to its simplicity and basic components as the following:

Time based optimization without LHI and other constraints:

The TBO 2 objective function and constraints are given below.

Objective function:

$$Min\ (ERT) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} x_{ijk} \left(T_k + t_{ijk}\right) \qquad (Ob.1)$$

$Subject\ to$:

1- Incident location demand constraint t

$$\sum_{j=1}^{m} \sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \qquad (1)$$

2- Emergency resource availability constraint t

$$\sum_{i=1}^{n} \mathrm{C}_k * x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (2)$$

5- Non-negativity constraint t

$x_{ijk}\ are\ postive\ integr\ variables\ and\ x_{ijk} \in (0,1) \quad \forall i \in \mathrm{I};\ \forall j \in \mathrm{J};\quad \forall k \in \mathrm{K}$ (3)

Variables Description:

"j" is the emergency response / Firefighting center or depot,$j = \{1, 2, \dots \dots m\}$; where m is the number of centers

"i" is emergency incident location,$i = \{1,2, \dots \dots, n\}$, where n is the number locations

"k" is the resource type, $j = \{1,2, \dots \dots, w\}$, where w is the number resource types/classes

"T_k" is the setup time of resource k

"t_{ijk}"= travel time from emergency response center "i" to location "j " for resource type "k".

“x_{ijk}” are binary variables that will have value 1 if resources$k$, has been dispatched from emergency response center i to location j, other with = 0

LHI$_i$ = Location Hazard Index for location “i”

“D$_i$”= is firefighting material demand for incident location i,

“R$_{jk}$”= is emergency resource type k located in emergency center$j$.

“C$_k$”= total hold up capacity of material volume for emergency truck type$k$.

The objective basic formula is to minimize the overall emergency response time by utilization sum of travel time t_{ijk} and setup time T$_k$ required for each type of resources used in the emergency response operation subject to vehicles availability and service constraint as the following:

The constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di). The constraint (2) is aimed to make sure that number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). The constraint (3) is non negativity constraint.

The model TBO 2 provides the results discussed below. The selected routes for emergency response based on given parameters are shown in Table 5.11.

- For incident location 1, one truck of K3 type with 4000 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 2 , two truck of K3 and K4 type with a total capacity of 10,000 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 4, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 7, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 8, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.

Table 5.19: Output results of the optimization case TBO 2.

	Depo				
Location i	1	2	3	4	5
1	K3				
2			K3+K4		
3				K1	
4		K2			
5			K2		
6		K1			
7			K1		
8				K1	
9	K1				
10			K1		

By analyzing the output result and dispatching strategy, it can be observed that optimization model has achieved its objectives as the following:

- For TBO 2 case, the initial time accumulated for all scenarios is 35.6 minute, while the overall response time for all resources was 38.6 minutes. For the top critical sites in this scenarios which has the highest LHI index (site 1 and site 2), it can be observed that early arrival time for initial resources is done within 2.4 minutes for both sites. The overall response time is 2.4 minutes for site 1 and 5.4 minutes for site 2 as site 2 required additional supplies. The longest early response time was for site 6 which is 8.4 minutes due to its location. The detailed results for all sites are highlighted in Table 5.16.
- Demand requirements for each incident location: by analyzing the output for allocated capacity for each site (Dif) vs required demand (Di), it can be seen that all demands has been positively fulfilled for all incident location considering that there is enough water to

cover all the demand (Dt). As shown in Table 5.19, the ∆Di value for each location is either zero (such as locations 2 and 6) or positive such as (1, 3,4,5,6,7,8,9 %10). For some locations, it can be observed that relatively high access capacity has been provided in some location but it is mainly due that the trucks capacity are fixed, so when selecting from next available capacity to fulfil the demand, the model will select from next available capacity which might be significantly higher that the demand or single location requirement. The second reason is that the main focus (objective) here is to reduce the emergency response time regardless the capacity as some larger trucks are available in nearby depots, but capacity is much higher than demand for that site. Then these larger trucks will be dispatched as they can reach the site faster.

Table 5.20: travel time output of case TBO 2.

Location i	1	2	3	4	5	Total	T Early
1	2.4					2.4	2.4
2			5.4			5.4	2.4
3				2		2	2
4		2.1				2.1	2.1
5			3.15			3.15	3.15
6		8				8	8.4
7			3			3	3.15
8				6		6	6
9	3					3	3
10			3			3	3
					Total time =	38.05	35.6

- Capacity utilization for each depot: As mentioned earlier, that each Depot or emergency response center will be provided with a limited number of resources or trucks which resemble real life situation. Such limitation (number and capacity of trucks in each depot) shall not be accepted. by analyzing the results, it can be seen that no demand case for all depose as the capacity of each depot has been respected and allocations were within each depot capacity as shown in Table 5.21.

Table 5.21: Results verifications of the mathematical model solution of TBO 2 case.

			Depo						
Location i	1	2	3	4	5	D sys	Di	∆ Di	%
1	4000					4,000	1,500	2,500	167
2			10000			10,000	10,000	-	-
3				400		400	400	-	-
4		1000				1,000	600	400	67
5			1000			1,000	500	500	100
6		400				400	400	-	-
7			400			400	300	100	33
8				400		400	250	150	60
9	400					400	200	200	100
10			400			400	100	300	300
						18,400	14,250	4,150	Total
Ck sys	4400	1400	11800	800	0	18,400			
Ck	23,800.00	12,800.00	12,800.00	7,800.00	7,800.00	65,000			
∆ Ck	19400	11400	1000	7000	7800	46,600			
%	81.51	89.06	7.81	89.74	-	268			

5.5.3 Model 3 (time optimization with the effect of LHI, RLHI, TBO3):

The LHI is very important element which has been introduced to the emergency response formula to improve the emergency response time by providing priorities to the location with high LHI. In order to examine this situation, TBO 3 is developed, TBO2 with the effect of LHI as shown in objective function and the constraints as shown below:

Objective function:

$$Min\ (ERT) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} \frac{x_{ijk}}{RLHI_i} \left(T_k + t_{ijk}\right) \qquad (Ob.1)$$

$Subject\ to$:

1- Incident location demand constraint

$$\sum_{j=1}^{m} \sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \qquad (1)$$

2- Emergency resource availability constraint

$$\sum_{i=1}^{n} \mathrm{C}_k \; * \; x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (2)$$

3- Non-negativity constraint

x_{ijk} $are\ postive\ integr\ variables\ and$ $x_{ijk} \in (0,1)$

$\forall i \in \mathrm{I};\ \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K}$ (3)

The objective of the main formula is to minimize the overall emergency response time by utilization of location hazard index (LHI) as weighing factor by multiplication the invert of the location Hazard index (LHI) by time sum or travel time t_{ijk} and setup time T_k required for each type of resources used in the emergency response operation subject to vehicles availability and service constraint as the following:

The constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di). The constraint (2) is aimed to make sure that number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). This to make sure that it does not overbook the resources and assign fire trucks which does not exist or assigned resources that have already been assigned to a different incident location. The constraint (3) is non negativity constraint.

Table 5.22: Output result of TBO 3 (time base with LHI).

	Depo				
Location i	1	2	3	4	5
1	K3				
2			K3+K4		
3				K1	
4		K2			
5			K2		
6			K1		
7			K1		
8				K2	
9	K1				
10				K1	

The overall output of TBO2 is shown in Table 5.22. The results of the mathematical model output is described as the following:

- For incident location 1, one truck of K3 type with 4000 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 2, two truck of K3 and K4 type with a total capacity of 10,000 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 4, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 3.

- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 7, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 8, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.

Table 5.23: Emergenct reponse time for TBO 3 model.

Location i	1	2	3	4	5	Total	Early
1	2.4					2.4	2.4
2			5.4			5.4	2.4
3				2		2	2
4		2.1				2.1	2.1
5			3.15			3.15	3.15
6			5			5	5
7			3			3	3
8				6.3		6.3	6.3
9	3					3	3
10				2		2	2
				Total time =		34.35	31.35

By analyzing the output result and dispatching strategy, it can be observed that optimization model has achieved its objectives as the following:

For TBO 3 case, the initial time accumulated for all scenarios is 31.35 minute, while the overall response time for all resources was 34.35 minutes. For the top critical sites in this scenario, which has the highest LHI index (site 1 and site 2), it can be observed that early arrival time for initial resources is done within 2.4 minutes for both sites. The overall response time is 2.4 minutes for site 1 and 5.4 minutes for site 2 as site 2 required additional supplies. The longest early response time was for site 8 which is 6.3 minutes due to its location. The detailed results for all sites are highlighted in Table 5.23.

Table 5.24: Supply and demand analyisis of emergency reponse of case TBO 3 .

			Depo						
Location i	1	2	3	4	5	D sys	Di	∆ Di	%
1	4000					4,000	1,500	2,500	167
2			10000			10,000	10,000	-	-
3				400		400	400	-	-
4		1000				1,000	600	400	67
5			1000			1,000	500	500	100
6			400			400	400	-	-
7			400			400	300	100	33
8				1000		1,000	250	750	300

9	400					400	200	200	100
10				400		400	100	300	300
						19,000	14,250	4,750	
Ck sys	4400	1000	11800	1800	0	19,000			
Ck	23,800.00	12,800.00	12,800.00	7,800.00	7,800.00	65,000			
Δ Ck	19400	11800	1000	6000	7800	46,000			
%	81.51	92.19	7.81	76.92	-				

- For the demand requirements for each incident location: by analyzing the output for allocated capacity for each site (Dif) vs required demand (Di), it is seen that all demands has been positively fulfilled for all incident location considering that there is enough water to cover all the demand (Dt). As shown in Table 5.20, the ΔDi value for each location is either zero (such as locations 2 and 6) or positive such as (1, 3, 4, 5, 6, 7, 8, 9 and 10). Generally, the demand analysis are very similar to case 0 or reference case.

- Results of Capacity utilization for each depot is very similar to previous case as each Depot or emergency response center was provided with limited number of resources or trucks to be used for emergency situations. From Table 5.24, it can be observed that all dispatched resources are within available capacities in each depot. For Depot 3 and 4, it can be observed that the available capacities has been significantly utilized to response to nearby emergency situation due to their central location to other incident's location and its proximity to high LHI sites such as locations 1 and 2. It can be said that there are no shortages and allocations are made within each depot capacity as ∆Ck value is always equal or more than zero as shown in Table 5.24.

5.5.4 Model 4 (time optimization with effect of K1 constraint, TBO4):

Effect of response vehicles structure (introducing K1 type of trucks as part of each response) in the real life situation, commander vehicles (K1) are always part of the initial response to any emergency or incident location. These vehicles (K1) are equipped with basic tools required for initial emergency control of the situation till they receive the required backup. Accordingly, to simulate the real life situation the TBO4 case has been presented which is based on TBO 1 cases (reference case) with one additional constraint related to dispatching K1 resource for each incident location as part of the site demand fulfillments. The objective function is very similar to the objective function used in TBO 2 model which is based on time optimization and one additional constraint related to emergency response structure of dispatching K1 type of resources for each operation as described below:

Objective function:

$$Min\ (ERT) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} x_{ijk} \left(T_k + t_{ijk}\right) \qquad (Ob. 1)$$

Subject to:

1- Incident location demand constraint

$$\sum_{j=1}^{m} \sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \qquad (1)$$

2- Emergency resource availability constraint

$$\sum_{i=1}^{n} \mathrm{C}_k\ *\ x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (2)$$

3- Quick response vehicles “K1” dispatch:

$$\mathrm{x}_{ij1} \geq 1 \qquad \forall i \in I;\ \forall j \in J; \qquad (3)$$

4- Non-negativity constraint

x_{ijk} *are postive integr variables and* $x_{ijk} \in (0,1)$

$$\forall i \in \mathrm{I};\ \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (4)$$

The newly introduced constraint is the third constraint (3) aimed to ensure that each emergency response to each incident is including K1 type of resources as a minimum. This is to simulate a real life scenario as normally commander van/ vehicle is dispatch first to site for initial quick control and arrange for the required resources.

TBO 4 provides the results as shown in Table 5.25. The results of the mathematical model output is described as the following.

- For incident location 1, two truck of K1+ K3 type with 4400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 2, three truck of K1+K3+K4 type with a total capacity of 10,400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 4, two truck of K1+K2 type with 1400 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, two truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 2 and K2 type trucks with capacity of 1000 Gallon from depot 3.
- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 5.
- For incident location 7, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 5.

- For incident location 8, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.

Table 5.25: Output result of case TBO 4 (time based optimization case with K1).

	Depo				
Location i	1	2	3	4	5
1	K1+K3				
2			K1+K3+K4		
3				K1	
4		K1+K2			
5		K1	K2		
6					K1
7					K1
8				K1	
9	K1				
10			K1		

Table 5.26: Emergency reponse time for TBO 4 model.

Location i	1	2	3	4	5	Total	Early
1	4.4					4.4	2
2			7.4			7.4	2
3				2		2	2
4		4.1				4.1	2
5		4	3.15			7.15	3.15
6					9	9	9
7					10	10	10
8				6		6	10
9	3					3	2
10			3			3	3
				Total time =		56.05	45.15

The emergency response time for case TBO 4 can be analyzed for the initial response time of resources which is planned to arrive first to site and then the backup resources. For this case, the overall initial response time was 45.15 min, while the overall response time for all resources was 56.05 min. Generally, both response times are higher that reference cases TBO 2 (38.6 minutes) which is mainly due to the introduction of K1 which lead to change the output result and response time due to following causes:

- The model mandated dispatching K1 resources to all incident location as a minimum requirement which increases the overall response time as any incident location which might have demand of more than 400 gallons will be receiving minimum 2 type of resources to fulfill its demand. This increase significantly the overall response time from 38.6 min to 56.05 min.
- The mandate of using K1 type of resource forced the model to use all K1 type available in MIC area regardless of its location due to its limited numbers and distribution of K1

resource. In the proposed model, it is assumed that each depot will have two K1 type of resources, and there are 10 incidents occurring at the same time, accordingly, all K1 type of resources need to be dispatched to fulfil the requirements, this forced the model to use resources from depots located in the far end of industrial city such as depot 5 and result in longer response time.

Table 5.27: Supply and demand analysis of emergency response of TBO 4.

			Depo						
Location i	1	2	3	4	5	D sys	Di	∆ Di	%
1	4400					4,400	1,500	2,900	193
2			10400			10,400	10,000	400	4
3				400		400	400	-	-
4		1400				1,400	600	800	133
5		400	1000			1,400	500	900	180
6					400	400	400	-	-
7					400	400	300	100	33
8				400		400	250	150	60
9	400					400	200	200	100
10			400			400	100	300	300
						20,000	14,250	5,750	40
Ck sys	4800	1800	11800	800	800	20,000			
Ck	23,800.00	12,800.00	12,800.00	7,800.00	7,800.00	65,000			
∆ Ck	19000	11000	1000	7000	7000	45,000			
%	79.83	85.94	7.81	89.74	-				

- For the demand requirements for each incident location in TBO 4 case, can observe by analyzing the output for allocated capacity for each site (Dif) vs required demand (Di) that all demands has been positively fulfilled for all incident location considering there is enough water to cover all the demand (Dt). As shown in Table 5.23, the ∆Di value for each location is either zero (such as locations 2 and 6) or positive such as (1, 3, 4, 5, 6, 7, 8, 9 and 10). Generally the demand analysis are very similar to reference case (TBO 2).

- Results of Capacity utilization for each depot is very different than TBO 1, as each depot was providing minimum two trucks for incident locations. This help to makes sure that there are no zero utilization of depots capacity C_{kf}. This can be seen very clear in depot 5 which was not used by the model as support depot due to its location (longer response time) and availability of sufficient resources in other nearby depots. In the reference case (TBO 2), it can be observed that C_{fk} for depot 5 was 0 while in TBO 4, is 800 Gallon. Also, K1 dispatch to each incident location helps to optimize further resources utilization Globally. for case 2, it can be observed from Table 19 that all dispatched resources are within available capacities in each depot and no shortage case for all depots as capacity of each depot has been respected and allocations was within each depot capacity as ∆Ck value is always equal or more than zero as shown in Table 5.27.

5.5.5 Model 5 (time optimization with the effect of Δ capacity utilization, TBO5):

In TBO 5, the demand constraint is introduced to improve the efficiency of resource utilization by limiting the difference between the demand and supply and each dispatch operation. This constraint will force the optimization model use the nearest available capacity and dispatch it to the required location. Accordingly, a simulation for TBO 5 has been presented based on TBO 2 with the addition to capacity constraint as part of optimization process as the following:

Objective function:

$$Min\ (ERT) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} x_{ijk} \left(T_k + t_{ijk}\right) \qquad (Ob.1)$$

Subject to:

1- Incident location demand constraint

$$\sum_{j=1}^{m} \sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \qquad (1)$$

2- Emergency resource availability constraint

$$\sum_{i=1}^{n} \mathrm{C}_k * x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (2)$$

3- Resource usage constraint

$$\sum_{i=1}^{\mathrm{n}}\sum_{j=1}^{\mathrm{m}}\sum_{k=1}^{w}(\mathrm{C}_k * x_{ijk}) - \sum_{i=1}^{\mathrm{n}}\mathrm{D}_i \leq \lambda * \sum_{i=1}^{\mathrm{n}}\mathrm{D}_i \tag{3}$$

4- Non-negativity constraint t

x_{ijk} $are\ postive\ integr\ variables\ and$ $x_{ijk} \in (0,1)$

$$\forall i \in \mathrm{I};\ \forall j \in \mathrm{J};\quad \forall k \in \mathrm{K} \tag{4}$$

The newly introduced constraint (3) minimizes the overutilization of resources by making sure that the difference between the dispatch capacities for each location and location demand in not exceeding required limits or % (normally from 1 to 100%). for our case we use λ = 3

TBO 5 results are given in Table 5.28. The results of the mathematical model output is described as the following.

- For incident location 1, one truck of K3 type with 4000 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 2, two truck of K3+K4 type with total capacity of 10,000 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.

- For incident location 4, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 7, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 8, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- The obtained results are identical to TBO 2 case simulation results.

Table 5.28: Output result of TBO 5.

	Depo				
Location	1	2	3	4	5
1	K3				
2			K3+K4		
3				K1	
4		K2			
5			K2		
6		K1			
7			K1		
8				K1	
9	K1				
10			K1		

Similarly, the emergency response time for case 3 can be analyzed for initial response time and the overall response time. The overall initial response time was 45.4 min, while the overall response time for all resources was 38.45 min. These results are identical to TBO 2 case output which indicate weak or minimum effect of the capacity constraint for this setup due to existing configuration and assumptions.

Table 5.29: Emergency response time for TBO 5 model.

Location i	1	2	3	4	5	Total	Early
1	2.4					2.4	2.4
2			5.4			5.4	2.4
3				2		2	2
4		2.1				2.1	2.1
5			3.15			3.15	3.15
6		8.4				8.4	8.4
7			3			3	3
8				6		6	6
9	3					3	3
10			3			3	3
				Total time =		38.45	35.45

Table 5.30: Supply and demand analyisis of emergency reponse of TBO 5 case.

			Depo						
Location i	1	2	3	4	5	D sys	Di	Δ Di	%
1	4000					4,000	1,500	2,500	167
2			10000			10,000	10,000	-	-
3				400		400	400	-	-
4		1000				1,000	600	400	67
5			1000			1,000	500	500	100
6		400				400	400	-	-
7			400			400	300	100	33
8				400		400	250	150	60
9	400					400	200	200	100

10			400			400	100	300	300
						18,400	14,250	4,150	29
Ck sys	4400	1400	11800	800	0	18,400.00			
Ck	23,800.00	12,800.00	12,800.00	7,800.00	7,800.00	65,000.00			
∆ Ck	19400	11400	1000	7000	7800	46,600.00			
%	81.51	89.06	7.81	89.74	-	268.13		38.05	

- For the demand analysis of each incident location in TBO 5 case, can observe by analyzing the output for allocated capacity for each site (Dif) vs required demand (Di) that all demands has been positively fulfilled for all incident location considering we have enough water to cover all the demand (Dt). As shown in Table 5.30, the ∆Di for each location is either zero (such as location 2, 3 and 6) or positive such as (1, 4, 5, 6, 7, 8, 9 and 10). Generally the demand analysis are very similar to that of TBO 2.
- For capacity utilization of each depot is on the contrary different than TBO 2, as each depot was providing minimum two trucks for incident locations. This help to makes sure that there are no zero utilization of depots capacity Ckf. This is can be seen that depot 5 is not used by the model due to its further location (with longer response time) and also due to the availability of sufficient resources in other nearby depots. In the reference case (TBO 2), it can be observed that Cfk for depot 5 was 0 while in TBO 3 and TBO 4, is 800 gallons. K1 dispatch to each incident location has helped to optimize further resources utilization. Globally, for TBO 5, it can be observed from Table 5.29 that all dispatched resources are

within available capacities in each depot and no shortage case for all depots as capacity of each depot has been respected and allocations is within each depot capacity as ΔCk value is always equal or more than zero as shown in Table 5.30.

5.5.6 Model 6 (time optimization with effect of LHI effect and response vehicles structure (K1 constraint), TBO6):

LHI effect and response vehicles structure (K1 constraint):

TBO6 cases is designed to show the effect of LHI, time and response vehicles structure (K1 constraint). The objective function and constraint are similar to TBO 3 with additional of K1 constraint as the following:

Objective function:

$$Min\ (ERT) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} \frac{x_{ijk}}{RLHI_i} \left(T_k + t_{ijk}\right) \qquad (Ob.1)$$

Subject to:

1- Incident location demand constraint

$$\sum_{j=1}^{m}\sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \tag{1}$$

2- Emergency resource availability constraint

$$\sum_{i=1}^{n} \mathrm{C}_k \ * \ x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \tag{2}$$

3- Quick response vehicles “K1” dispatch:

$$\mathrm{x}_{ij1} \geq 1 \qquad \forall i \in I;\ \forall j \in J; \tag{3}$$

4- Non-negativity constraint

x_{ijk} *are postive integr variables and* $x_{ijk} \in (0,1)$

$$\forall i \in \mathrm{I};\ \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \tag{4}$$

The objective of the main formula is to minimize the overall emergency response time by utilization of location hazard index (LHI) as weighing factor by multiplication the invert of the location Hazard index (LHI) by time sum or travel time t_{ijk} and setup time T_k required for each type of resources used in the emergency response operation subject to vehicles availability and service constraint s as the following:

The constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di). The constraint (2) is aimed to make sure that the number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). This to make sure that it does not overbook the resources and assign fire trucks which does not exist or assigned resources that have already been assigned to a different incident location. The constraint (3) aimed to ensure that each emergency response to each incident is including K1 type of resources as a minimum. This is to simulate a real life scenario as normally commander van/ vehicle is dispatch first to site for initial quick control and arrange for the required resources. The constraint (4) is non negativity constraint.

TBO 6 results are shown in Table 5.31. The results of the mathematical model output is described as the following:

- For incident location 1, two truck of K1+ K3 type with 4400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 2, three truck of K1+K3+K4 type with total capacity of 10,400 Gallon of water capacity has been dispatched from Depot 3 (K3, K4) and Depot 5 (K1).
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.

- For incident location 4, two truck of K1+K2 type with 1400 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, two truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 2 and K2 type trucks with capacity of 1000 Gallon from depot 3.
- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 5.
- For incident location 7, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 8, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.

Table 5.31: Output result of TBO 6 case (Time based + LHI+ K1).

	Depo				
Location i	1	2	3	4	5
1	K1+K3				
2			K3+K4		K1
3				K1	
4		K1+K2			
5		K1	K2		
6					K1
7			K1		
8			K1		
9	K1				
10				K1	

By analyzing the output result and dispatching strategy, the optimization model has achieved its objectives as the following:

•For this case (TBO 6), the initial time accumulated for all scenarios is 38.65 minute, while the overall response time for all resources was 65.05 minutes. For the top critical sites in this scenario which has the highest LHI index (site 1 and site 2), it can be observed that early arrival time for initial resources is done within 2 and 2.4 minutes, respectively. The longest early response time was for site 8 which is 10 minutes due to its location. The detailed results for all sites are highlighted in Table 5.32.

Table 5.32: Emergency response time for TBO 6 case.

Location i	1	2	3	4	5	Total	Early
1	4.4					4.4	2
2			5.4		15	20.4	2.4
3				2		2	2
4		4.1				4.1	2.1
5		4	3.15			7.15	3.15
6					9	9	8
7			3			3	3
8			10			10	10
9	3					3	3
10				2		2	3
				Total time =		65.05	38.65

- For the demand analysis of each incident location, in TBO6 case, it can be observed by analyzing the output of allocated capacity for each site (Dif) vs required demand (Di) that all demands has been positively fulfilled for all incident location considering that there is enough water to cover all the demand (Dt). As shown in Table 5.28, the ΔDi value for each location is either zero (such as locations 2 and 6) or positive such as (1, 2, 4, 5, 6, 7, 8, 9 and 10).
- Results of capacity utilization for each depot is shown in Table 5.33. Globally, for TBO 6 case, it can be observed that all dispatched resources are within available capacities in each depot and no shortage case for all depots as capacity of each depot has been respected and allocations was within each depot capacity as ΔCk value is always equal or more than zero as shown in Table below.

Table 5.33: Supply and demand analyisis of emergency reponse of TBO 6 case.

	Depo								
Location i	*1*	*2*	*3*	*4*	*5*	*D sys*	*Di*	*∆ Di*	*%*
1	4400					4,400	1,500	2,900	193
2			10000		400	10,400	10,000	400	4
3				400		400	400	-	-
4		1400				1,400	600	800	133
5		400	1000			1,400	500	900	180
6					400	400	400	-	-
7			400			400	300	100	33
8			400			400	250	150	60
9	400					400	200	200	100
10				400		400	100	300	300
						20,000	14,250	5,750	40
Ck sys	4800	1800	11800	800	800	20,000			
Ck	23,800	12,800	12,800	7,800	7,800	65,000			
∆ Ck	19000	11000	1000	7000	7000	45,000			
%	79.83	85.94	7.81	89.74	-				

5.5.7 Model 7: time based optimization with effect of response vehicles structure (K1 constraint) and the supply optimization, TBO7):

TBO7 uses LHI, time, demand optimization and response vehicles structure (K1 constraint). To show the impact of not using LHI, the objective function is modified by removing LHI. Elements used in the objective function are similar to TBO 2 with all constraints (similar to one used in TBO 1) or similar to case 6, but without LHI. The used formulas and constraint are as the following:

Objective function:

$$Min\ (ERT) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} x_{ijk} \left(T_k + t_{ijk}\right) \qquad (Ob.1)$$

Subject to:

1- Incident location demand constraint

$$\sum_{j=1}^{m} \sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \qquad (1)$$

2- Emergency resource availability constraint

$$\sum_{i=1}^{n} \mathrm{C}_k\ *\ x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (2)$$

3- Resource usage constraint

$$\sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} (\mathrm{C}_k * x_{ijk}) - \sum_{i=1}^{\mathrm{n}} \mathrm{D}_i \leq \lambda * \sum_{i=1}^{\mathrm{n}} \mathrm{D}_i \qquad (3)$$

4- Quick response vehicles “K1” dispatch:

$$\mathrm{x}_{ij1} \geq 1 \qquad \forall i \in I;\ \forall j \in J; \qquad (4)$$

5- Non-negativity constraint

x_{ijk} $are\ postive\ integr\ variables\ and\ x_{ijk} \in (0,1)$

$$\forall i \in \mathrm{I};\ \forall j \in \mathrm{J};\quad \forall k \in \mathrm{K} \qquad (5)$$

Variables Description:

"j" is the emergency response / Firefighting center or depot, $j = \{1, 2, \ldots \ldots m\}$; where m is the number of centers

"i" is emergency incident location, $i = \{1,2, \ldots \ldots, n\}$, where n is the number locations

"k" is the resource type, $j = \{1,2, \ldots \ldots, w\}$, where w is the number resource types/classes

"T_k" is the setup time of resource k

"t_{ijk}"= travel time from emergency response center "i" to location "j " for resource type "k".

"x_{ijk}" are binary variable that will have value 1 if resources k, has been dispatched from emergency response center i to location j, other with = 0

LHI_i = Location Hazard Index for location "i"

"D_i"= is firefighting material demand for incident location i,

"R_{jk}"= is emergency resource type k located in emergency center j.

"C_k"= total hold up capacity of material volume for emergency truck type k.

"λ" = resources optimum utilization factor %. Normally range of $0 \leq \lambda \leq 100$ %.

"Ck sys" = Dispatched capacity by the model.

"ΔCk " = Difference between the total capacity and dispatched capacities.

The objective of the main formula is to minimize the overall emergency response time by utilization of location hazard index (LHI) as weighing factor by multiplication the invert of the location Hazard index (LHI) by time sum or travel time t_{ijk} and setup time T_k required for each type of resources used in the emergency response operation subject to vehicles availability and service constraint s as the following:

The constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di). The constraint (2) is aimed to make sure that number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). The constraint (3) is to minimize the overutilization of resources by making sure that the difference between the dispatch capacities for each location and location demand in not exceeding λ. For our test case we apply $\lambda = 3$. The constraint (4) aimed to ensure that each emergency response to each incident is including K1 type of resources as minimum. This is to simulate a real life scenarios as normally commander van/vehicle is dispatch first to site for initial quick control and arrange for the required resources. The constraint (5) is non negativity constraint.

TBO 7 results are shown in Table 5.34. The results of the mathematical model output is described as the following:

- For incident location 1, two truck of K1+ K3 type with 4400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 2, three truck of K1+K3+K4 type with a total capacity of 10,400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 4, two truck of K1+K2 type with 1400 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, two truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 2 and K2 type trucks with capacity of 1000 Gallon from depot 3.
- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 5.
- For incident location 7, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 5.
- For incident location 8, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.

Table 5.34 : Output result of TBO 7 case (Time based + K1+ ΔDi)

	Depo				
Location i	1	2	3	4	5
1	K1+K3				
2			K1+K3+K4		
3				K1	
4		K1+K2			
5		K1	K2		
6					K1
7					K1
8				K1	
9	K1				
10			K1		

By analyzing the output result and dispatching strategy, the following is observed:

•For TBO 7, the initial time accumulated for all scenarios is 38.65 minute, while the overall response time for all resources was 65.05 minutes. For the top critical sites in this scenario, which has the highest LHI index (site 1 and site 2), it is observed that early arrival time for initial resources is done within 2 and 2.4 minutes respectively. The longest early response time was for site 8 which is 10 minutes due to its location. The detailed results for all sites are highlighted in Table 5.35.

Table 5.35: Emergency response time for TBO 7 case.

Location i	1	2	3	4	5	Total	Early
1	4.4					4.4	2
2			7.4			7.4	2
3				2		2	2
4		4.1				4.1	2
5		4	3.15			7.15	3.15
6					9	9	9
7					10	10	10
8				6		6	10
9	3					3	2
10			3			3	3
				Total time =		56.05	45.15

- For the demand analysis in TBO 7 case, it is observed by analyzing the output of allocated capacity for each site (Dif) vs required demand (Di) that all demands has been positively fulfilled for all incident location considering that there is enough water to cover all the demand (Dt). As shown in Table 5.34, the ΔDi value for each location is either zero (such as location 3 and 6) or positive such as (1, 2, 4, 5, 6, 7, 8, 9 and 10).
- Results of capacity utilization for each depot is shown in Table 5.36. Globally for TBO 6 case, it is observed that all dispatched resources are within available capacities in each depot and no shortage case for all depots as capacity of each depot has been respected and allocations was within each depot capacity as ΔCk value is always equal or more than zero as shown in Table below.

Table 5.36: Supply and demand analyisis of emergency reponse of TBO 7 case.

	Depo								
Location i	1	2	3	4	5	D sys	Di	∆ Di	%
1	4400					4,400	1,500	2,900	193
2			10400			10,400	10,000	400	4
3				400		400	400	-	-
4		1400				1,400	600	800	133
5		400	1000			1,400	500	900	180
6					400	400	400	-	-
7					400	400	300	100	33
8				400		400	250	150	60
9	400					400	200	200	100
10			400			400	100	300	300
						20,000	14,250	5,750	40
Ck sys	4800	1800	11800	800	800	20,000			
Ck	23,800.00	12,800.00	12,800.00	7,800.00	7,800.00	65,000			
∆ Ck	19000	11000	1000	7000	7000	45,000			
%	79.83	85.94	7.81	89.74	-				

5.5.8 Model 8: time based optimization with effect LHI/ RLHI and the supply optimization, TBO8):

TBO 8 is special case of TBO 1 at which the response vehicles structure (K1 constraint) effect disabled. The used formulas and constraint are as the following:

Objective function:

$$Min\ (ERT) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} \frac{x_{ijk}}{RLHI_i} \left(T_k + t_{ijk}\right) \qquad (Ob.1)$$

Subject to:

1- Incident location demand constraint

$$\sum_{j=1}^{m} \sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \qquad (1)$$

2- Emergency resource availability constraint

$$\sum_{i=1}^{n} \mathrm{C}_k * x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (2)$$

3- Resource usage constraint

$$\sum_{i=1}^{\mathrm{n}}\sum_{j=1}^{\mathrm{m}}\sum_{k=1}^{w}(\mathrm{C}_k * x_{ijk}) - \sum_{i=1}^{\mathrm{n}} \mathrm{D}_i \leq \lambda * \sum_{i=1}^{\mathrm{n}} \mathrm{D}_i \tag{3}$$

4- Non-negativity constraint

x_{ijk} *are postive integr variables and* $x_{ijk} \in (0,1)$

$$\forall i \in \mathrm{I};\ \forall j \in \mathrm{J};\quad \forall k \in \mathrm{K} \tag{4}$$

"j" is the emergency response / Firefighting center or depot, $j = \{1, 2, \ldots \ldots m\}$; where m is the number of centers

"i" is emergency incident location, $i = \{1,2, \ldots \ldots, n\}$, where n is the number locations

"k" is the resource type, $j = \{1,2, \ldots \ldots, w\}$, where w is the number resource types/classes

"T_k" is the setup time of resource k

"t_{ijk}"= travel time from emergency response center "i" to location "j " for resource type "k".

"x_{ijk}" are binary variable that will have value 1 if resources k, has been dispatched from emergency response center i to location j, other with = 0

LHI_i = Location Hazard Index for location "i"

"$\mathrm{D_i}$"= is firefighting material demand for incident location i,

"$\mathrm{R_{jk}}$"= is emergency resource type k located in emergency center j.

“C_k”= total hold up capacity of material volume for emergency truck type k.

"λ" = resources optimum utilization factor %. Normally range of 0 ≤λ≤ 100 %.

“Ck sys” = Dispatched capacity by the model.

“ΔCk “ = Difference between the total capacity and dispatched capacities.

The objective of the main formula is to minimize the overall emergency response time by utilization of location hazard index (LHI) as weighing factor by multiplication the invert of the location Hazard index (LHI) by time sum or travel time t_{ijk} and setup time T_k required for each type of resources used in the emergency response operation subject to vehicles availability and service constraint as the following:

The constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di). The constraint (2) is aimed to make sure that the number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). The constraint (3) is to minimize the overutilization of resources by making sure that the difference between the dispatch capacities for each location and location demand in not exceeding λ. For our case, we apply λ = 3 .The fourth constraint (4) is non negativity constraint.

TBO 8 results are shown in Table 5.37. The results of the mathematical model output is described as the following

- For incident location 1, on truck of K3 type with 4000 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 2, two truck of K3+K4 type with a total capacity of 10,000 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 3, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 4, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 2.
- For incident location 5, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 6, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 7, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 3.
- For incident location 8, one truck of K2 type with 1000 Gallon of water capacity has been dispatched from Depot 4.
- For incident location 9, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 1.
- For incident location 10, one truck of K1 type with 400 Gallon of water capacity has been dispatched from Depot 4.

Table 5.37: Output result of TBO 8 case (time based+ LHI+ ΔDi).

	Depo				
Location i	1	2	3	4	5
1	K3				
2			K3+K4		
3				K1	
4		K2			
5			K2		
6			K1		
7			K1		
8				K2	
9	K1				
10				K1	

By analyzing the output result and dispatching strategy, the following is observed:

- In this case TBO 8, the initial time accumulated for all scenarios is 31.35 minute, while the overall response time for all resources was 34.35 minutes. For the top critical sites in this scenarios which has the the highest LHI index (site 1 and site 2), is observed that early arrival time for initial resources is done within 2.4 minutes for each. The longest early response time was for site 8 which is 6.3 minutes due to its location. The detailed results for all sites are highlighted in Table 5.38.

Table 5.38: Emergency response time for TBO 8 case.

Location i	1	2	3	4	5	Total	Early
1	2.4					2.4	2.4
2			5.4			5.4	2.4
3				2		2	2
4		2.1				2.1	2.1
5			3.15			3.15	3.15
6			5			5	5
7			3			3	3
8				6.3		6.3	6.3
9	3					3	3
10				2		2	2
				Total time =		34.35	31.35

- For the demand analysis of each incident location, in TBO 6 case, it is observed by analyzing the output of allocated capacity for each site (Dif) vs required demand (Di) that all demands has been positively fulfilled for all incident location considering that there is enough water to cover all the demand (Dt). As shown in Table 5.38, the ΔDi value for each location is either zero (such as location 2, 3 and 6) or positive such as (1, 4, 5, 6, 7, 8, 9 and 10).
- Results of Capacity utilization for each depot is shown in Table 5.38. Globally for TBO 8 case, it is observes that all dispatched resources are within available capacities in each depot and no shortage case for all depots as capacity of each depot has been respected and allocations was within each depot capacity as ΔCk value is always equal or more than zero as shown in Table 5.39 below.

Table 5.39: Supply and demand analyisis of emergency reponse of TBO 8 case.

	Depo								
Location i	1	2	3	4	5	D sys	Di	∆ Di	%
1	4000					4,000	1,500	2,500	167
2			10000			10,000	10,000	-	-
3				400		400	400	-	-
4		1000				1,000	600	400	67
5			1000			1,000	500	500	100
6			400			400	400	-	-
7			400			400	300	100	33
8				1000		1,000	250	750	300
9	400					400	200	200	100
10				400		400	100	300	300
						19,000	14,250	4,750	33
Ck sys	4400	1000	11800	1800	0	19,000			
Ck	23,800	12,800	12,800	7,800.00	7,800.00	65,000			
∆ Ck	19400	11800	1000	6000	7800	46,000			
%	81.51	92.19	7.81	76.92	-				

5.6 Summary of TBO Parametric Sensitivity analysis:

For the purpose of sensitivity analysis, seven sets of different combination of objectives functions and constraint are developed. This set is tested against with the same demand, supply, and incidents location to depot configuration as shown in Figure 5.2.

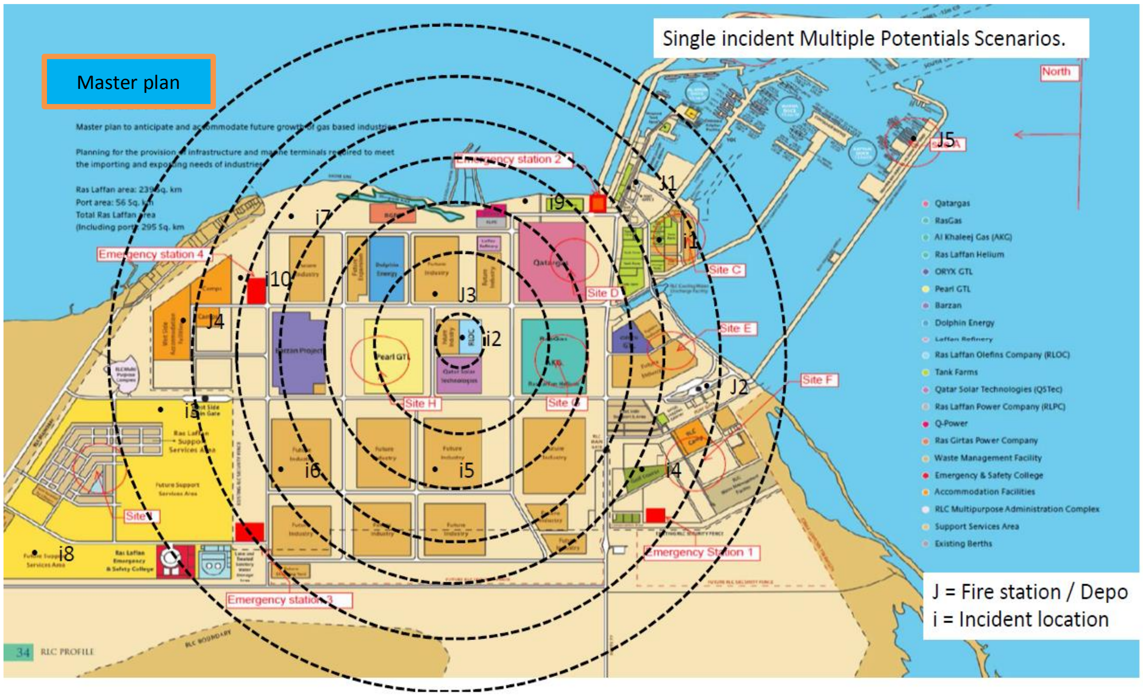


Figure 5.2: Sitemap with incident and depots location.

For comparison and performance analysis of each case, selected indicators such as total response time for the emergency response vehicles (T total), the total time required for first batch or response vehicles to reach the site (T early), the total setup time for all emergency vehicles (Ts), dispatched capacities of supply to the incident locations by the model or the system (Dsys), the difference between the supply and the demand (ΔDi), the amount of supplies dispatched by the system from all depots (Cksys), and finally the remaining or available supplies in each depot after the dispatch process (ΔCk) are considered. The summary of the selected parameters are shown in Table 5.40 for the eight cases discussed before. Furthermore, one additional reference case which has presented allocations of emergency resources (outcomes) based on manual process used today (First-come – first-serviced based on priority for highest LHI sites) is also added. This manual process outcomes are used for benchmark and comparison with other eight cases.

Table 5.40: Parametric sensitivity analysis.

Model	Main elements	TTT	T total	T early	Ts	D sys	ΔDi	Ck sys	ΔCk
TBO 1 (Time base+ LHI+K1+ΔDi) Full model	Time base+ LHI+K1+ΔDi	229.22	65.05	38.65	120.00	20,000	5,750	20,000	45,000
TBO 2 (Time base)	Time base	138.05	38.05	35.6	100	18,400	4,150	18,400	46,600
TBO 3 (Time base + LHI)	Time base+ LHI	205.02	34.35	31.35	105.00	19,000	4,750	19,000	46,000
TBO 4 (Time base +K1)	Time base+K1	176.05	56.05	45.15	120.00	20,000	5,750	20,000	45,000
TBO 5 (Time base + ΔDi)	Time base+ ΔDi	138.45	38.45	35.45	100.00	18,400	4,150	18,400	46,600
TBO 6 (Time base + LHI+K1)	Time base+ LHI+K1	229.22	65.05	38.65	120.00	20,000	5,750	20,000	45,000
TBO 7 (Time base +K1+ΔDi)	Time base+K1+ΔDi	176.05	56.05	45.15	120.00	20,000	5,750	20,000	45,000
TBO 8 (Time base + LHI+ΔDi)	Time base+ LHI+ΔDi	205.02	34.35	31.35	105.00	19,000	4,750	19,000	46,000

The outputs of the eight test cases are summarized as the following:

- **Total response time (T total):**

  The total response time is very important elements of the emergency response operation which basically reflects how efficiently the model can reduce the travel time by allocations of required resources from nearest possible location considering resource availability and other constraint used in each model. For the existing setup and configurations, comparison of the overall time output of the eight proposed cases shows that shortest the total delivery time is obtained by TBO 3 and 8 case which is 34.35 minutes, Then by TBO 2 cases of 38.05 minutes (3.7 min more), TBO 5 cases was 38.45 min (4.1 min more than lowest case), followed by TBO 3 and 7 each 56.05 min (21.7 min more than lowest case), and finally, TBO 6 and 1 each 65.05 min (30.7 min more than lowest case). Generally we can see that all the optimization cases had obtained significantly improved results by dispatching required resources with shorts overall response results comparing it with manual dispatch process. By examining the results in Table 36, TBO 3 and TBO 8 cases have achieved significantly improved results, by 55.99% less than the manual calculation case, while the less improvement achieved among all cases was for cases 5 and 6 with only 16.66 % improvements.

  - When LHI is introduced in TBO 3, the model provides improved results with reduced response time as 3.7 minutes. Similarly, the improvements in TBO 5 results from 38.45 to 34.35 (improvements of 4.1 min) after LHI is introduced (TBO 8).
  - Other constraints such as K1 (response structure) has contributed to increases the overall response time. Comparing the results of TBO 2 vs TBO 4, there is an 18 minutes increase

in the response time and difference between TBO 1 and TBO 8 is 30.7 minutes due to K1 constraint. As expected, applying K1 constraint will lead to an increase in emergency response time unless it is not mandatory by regulations.

- A comparison of TBO 2 vs TBO 5 and TBO 1 vs TBO 6 shows that there is no significant effect on resource utilization.

Table 5.41: Output analysis comparing to reference manual case.

Model	TTT	T total	∆TT	T early	∆Te	Ts	∆Ts	D sys	∆D sys	DDi	∆DDi	Ck sys	∆ Ck sys	DCk	∆DCk
TBO 1 (Basic+ LHI+K1+DDi) Full model	229.22	65.05	0.00%	38.65	0.00%	120	0.00%	20000	0.00%	5750	0.00%	20000	0.00%	45000	0.00%
TBO 2 (Basic)	138.05	38.05	-41.51%	35.6	-7.89%	100	-16.67%	18400	-8.00%	4150	-27.83%	18400	-8.00%	46600	3.56%
TBO 3 (Basic+ LHI)	205.02	34.35	-47.19%	31.35	-18.89%	105	-12.50%	19000	-5.00%	4750	-17.39%	19000	-5.00%	46000	2.22%
TBO 4 (Basic+K1)	176.05	56.05	-13.84%	45.15	16.82%	120	0.00%	20000	0.00%	5750	0.00%	20000	0.00%	45000	0.00%
TBO 5 (Basic+ DDi)	138.45	38.45	-40.89%	35.45	-8.28%	100	-16.67%	18400	-8.00%	4150	-27.83%	18400	-8.00%	46600	3.56%
TBO 6 (Basic+ LHI+K1)	229.22	65.05	0.00%	38.65	0.00%	120	0.00%	20000	0.00%	5750	0.00%	20000	0.00%	45000	0.00%
TBO 7 (Basic+K1+DDi)	176.05	56.05	-13.84%	45.15	16.82%	120	0.00%	20000	0.00%	5750	0.00%	20000	0.00%	45000	0.00%
TBO 8 (Basic+ LHI+DDi)	205.02	34.35	-47.19%	31.35	-18.89%	105	-12.50%	19000	-5.00%	4750	-17.39%	19000	-5.00%	46000	2.22%

- **Early response time (T early):**

  The early response time is a crucial element which reflecting how efficiently the model can dispatch as early as possible initial emergency response vehicles to site which can help to control as assist the emergency situations. From the outputs, it is observed that overall results are similar and following the same trend of T total with minor deviations. The of earliest initial delivery time was obtained by TBO and TBO 8 cases which is 31.35 minutes, Then followed by TBO 5 cases of 35.45 minutes (4.1 min more), TBO 2 cases was 35.6 min (4.25 min more than lowest case), followed by TBO 1 and 6 each 38.65 min (7.3 min more than lowest case), and finally, TBO 7 and 4 each 45.15 min (13.8 min more than lowest case). Generally, it is observed that response time optimization is evident and similar to the overall response time, but with some deviation due to the difference between cases related to constraint and active elements in each one. The main reason that early or initial response time will vary and change the order which is related to the size of the emergency cases and amount of demand at which bigger demand sites would require generally bigger Total response time. Accordingly, TBO 3 and TBO 8 cases have achieved significantly improved results by 51.77% less than the manual calculation case, while the less improvement achieved among all cases was for cases TBO 4 and 7 with only 30.54 % improvements.

- **Setup time (Ts)**:

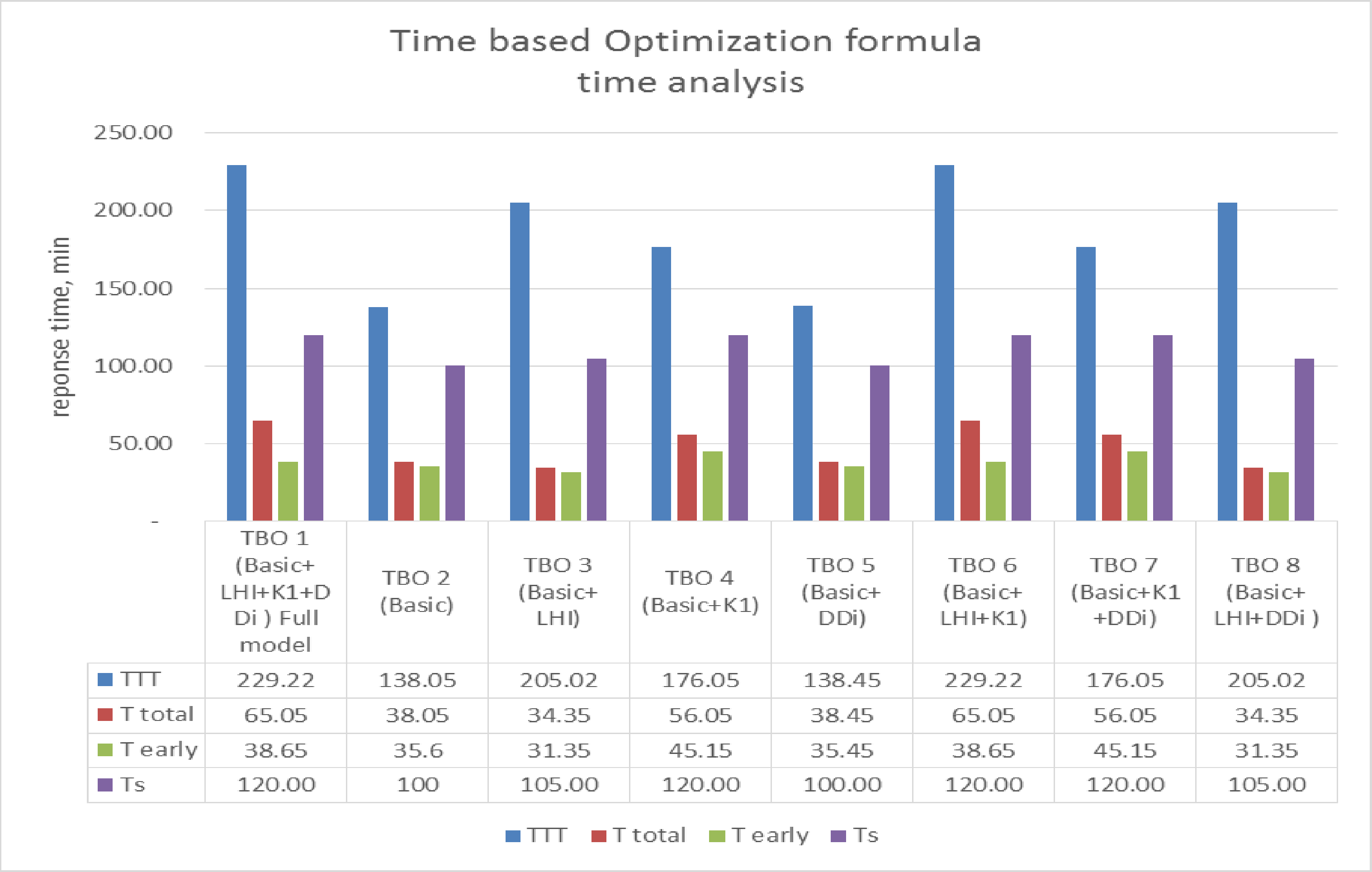
  The setup time reflects the time required to prepare different type of resources or trucks. In the optimization model, it reflects how efficient the mathematical model of allocation of suitable resources supplies to match as close as possible to demand of each site. As only one configuration is considered to test the results, the lower the value of Ts the more desirable the solution. The outputs show that TBO 2 and TBO 5 produce lowest setup time for the dispatch, followed by results of TBO 3 and TBO 8 (which has a longer setup time of 105 minutes). All other cases (TBO 1, 4, 6, and 7) has resulted in to similar output of 120 minutes. The setup time optimization is linked with capacity as bigger capacity trucks has a longer setup time. Therefore, optimization of dispatch capacity would also help in reducing the total time. The results with capacity optimization are shown in Figures 5.3, 5.4 and 5.5.

- **Dispatched capacities (D sys) and Difference between the supply and the demand (ΔDi) :**

  These two elements are linked with capacities optimization as the first one shows the amount of overall supplies has been dispatched to the emergency locations (D sys) and the second is how accurate and efficient to operation by measuring the difference between the dispatched resources and demand of the emergency sites (ΔDi) Ultimately, efficient model would results in less deviation (ΔDi) as much as possible zero or close to zero. Looking through results in Table 5.36, is observed that TBO 2 and TBO 5 provides the lowest value of capacity deviation for the dispatch of emergency resources with only 4150 capacity differences, followed by the results of TBO 3 and TBO 8 which provides the variance of 4750 capacity units more that the required quantities. All other cases (TBO 4, 6, 1, 7) have result in similar variances. Generally, it is seen that the overall trend is similar to Ts trend and behaviors, which is related to capacities and supplies optimization. The output result analysis are shown in Figures 5.3, 5.4 and 5.5.

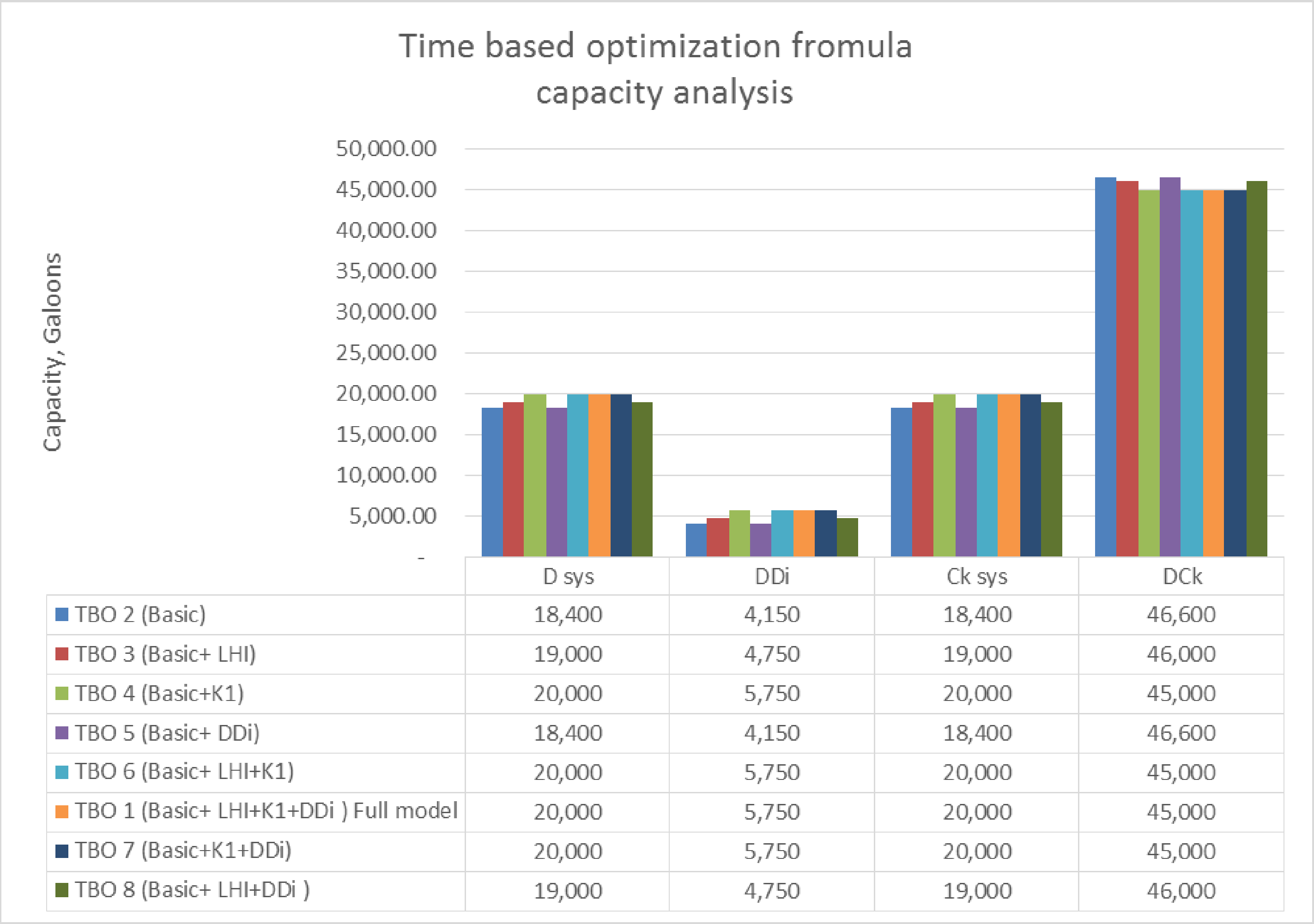
- **Amount of supplies dispatched by the system from all depots (Ck sys) and Remaining or available supplies in each depot after the dispatch process (ΔDi):**

  The Supplies optimization can be consider as consequence or result of the demand optimization as the experiment or test cases are done for fixed amount of supply at the depots and fixed demand at the emergency locations. For this case, Ck sys is equal to D sys as the supplied quantities are equals to quantities dispatched from the depots and its overall trend and behavior is similar to D sys explained earlier. The ΔCk, is function of original capacities allocated to the depots and the amount dispatched by the model to the emergency locations. The ideal case is would be distribute the supplies requirements to all depots and avoid having any dope with zero supplies. From the overall results shown in Table 36 and Figures 13 to 16, 3 groups can be considered. The first group of TBO 2 and TBO 5 results in higher ΔCk of 46,600. The second group includes TBO 3 and TBO 8, which results in ΔCk of 46,000 and finally, group 3 includes TBO 4, TBO 1 and TBO 7 which results in lowest ΔCk of 45,000.



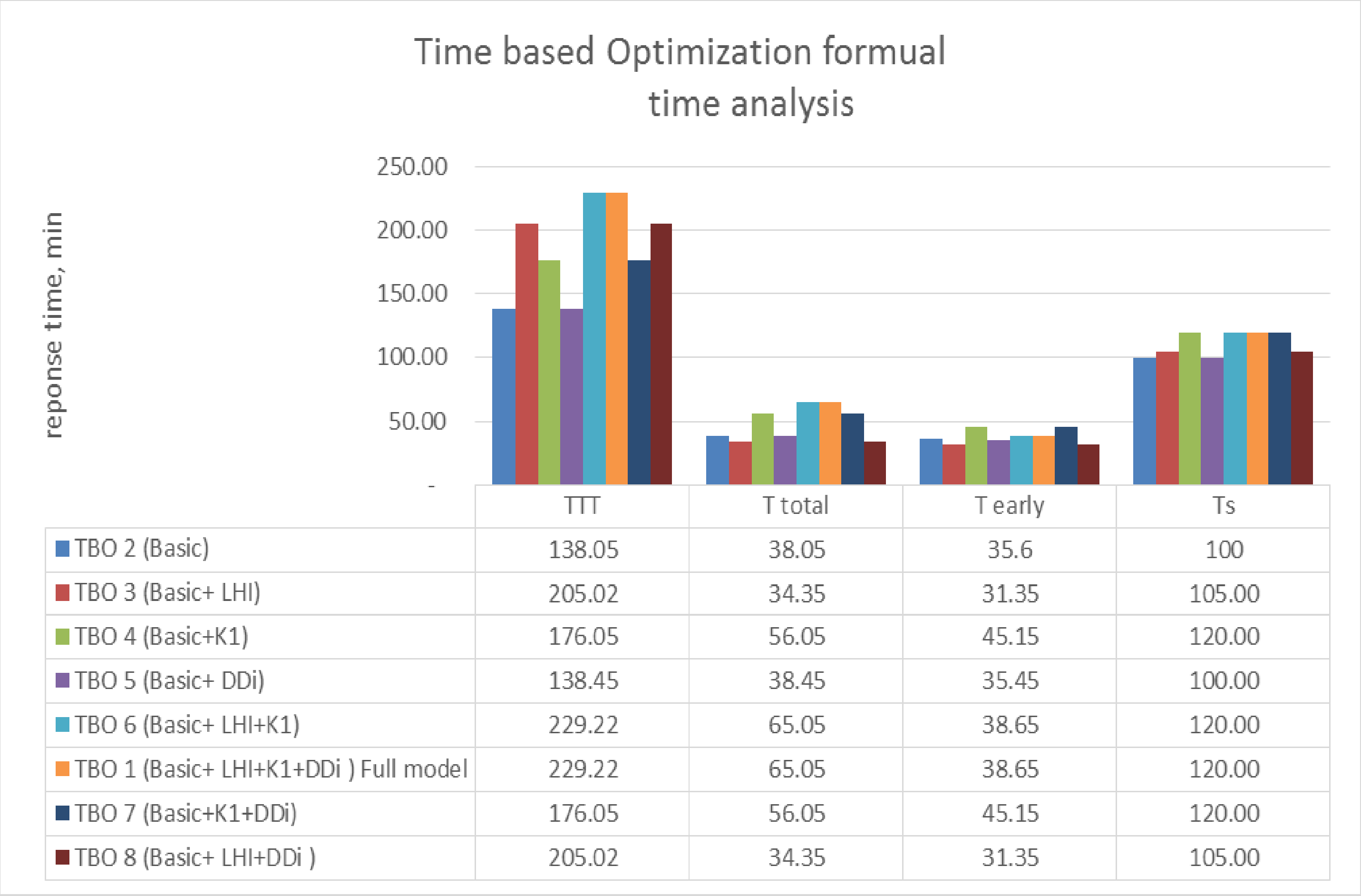
	TBO 1 (Basic+ LHI+K1+D Di) Full model	TBO 2 (Basic)	TBO 3 (Basic+ LHI)	TBO 4 (Basic+K1)	TBO 5 (Basic+ DDi)	TBO 6 (Basic+ LHI+K1)	TBO 7 (Basic+K1 +DDi)	TBO 8 (Basic+ LHI+DDi)
🟦 TTT	229.22	138.05	205.02	176.05	138.45	229.22	176.05	205.02
🟥 T total	65.05	38.05	34.35	56.05	38.45	65.05	56.05	34.35
🟩 T early	38.65	35.6	31.35	45.15	35.45	38.65	45.15	31.35
🟪 Ts	120.00	100	105.00	120.00	100.00	120.00	120.00	105.00

Figure 5.3: Time based optimization results (Time analysis)



	D sys	DDi	Ck sys	DCk
■ TBO 2 (Basic)	18,400	4,150	18,400	46,600
■ TBO 3 (Basic+ LHI)	19,000	4,750	19,000	46,000
■ TBO 4 (Basic+K1)	20,000	5,750	20,000	45,000
■ TBO 5 (Basic+ DDi)	18,400	4,150	18,400	46,600
■ TBO 6 (Basic+ LHI+K1)	20,000	5,750	20,000	45,000
■ TBO 1 (Basic+ LHI+K1+DDi) Full model	20,000	5,750	20,000	45,000
■ TBO 7 (Basic+K1+DDi)	20,000	5,750	20,000	45,000
■ TBO 8 (Basic+ LHI+DDi)	19,000	4,750	19,000	46,000

Figure 5.4: Time based optimization results (Capacity analysis).



	TTT	T total	T early	Ts
■ TBO 2 (Basic)	138.05	38.05	35.6	100
■ TBO 3 (Basic+ LHI)	205.02	34.35	31.35	105.00
■ TBO 4 (Basic+K1)	176.05	56.05	45.15	120.00
■ TBO 5 (Basic+ DDi)	138.45	38.45	35.45	100.00
■ TBO 6 (Basic+ LHI+K1)	229.22	65.05	38.65	120.00
■ TBO 1 (Basic+ LHI+K1+DDi) Full model	229.22	65.05	38.65	120.00
■ TBO 7 (Basic+K1+DDi)	176.05	56.05	45.15	120.00
■ TBO 8 (Basic+ LHI+DDi)	205.02	34.35	31.35	105.00

Figure 5.5: Time based optimization results (time analysis) .

TBO 3 case results in lowest overall response time (T total) and lowest early response time (T early) of 34.35 and 31.35 minutes, respectively. This is a significant improvement when compared with TBO 2 (which is optimization based time element only) which gave 38.05 & 35.6 minutes, respectively. This improvement is due to the introduction of LHI which is considered as weighing factor in the objective.

The introduction of K1 (response structure) has contributed to an increase in the initial response time (T early) as well as the Total response time (T total) as can be observed in TBO 4, TBO 6 and TBO 1 outputs. The increases effect is logical and expected considering existing configuration of the supply (size and capacities of the emergency response trucks) and demands (The demand for each location) setup. The application or activation this constraint/condition is subject to operation and emergency response regulations and strategy for emergency management body and if its mandatory to be applied to each dispatch operation then it need to be considered in the design and planning phases of establishing the emergency resources capacities such as selecting the proper size of the trucks, their numbers and its distribution near the expected or high potential risk areas. This constraint or condition might be helpful considering you have enough K1 resources distributed strategically in the area to be dispatched in short period to incident locations or if this constraint is applied as part of emergency response regulations which can’t be avoided. Similarly, the effect of supplies optimization constraint (ΔDi) which, is a function of demands or requirements for each emergency location and the available capacity of each truck. The Structural difference between the minimum demand and minimum truck capacity is minimum variance between demand and dispatch reprices capacities that can be achieved. This constraint is very useful and to be strongly effective, it need to be considered in the design phases to properly select and size the trucks capacities in view of forecasted demands, which will allow proper resources allocation and minimization of oversupply capacities with each dispatch operation.

5.7 Alternative Optimization cases: Optimal Resources Utilization (ORU)

The proposed Mathematical model has a very comprehensive view and coverage of important elements in the operations and management of emergency response operations. The objective function reflects the impact of LHI on the optimization function as the inverse of LHI has been used as a weight factor to reflect its importance in minimization function. Furthermore, five constraint equations have been introduced to improve the optimization as described below:

Objective function:

$$Min\ (\Delta) = \sum_{i=1}^{\mathrm{n}} \sum_{j=1}^{\mathrm{m}} \sum_{k=1}^{w} \frac{1}{\mathrm{LHI}_j}\ (\mathrm{C}_k * x_{ijk}) - \sum_{j=1}^{\mathrm{m}} \mathrm{D}_j \qquad (Ob.2)$$

$Subject\ to$:

1- Incident location demand constraint

$$\sum_{j=1}^{m} \sum_{k=1}^{w} \mathrm{C}_k * x_{ijk} \geq \mathrm{D}_i \qquad \forall i \in \mathrm{I} \qquad (1)$$

2- Emergency resource availability constraint

$$\sum_{i=1}^{n} \mathrm{C}_k * x_{ijk} \leq \mathrm{R}_{jk} \qquad \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K} \qquad (2)$$

3- Quick response vehicles "K1" dispatch:

$$\mathrm{x}_{ij1} \geq 1 \qquad \forall i \in I;\ \forall j \in J; \qquad (3)$$

4- Travel time constraint:

$$t_{ijk} \leq 15 \qquad \forall i \in I;\ \forall j \in J;\ \ \forall k \in K \qquad (5)$$

5- Non-negativity constraint

x_{ijk} *are postive integr variables and* $x_{ijk} \in (0,1)$

$\forall i \in \mathrm{I};\ \forall j \in \mathrm{J}; \quad \forall k \in \mathrm{K}$ (4)

Variables Description:

"j" is the emergency response / Firefighting center or depot, $j = \{1, 2, \dots \dots m\}$; where m is the number of centers

"i" is emergency incident location, $i = \{1,2, \dots \dots, n\}$, where n is the number locations

“k” is the resource type, $j = \{1,2, \dots \dots, w\}$, where w is the number resource types/classes

“T_k" is the setup time of resource k

“t_{ijk}”= travel time from emergency response center “i” to location “j ” for resource type “k”.

“x_{ijk}” are binary variable that will have value 1 if resources k, has been dispatched from emergency response center i to location j, other with = 0

LHI_i = Location Hazard Index for location “i”

“D_i”= is firefighting material demand for incident location i,

“R_{jk}”= is emergency resource type k located in emergency center j.

“C_k”= total hold up capacity of material volume for emergency truck type k.

The objective of the main formula is to minimize the over utilization of resources capacity by making sure that the difference between the dispatch capacities C_k for each incident location and location demand Di is minimum subject to vehicles availability and service constraint as the following:

The first constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di). The constraint (2) is aimed to make sure that number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). This to make sure that it does not overbook the resources and assign fire trucks which is not exist or has been assigned to a different incident location. The constraint (3) aimed to ensure that each emergency response to each incident is including K1 type of resources as a minimum. This is to simulate a real life scenario as normally commander van/ vehicle is dispatched first to site for initial quick control and arrange for the required resources. The constraint (4) is travel time constraint which will allow the model to accept the only vehicle which are located within acceptable travel time. The constraint (5) is non negativity constraint.

5.7.1 Optimization model output based on ORU:

When objective function and the constraints (1 to 5) for same conditions, assumptions used for the test case as per in Section 5.5, and the setup cost per trip values shown in Table 5.42 are used, the results on the response time is obtained as given in Table 5.43.

Table 5.42: Output result of ORU6 case.

ORU 6 : Basic + LHI+K1+ time (full case)					
			Depo		
Location i	1	2	3	4	5
1	K1+K2		K2		
2	K3	K1	K4		
3				K1	
4				K2	K1
5		K1			K2
6					K1
7				K1	
8			K1		
9			K1		
10	K1				

The response time can be divided two components. The first is the initial response time which measures travel time for the first units arrived to emergency site before other back resources as required and, the second is the overall response time at which all the required resources will be available on location. For the case (ORU 6), the initial time accumulated for all scenarios is 54 min, while the overall response time for all resources was 90.15 minutes.

For the top critical sites in this scenarios which has the highest LHI index (site 1 and site 2), it is observed that early arrival time for initial resources is done within 2 and 3 minutes consecutively. The overall response time is 8.3 minutes for site 1 and 15 minutes for site 2 as site two required additional supplies. The longest early response time was for site 10 which is 12 minutes due to its location and low priority (low LHI = 0.1). The detailed results for all sites are highlighted in Table 5.43.

Table 5.43 : Emergency response time for ORU 6 model.

Location i	1	2	3	4	5	Total	Early
1	4.1		4.2			8.3	2
2	6	6	3			15	3
3				2		2	2
4				10.5	6	16.5	6
5		4			7.35	11.35	4
6					9	9	9
7				3		3	3
8			10			10	10
9			3			3	3
10	12					12	12
				Total time =		90.15	54

- For the demand analysis of each incident location used in case ORU 6, it is observed by analyzing the output of allocated capacity for each site (Dif) vs required demand (Di) that all demand have been positively fulfilled for all incident location considering that there is enough water to cover all the demand (Dt). As shown in Table 5.42, the ΔDi value for each location is either zero (such as location 3 and 6) or positive such as (1, 2, 4, 5, 6, 7, 8, 9 and10). Generally, the demand analysis are very close to case 3 and identical to case 4 at which all the demand has been fulfilled positively.
- Results of Capacity utilization for each depot is acceptable. Globally, it is observed that all dispatched resources are within available capacities in each depot and no shortage case for all depots as capacity of each depot has been respected and allocations was within each depot capacity as ΔCk value is always equal or more than zero as shown in Table 5.44

Table 5.44 : Supply and demand analyisis of emergency reponse of case 6.

			Depo						
Location i	1	2	3	4	5	D sys	Di	Δ Di	%
1	1400		1000			2,400	1,500	900	60
2	4000	400	6000			10,400	10,000	400	4
3				400		400	400	-	-
4				1000	400	1,400	600	800	133
5		400			1000	1,400	500	900	180
6					400	400	400	-	-
7				400		400	300	100	33
8			400			400	250	150	60
9			400			400	200	200	100
10	400					400	100	300	300
						18,000	14,250	3,750	26
Ck sys	5800	800	7800	1800	1800	18,000			
Ck	23,800	12,800	12,800	7,800	7,800	65,000			
Δ Ck	18000	12000	5000	6000	6000	47,000			
%	75.63	93.75	39.06	76.92	-				

5.8 Parametric Sensitivity analysis for ORU model:

For the sensitivity analysis, parameter that might have direct impact on emergency response time such as the LHI, resources dispatch structure (i.e., sending K1 type of trucks with each response), and capacity utilization are considered. The basic model developed here is the ORU 1which will be used as the reference case for comparison of the overall emergency response time as the following. The used objective function (Ob.2) and constrain are explained in 5.7 :

5.8.1 ORU 1 (resources based model): *Optimal Resources Utilization without LHI and other constraint:*

The basic case's Formula is optimization based on demand basic fulfillment of the demand of the emergency locations the objective of the basic formula is to minimize the overall difference between supply and demand to the emergency or incident locations. It aims to preserve the valuable emergency resources so they can be used only when it's required. The formula explored all different combinations of available resources capacities and try to match with the demand of every incident location with a minimum difference. Emergency response time then will be calculated based on the travel time between the selected resource and the incident location as the following:

The first Constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di).

The second constraint (2) is aimed to make sure that the number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). This to make sure that it does not overbook the resources and assign fire trucks which does not exist or assigned resources that have already been assigned to a different incident location.

The third constraint (3) is no negative constraint which is used to makes sure that value of trucks capacity (Ck), LHI, and D (demand) are positive figures. The negative Figure s are not acceptable as such numbers might cause wrong results and outputs of the formula. The results of ORU 1 are shown in Table 5.45.

Table 5.45: Output results of the optimization case ORU 1.

ORU 1 : Basic					
			Depo		
Location i	1	2	3	4	5
1		K2			K2
2	K4	K3			
3	K1				
4		K1+K1			
5				K1+K1	
6					K1
7			K1		
8					K1
9			K1		
10	K1				

5.8.2 ORU 2 *(Effect of LHI on the emergency response time optimization) :*

The LHI is very important element which has been introduced to the emergency response formula to improve the emergency resources optimization by providing priorities to the location with high LHI. To examine that, we introduce ORU 2 which is basically similar to ORU 1, but with the effect of LHI.

The objective of the main formula is to minimize the overall difference between the demand and allocated emergency resources enhanced by utilization of location hazard index (LHI) as weighing factor by multiplication the invert of the location Hazard index (LHI) by difference between the allocated resources capacities and demand for each emergency response operation subject to vehicles availability and service constraint as the following:

The first Constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di).

The second constraint (2) is aimed to make sure that the number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). This to make sure that it does not overbook the resources and assign fire trucks which does not exist or assigned resources that have already been assigned to a different incident location.

The third constraint (3) is no negative constraint which is used to makes sure that value of trucks capacity (Ck), LHI, and D (demand) are positive figures. The negative Figure s are not acceptable as such numbers might cause wrong results and outputs of the formula. The results of ORU 2 are shown in Table 5.46.

Table 5.46 : Output result of ORU 2 (Basic case with LHI).

ORU 2 : Basic + LHI					
	Depo				
Location i	1	2	3	4	5
1		K2			K2
2	K3				K4
3				K1	
4					K1+K1
5			K1+K1		
6	K1				
7		K1			
8	K1				
9				K1	
10		K1			

5.8.3 ORU 3: Effect of response vehicles structure (introducing K1 type of trucks as part of each response):

In the real life situation, commander vehicles (K1) are always part of the initial response to any emergency or incident location. These vehicles (K1) are equipped with basic tools required for initial emergency control of the situation till they receive the required backup. Accordingly, to simulate the real life situation the ORU 3 case has been presented which is based on ORU 1 cases (reference case) with one additional constraint related to dispatching K1 resource for each incident location as part of the site demand fulfillment. The objective function is very similar to the objective function used in ORU 1 model which is based on resources capacity optimizations and one additional constraint related to emergency response structure of dispatching K1 type of resources for each operation. The newly introduced constraint (3) ensures that each emergency response to each incident is including K1 type of resources as minimum. This is to simulate a real life scenario as normally commander van/ vehicle is dispatched first to site for initial quick control and arrange for the required resources. The results of ORU 3 are shown in Table 5.47.

Table 5.47: Output result of case ORU 3 (Basic case with K1).

ORU 3 : Basic + K1					
			Depo		
Location i	1	2	3	4	5
1	K2+K2		K1		
2	K4	K3		K1	
3	K1				
4					K1+K2
5			K1	K2	
6	K1				
7					K1
8		K1			
9		K1			
10				K1	

5.8.4 ORU 4 (Effect of Time constraint on Basic case):

Furthermore in ORU 4 model, time constraint is introduced to improve the efficiency of resource optimization by limiting the maximum travel time for the selected emergency resources from the depot to incident location by 15 min to avoid late response to the emergency situation This constraint will force the optimization model use the nearest available capacity and dispatch it to required location. Accordingly, a simulation for ORU 4 has been presented based on ORU 1 with addition to time constraint as part of optimization process. The newly introduced constraint is the fifth constraint (5) aimed to minimize the delay in the emergency response by limiting the choice within available resources which can reach the emergency situation in less than 15 minutes. The 15 min constraint has been selected for this model and can be changed based on regulations, requirements and conditions of each emergency response organization. The results of ORU 4 are shown in Table 5.48.

Table 5.48: Output result of ORU 4 .

ORU 4 : Basic + time					
			Depo		
Location i	1	2	3	4	5
1	K2				K2
2	K4	K3			
3				K1	
4				K1	K1
5		K1	K1		
6					K1
7	K1				
8			K1		
9	K1				
10		K1			

5.8.5: ORU 5: time based optimization with LHI effect and response vehicles structure (K1 constraint):

ORU5 cases is designed to show the effect of important elements directly affecting the emergency response process such as LHI, time and response vehicles structure (K1 constraint). These elements even though each was incorporated in previous cases but in ORU 5 case, the combined effect K1 constraint is examined. The objective of the main formula is to minimize the overall difference between demand and allocated resources capacity by utilization of location hazard index (LHI) as weighing factor by multiplication the invert of the location hazard index (LHI) subject to vehicles availability and service constraint as the following:

The constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di). The constraint (2) is aimed to make sure that the number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). This to make sure that it does not overbook the resources and assign fire trucks which does not exist or assigned resources that have already been assigned to a different incident location. The constraint (3) aimed to ensure that each emergency response to each incident is including K1 type of resources as a minimum. This is to simulate a real life scenario as normally commander van/ vehicle is dispatched first to site for initial quick control and arrange for the required resources. The constraint (4) control the selection of available resources which can reach the incident location in any time equal or less than 15 min. The constraint (5) is non negativity constraint. The results of ORU 5 are shown in Table 5.49.

Table 5.49: Output result of ORU 5 case (Basic + LHI+ K1).

ORU 5 : Basic +LHI+ K1					
	Depo				
Location i	1	2	3	4	5
1	K2+K2		K1		
2	K3			K1	K4
3	K1				
4			K2		K1
5		K1		K2	
6	K1				
7		K1			
8					K1
9			K1		
10				K1	

5.8.6 ORU 6: time based optimization with LHI effect response vehicles structure (K1 constraint) and the time optimization (Full case):

The proposed ORU 6 case has a very comprehensive view and coverage of important elements in the operations and managements of emergency response operations. The objective function reflects the impact of LHI on the optimization function as the inverse of LHI has been used as a weight factor to reflect its importance in minimization function. Furthermore, five constraint equations have been introduced to improve the optimization. The objective of the main formula is to minimize the overall difference between demand and allocated resources capacity by utilization of location hazard index (LHI) as weighing factor then refined by other constraints as the following:

The constraint (1) is to ensure that each incident location is receiving sufficient firefighting suppliers equal or more than its demand. This can be achieved by assigning fire trucks with capacity (Ck) equal or more than the required demand for each incident location (Di). The constraint (2) is aimed to make sure that the number of allocated resources for each incident location (i) and from each emergency center/ depot (j), will not exceed the total available resources available in each center (j). This to make sure that it does not overbook the resources and assign fire trucks which does not exist or assigned resources that have already been assigned to a different incident location. The constraint (3) aimed to ensure that each emergency response to each incident is including K1 type of resources as a minimum. This is to simulate a real life scenario as normally commander van/ vehicle is dispatched first to site for initial quick control and arrange for the required resources. The constraint (4) is the time constraint which control the selection of available resources which can reach the incident location at any time equal or less than 15 min. The constraint (5) is the non negativity constraint. The results of the simulation are shown in Table 5.50.

Table 5.50: Output result of ORU 6 case.

ORU 6 : Basic + LHI+K1+ time (full case)					
	Depo				
Location i	1	2	3	4	5
1	K1+K2		K2		
2	K3	K1	K4		
3				K1	
4				K2	K1
5		K1			K2
6					K1
7				K1	
8			K1		
9			K1		
10	K1				

5.8.7 ORU 7: Resources optimization with effect of response vehicles structure (K1 constraint) and time constraint but without LHI (ORU 6 without LHI effect):

ORU7 case is designed to show the deeper effect of important elements directly effecting the emergency response process such as LHI, time, demand optimization and response vehicles structure (K1 constraint). In this case, to show the effect without LHI, objective function is modified. The objective function is similar to ORU 1 and the full constraints (similar to one used in ORU 6) but without the effect of LHI. The results of ORU 7 are shown in Table 5.51.

Table 5.51: Output result of ORU 7 case (Basic + K1+ ∆Di).

ORU 7 : Basic +K1+ time					
			Depo		
Location i	1	2	3	4	5
1	K2+K2	K1			
2	K4	K1+K3			
3			K1		
4					K1+K2
5				K1+K2	
6					K1
7			K1		
8				K1	
9	K1				
10	K1				

5.8.8 ORU 8: capacity based optimization with effect of LHI and The supply optimization:

ORU 8 is special case of ORU 6 in which K1 constraint is removed. The results of ORU 8 are shown in Table 5.52.

Table 5.52: Output result of ORU 8 case (Basic + LHI+ time).

ORU 8 : Basic +LHI+ time					
			Depo		
Location i	1	2	3	4	5
1	K2				K2
2	K3			K4	
3				K1	
4		K1			K1
5				K1	K1
6			K1		
7	K1				
8			K1		
9	K1				
10		K1			

5.9 **Summary of Parametric ORU Sensitivity analysis:**

Eight models were considered for parametric analysis. The summary of results are given in Table 5.53.

The behavior of eight test cases can be summarized and presented as the following:

- **Total response time (T total):** The total response time is very important elements of the emergency response operation which basically reflects how efficiently the model can reduce the travel time by allocations of required resources from nearest possible location considering resource availability and other constraint used in each model. For the existing setup and configurations, it is observed that the shortest total delivery time is obtained by OUR 8 case, which is 77.6 minutes, followed by OUR 6 with 90.15 min (12.7 min less than ORU 8), by ORU 4 and ORU 7 92.5 minutes (14.9 min more), OUR 1 with 107.4 min (29.8 min more than lowest case), ORU 3 with 113.5 min (35.9 min more than lowest

Table 5.53: Parametric Sensitivity analysis.

Model	TTT	T total	T early	Ts	D sys	ΔDi	Ck sys	ΔCk
ORU 1 (Resource Optimization)	16,000	107.4	68	105	16,000	1,750	16,000	49,000
ORU 2 (Resource Optimization + LHI)	11,147	122.2	80.2	105	16,000	1,750	16,000	49,000
ORU 3 (Resource Optimization +K1)	18,000	113.5	80.1	125	18,000	3,750	18,000	47,000
ORU 4 (Resource Optimization + time)	16,000	92.3	60.3	105	16,000	1,750	16,000	49,000
ORU 5 (Resource Optimization + LHI+K1)	12,597	129.25	83.1	125	18,000	3,750	18,000	47,000
ORU 6 (Resource Optimization + LHI+K1+ time)	12,597	90.15	54	125	18,000	3,750	18,000	47,000
ORU 7 (Resource Optimization + K1+ time)	18,000	92.5	61.00	125	18,000	3,750	18,000	47,000
ORU 8 (Resource Optimization + LHI+ time)	11,147	77.6	54.10	105.	16,000	1,750	16,000	49,000

case), and finally, ORU 2 and ORU 5 with 122.2 and 129.25 min, respectively (44.6 and 51.56 min more than lowest case).

- It is observed ORU 1 results are pure resource based optimization without any priorities as all site has been treated equally and supported by closest available resources based on travel time only. When LHI is introduced in ORU 2, the model provides different results and increase the response time with 2.5 minutes. On the other hand, ORU 6 reduces time from 107.4 to 90.15 (improvements of 17.25 min).
- Other constraints such as K1 (response structure) has contributed to increases the overall response time. For ORU 1 vs ORU 3 which has been increased by 6.1 minutes and difference between ORU 6 and ORU 8 of 12.55 minutes due to K1 constraint only. As expected, with K1 constraint there would be an increase in emergency response time unless it is not mandatory.
- The time optimization constraint is important elements of the optimization process. Comparing results of ORU 1 vs ORU 4, the response time is reduced from 107.4 to 93.3 min. Also between ORU 6 vs ORU 5, the overall emergency response time is been reduced from 129.25 to 90.15 min (reduced by 39.1 min).

- **Early response time (T early)** : From the outputs, it can be observed that overall results are similar and following the same trend of T total with minor deviations. The earliest initial delivery time is obtained by ORU 6 and ORU 8 cases is 54 and 54.1 minutes, followed by ORU 4 with 60.3 minutes (6.3 min more), ORU 7 with 61 min (7 min more than lowest case), ORU 1 with 68 min (14 min more than lowest case), and finally, with ORU 2 and ORU 3 each 80.2/80.1 min (26.2 min more than lowest case).

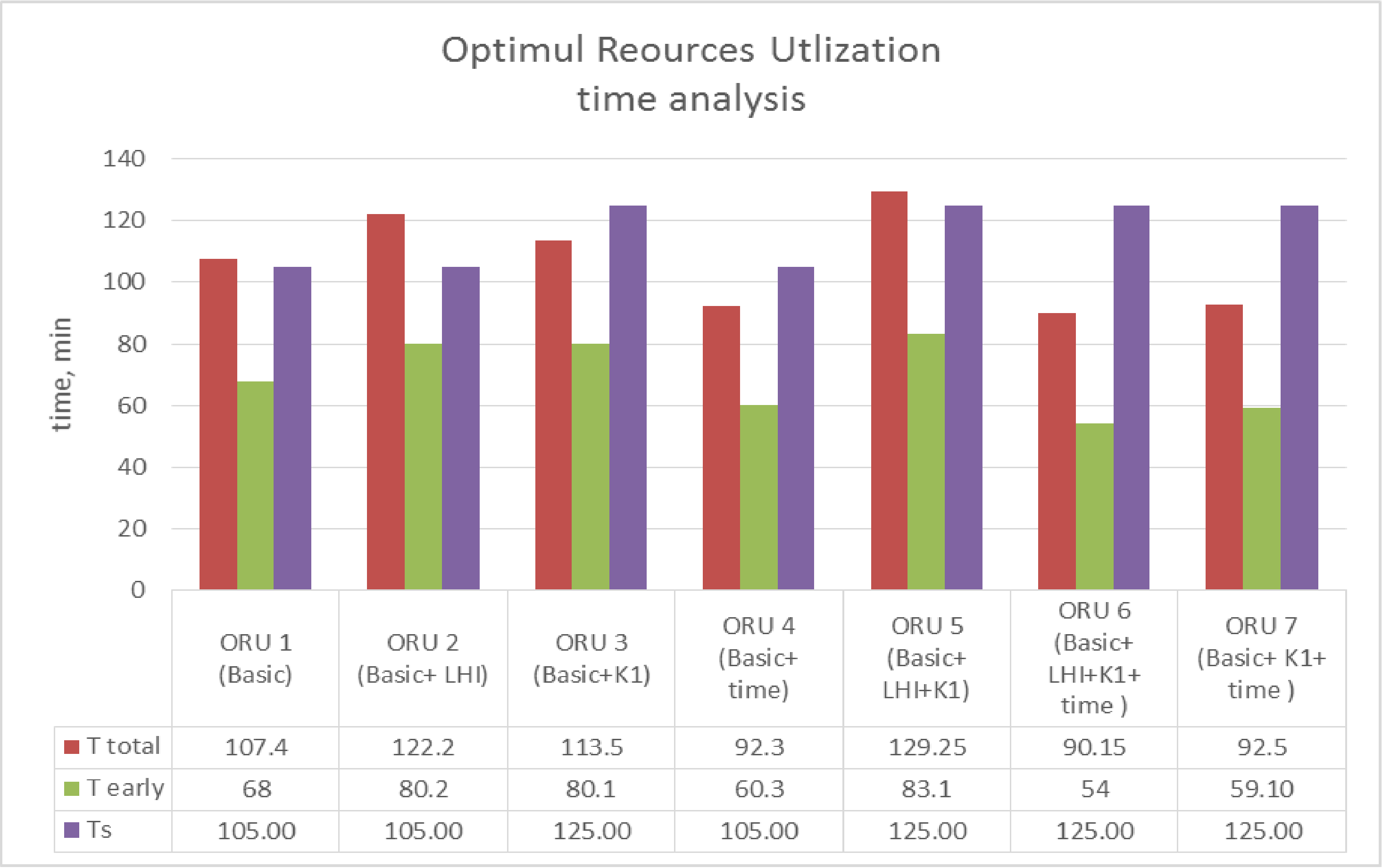
- **Dispatched capacities (D sys) and Difference between the supply and the demand (ΔDi)** From Table 5.16, it is observed that ORU 1, ORU 2, ORU 4 and ORU 8 provide the lowest capacity deviations for the dispatch of emergency resources with only 1750 capacity units difference, followed by the results of ORU 3, ORU 5, ORU 6 and ORU 7 which obtained the variance of 3750 capacity units more than the required quantities. Generally, it is seen that the overall trend is similar to Ts trend and behaviors, which is related to capacities and supplies optimization. The output result analysis are shown in Figure s 5.12, 5.13 and 5.14.

- **Amount of supplies dispatched by the system from all depots (Ck sys) and Remaining or available supplies in each depot after the dispatch process (ΔCk)**: it is assumed that Ck sys is equal to D sys as the supplied quantities are equal to the quantities dispatched from the depots and its overall trend and behavior is similar to D sys as explained earlier. ΔCk is the function of original capacities allocated to the depots and the amount dispatched by the model to the emergency locations. The ideal case would be to distribute the resource requirements to all depots and avoid having any depot with no supplies. For the overall results shown in Table 5.16 and Figures 5.6, 5.7 and 5.8, it can be concluded that all cases have good resource allocations. They can be divided into two groups. The first group of

ORU 1, ORU 2, ORU 4 and ORU 8, which results in ΔCk of 49,000. The second group includes OUR 3, OUR 5, OUR 6 and OUR7 which result in ΔCk of 47,000.

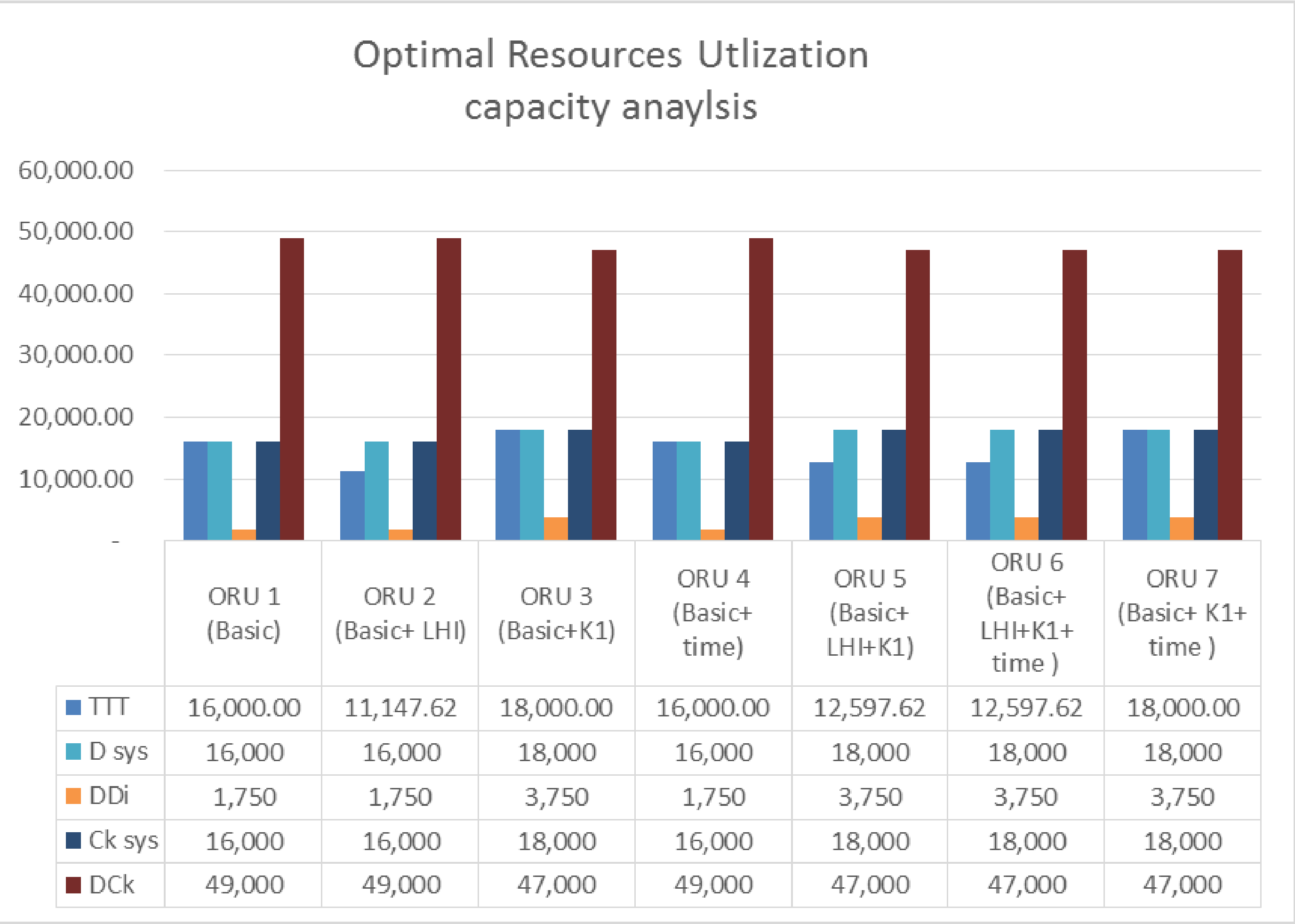
Generally, ORU 8 resulted in lowest overall response time (T total) and low early response time (T early) of 77.6 and 54.1 minutes, respectively, which is considered as an improvement when compared with ORU 1. This improvement is due to the combined effect of different parameters such as LHI, time and K1 constraint to refine the final selection and allocations of resources.

The introduction of K1 (response structure) has contributed to an increase in the initial response time (T early) as well as the total response time (T total) as given in ORU 3 output comparing it to the ORU 1. The increased effect is logical and expected considering existing configuration of the supply (size and capacities of the emergency response trucks) and demand in each location. Similarly, the effect of travel time constraint (t_{ijk}) limits the selection process. It should be noted that 15 minutes is the maximum time set up for emergency response. This type of constraint is very useful if they are considered during the design phase to properly select the resources capacity and depots locations.



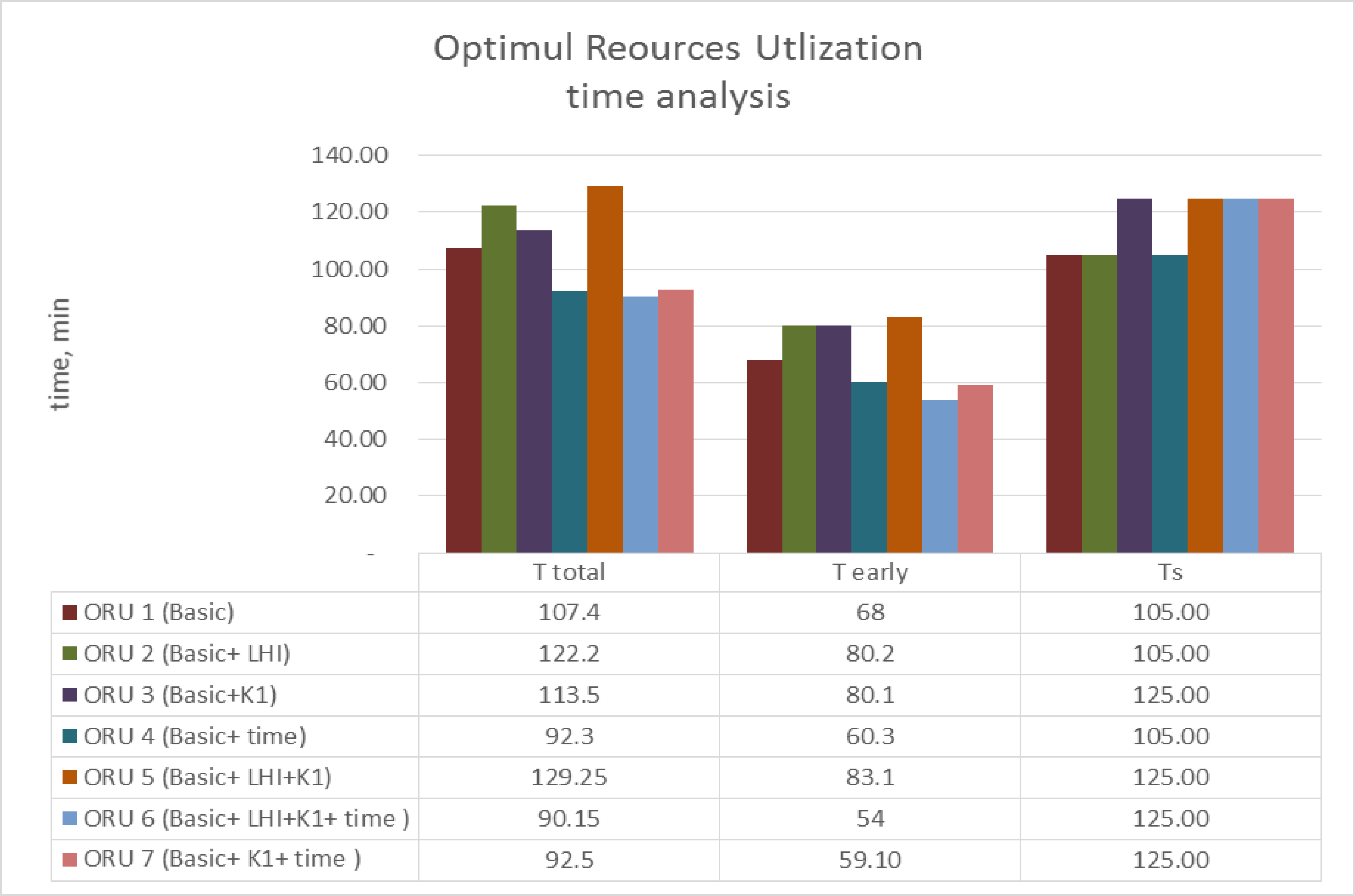
	ORU 1 (Basic)	ORU 2 (Basic+ LHI)	ORU 3 (Basic+K1)	ORU 4 (Basic+ time)	ORU 5 (Basic+ LHI+K1)	ORU 6 (Basic+ LHI+K1+ time)	ORU 7 (Basic+ K1+ time)
🟥 T total	107.4	122.2	113.5	92.3	129.25	90.15	92.5
🟩 T early	68	80.2	80.1	60.3	83.1	54	59.10
🟪 Ts	105.00	105.00	125.00	105.00	125.00	125.00	125.00

Figure 5.6 : Resources based optimization results (Time analysis) .



	ORU 1 (Basic)	ORU 2 (Basic+ LHI)	ORU 3 (Basic+K1)	ORU 4 (Basic+ time)	ORU 5 (Basic+ LHI+K1)	ORU 6 (Basic+ LHI+K1+ time)	ORU 7 (Basic+ K1+ time)
TTT	16,000.00	11,147.62	18,000.00	16,000.00	12,597.62	12,597.62	18,000.00
D sys	16,000	16,000	18,000	16,000	18,000	18,000	18,000
DDi	1,750	1,750	3,750	1,750	3,750	3,750	3,750
Ck sys	16,000	16,000	18,000	16,000	18,000	18,000	18,000
DCk	49,000	49,000	47,000	49,000	47,000	47,000	47,000

Figure 5.7 : Resources based optimization results (Capacity analysis) .



	T total	T early	Ts
ORU 1 (Basic)	107.4	68	105.00
ORU 2 (Basic+ LHI)	122.2	80.2	105.00
ORU 3 (Basic+K1)	113.5	80.1	125.00
ORU 4 (Basic+ time)	92.3	60.3	105.00
ORU 5 (Basic+ LHI+K1)	129.25	83.1	125.00
ORU 6 (Basic+ LHI+K1+ time)	90.15	54	125.00
ORU 7 (Basic+ K1+ time)	92.5	59.10	125.00

Figure 5.8: Resources based optimization results (time analysis)

5.10 Summary of Numerical Study

In this chapter both Time based optimization (TBO) and optimal resource utilizations (ORU) are presented. The following is the summary of the results obtained.

TBO Model: The TBO 3 case result in lowest overall response time (T total) and lowest early response time (T early) of 34.35 and 31.35 minutes respectively which is considered as significant improvement when compared with TBO 2 model with time optimization only. This improvement is due to introduction of LHI in the formulation.

The introduction of K1 (response structure) has contributed to an increase in the initial response time (T early) as well as the Total response time (T total) as shown in the results for TBO 4, TBO 6 and TBO 1. The activation of this constraint/condition is subject to the operation and emergency response regulations and strategy for emergency management body. If this constraint refers to mandatory regulations, having more of K1 resources might be a better strategy for the industrial city.

The effect of supplies optimization constraint (ΔDi) is also important because the attempt would be to minimize the waste of resources at the end of the response. This type of consideration should be done during the design phases to properly select and size the resource capacities.

ORU 8 case resulted in lowest overall response time (T total) and low early response time (T early)This is due to the combined effect of different parameters such as LHI, time and K1 constraint to refine the final selection and allocations of resources.

The use of K1 (response structure) contributes to the total response time as shown in ORU 3. However, it might be a mandatory requirement to have these vehicles in order to assess the incident situation first. Therefore, planning for the use of such resources can help in speeding up the response time in the industrial city.

It is also observed that the maximum response time should be limited. Here 15 minutes was considered. If there are more restrictions, the resource allocations might have to be changed as the routes are generally fixed in the industrial city. This can also help the planners to identify resources capacity and depot location in such a way that the demand is fulfilled within the planned time.

CHAPTER 6: CONCLUSIONS AND RECOMMENDATIONS

Emergency management in the industrial city is important and it should consider the criticality of the hazard in a particular location inside the industrial city based on the chemicals being handled and geographical and meteorological setting. It should also consider the response time and the resources available in order to provide an efficient and effective response management system.

In this study, an index-based emergency response management system framework (IERMSF) is proposed. The framework provides the opportunity to develop an integrated decision support in order to respond to an emergency incident in an area within the industrial city. The framework is implemented through several modules but essentially, it contains the two main parts: (1) development an index for hazard for a particular location, and (2) optimization of response time and resource allocations.

For the development of hazard index for a location, where an incident has occurred or has a potential to occur, is considered based on the chemical, geographical, demographic, and meteorological characteristics. Geographical context is important here as the incident site may not only cause problem in the incident location but also on the cluster of facilities around it. Likewise, the cluster of industries may be impacted more due to the resultant impact of the incidence in a location. Also, when there are people around the facility, the urgency to evacuate the people from that area becomes more important. Therefore, characterization of the incidence through the local hazard and global hazard index will help the decision makers on the requirements of resources and the assessment of response time. Therefore, as mentioned earlier, the development of this index for industrial city context is an important contribution mentioned in this thesis.

In this thesis, different response policies are considered through the case studies. These policies either relax or constrain the objective functions based on which the resource allocations and response time would change. It is also shown that when the hazard index is not considered, the resources requirements might be underestimated and the real impact of the incidence may not be contained. This relaxation of the index would mean that all the location where incidence occurs are treated in the same way, and therefore, at some places, there might allocated resource surplus (with a redundancy), while in the other place, there might be a difficulty in terms of containing the impact of incidence due to higher severity of the incidence.

For the time based optimization model, the TBO3 case results in the lowest overall response time (T total) and lowest early response time (T early) of 34.35 and 31.35 minutes, respectively. This is a significant improvement over TBO2 case (which is optimization based time element only) that gives 38.05 (T total) and 35.6 (T early) minutes, respectively. This improvement is due to the introduction of LHI which can be considered as the weighting factor which enhances the optimization process to focus on critical locations with high LHI as priority compared with other emergency locations with less LHI. The requirement of K1 (resource) contributes to an increase in the response times (T early, T total) as can be observed from the outputs of TBO 4, TBO 6 and TBO 1. The increased effect is logical and expected considering existing configuration of the supply (size and capacities of the emergency response trucks) and demands (The demand for each location) setup. This constraint or condition might be helpful if there are enough K1 resources distributed strategically in the industrial city so that they can be dispatched in a short period of time. Similarly, the model also considers the matching of the demand with the supply and to minimize the losses (or the level of extra resources) dispatched to the incident location. It should be noted that the model considers that there should be no deficit in supply, even if that means sending extra resources. Therefore, the attempt should be to send the resources that can have minimum losses.

For optimal resources utilization, the ORU 8 case resulted in the lowest overall response time (T total) and low early response time (T early) of 77.6 and 54.1 minutes, respectively. This is an improvement compared to ORU 1 case (which is optimization based resources capacity allocation only) which gave 107.4 and 68 minutes, respectively. This improvement is due to the combined effect of different parameters such as LHI, time and K1 constraint to refine the final selection and allocations of resources.

The analysis with ORU model also shows that the requirement of K1 type of resource contributes to an increased response time (T early and T total). This is the same result obtained with the time based optimization model.

6.1 Implications for the implementation of thesis results

The proposed IERMS framework represents a useful tool to support decision making related to emergency response and resource allocation before, during and after the emergency or disaster situation. The framework can be used as a planning tool for assessing the suitability and adequacy of emergency response resources in a given industrial city. The model can help to validate or support the development of new requirements of the resources in terms of their numbers, distribution, and depots location to respond to expected emergency situations. The model also provides the overview of response time based on the current and future resource location and resource requirements in order to meet the demand for emergency management. It should be noted that although the model has used location and clusters around it for the evaluation of the location hazard index, every cluster in a location would have a similar probability for the occurrence of incidence.

The concept of IERMS can also be applied for different types of emergency other than industrial fires or disasters. It can be applied to urban incidence cases by using the principle of LHI for specific locations in the city. This can, therefore, help in establishing the requisite number of response depots and the resources in each of the locations.

As the IERMS framework is developed by considering the industrial areas with chemical processing installations, it can be implemented in other similar industrial areas as well. The model is therefore portable. In any industrial area, the nature of chemical can change but the characteristics of the hazard index and the decision making generally remains the same.

In emergency situations, the cost may not surface as the primary factor as the main concern would be to contain the impact of incidence and minimize the time to recover the asset (facility) for full functioning. Any delay in asset functioning as a result of incidence can have a significant impact of the economy, especially in Qatar, where a large percentage of industries are based on oil and gas and they are mostly located in the industrial cities. Therefore, it can be argued that cost optimization for resources is not the main concern in these situations. This is the status-quo based on the interview of the HSE officials. Therefore, the does not explicitly consider cost optimization in the framework. However, it should be noted that as a result of developing optimality conditions for response time and the resource optimization, the model implicitly provides a more useful direction on the effective utilization of resources, which essentially means that cost for resources are optimized through the proposed model. Such an optimality is essentially the main goal of decision makers without compromising emergency response capabilities.

There the model initiates the need for examining the current resource requirements, their location around the industrial cities for minimum response time. This will help in fully utilizing the required capacities in order to mitigate the impact. It should also be noted that model has some static characteristics, like the location of the incidence, cluster of industries around the location, type of chemicals being handled, the processes in the facility and the number of people engaged in the operation of the facility. However, it also has dynamic characteristics like wind velocity and wind direction at the time of incidence. The dynamic characteristics can change the level of resource requirements. Once the model is set up, such changes can be easily provided to the model to develop the most effective emergency response model.

Presently, the emergency response planning activities related to emergency resource distribution and allocations is done based on a conventional method which is based on worst or biggest expected single or multiple risk or disaster situations based on applied emergency response policy and procedures. This can cause significant increase is initial investment cost and operation cost which can be avoided by utilization of optimization tool such as IERMS to simulate the resources needs based on given scenarios. Therefore, the proposed framework can serve as the planning tool for allocating and locating emergency response resources in the industrial cities.

In the event of multiple emergency situations, the resources dispatch is done based on first-come-first served principle. This principle ignores the severity of the events and potential risk propagation in case of delayed response to locations with high risk potential. The application of IERMS will contribute to solve this issue due to the consideration of hazard and its impact pertaining to each location.

6.2 Limitations

The research is done based on available information from the local industrial city (case study) with some assumption to simplify the case (some of which are given in assumptions made for the development of the mathematical models). The proposed model, may have to be validated in other cities, where the facilities can be of different composition and in differently distributed locations.

The research work covers the single operation of emergency response—firefighting services. The IERMS can be expanded to include other emergency response services such as paramedic, civil defense or police. Although this will increase the complexity of the problem on emergency response, it will add to a more pragmatic situation on resource mobilization.

6.3 Potential future directions

Based on the research conducted here, the following points can be considered for future research opportunities:

- Development of a comprehensive database of spatial information that can be used as input for the LHI module and IERMS model to provide live update of hazard evaluation and resources optimization during life disasters scenarios. With current GIS platforms, such an inclusion should be possible. The use of GIS platform can help in adding topographical and environmental feathers, if necessary, in order to develop the location hazard index. Such results can be more accurate and help decision makers to provide better resource allocations.
- The exiting model considers a static situation. Therefore, the outcome is based on one time analysis of the hazard and feedback from the reconnaissance by the staff that arrive at the scene immediately after the incident. However, in real life situation, the effect of impact can change dynamically. This requires continuous or periodic feed of real time data on the resource requirements from the incident site. The resulting impact of the incident (to the nearby location) can also be different over time compared to the initial

state. In order to capture such a situation, dynamic modeling would be necessary. Although, it can be done with the current model, the dynamism of already sent resources and requirement of additional resources cannot be captured in the current model.

- The cost of emergency resources can be introduced in the optimization, although that may be refuted by the HSE planner, it would provide knowledge on the resource utilization so that decision makers can make up their informed decision. The models can be developed to consider minimization of waste of allocated resources, or minimizing the difference between the demand and supply (demand=> supply is a must situation here).
- The study considers the available resources, which are heterogeneous. However, resource allocation and resource management are normally better when the fleet is standardized. This will also impact the resource utilization proposed in this thesis.

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Appendix

Appendix A: Index-based Emergency Response Management System (IERMS):

The prototype model of IERMS will be validated on in two steps as the following:

A.1 Location Hazard index (LHI) calculation using MS Excel:

The preparation for LHI calculation start with preparation of input data which is basically set of input data used. The source of basic input data are international standards taken from best practices as well as site information from industrial city and other operators records as the following:

- **Chemicals Substance Data base**: This Data bases contains list of commonly used chemicals with classifications of its important properties such as Toxicity (Tc), Flammability (Fc) , and Reactivity (Rc). The databases is bases on NFPA 704 (Standard System for the Identification of the Hazards of Materials for Emergency Response) which is a standard maintained by the U.S.-based National Fire Protection Association. The NFPA 704 defines the colloquial "fire diamond" used by emergency personnel to quickly and easily identify the risks posed by hazardous materials. This helps to determine emergence response level required, special equipment needed, response procedures to be followed, or precautions taken during the initial stages of an emergency response (See Table A.1). These rating are based chemicals properties as shown in Table A.2.
- **Metrological information:** These are standard information published by national weather agency or local weather monitoring stations located in the industrial cities. These weather stations are on-line connected with easy access portals available over

internet. For the LHI calculation, we need information such as wind speed, and wind direction. The wind scale is based on Beaufort scale, which is developed in 1805 by Sir Francis Beaufort for measuring wind speeds. It is based on observation rather than accurate measurement. It is the most widely used system to measure wind speed today. The effect of wind in calculation formula is captured on scale of 1 to 0. This information are captured and then converted into input to the LHI formula as shown on Table A.3

- **Demographic information (Population):** As people and humans, safety is very important and consider one of the main element for risk assessment. The Human population effect in LHI are considered in two way. The first element is through head count effect, which range from 1 or 100% if the location has more than five individuals or 0.001 for unpopulated locations. The second elements is population location in adjacent sites relevant to wind direction as the fire or risk might be spread over and harm more individuals. Bothe elements effect are listed in Table A.4 and A.5.
- **Chemicals volumes effects ICV :** The volume effect of chemicals substances are very important in determining and quantification the effect of chemicals substance accident and directly on hazard index. Accordingly, Control of Major Accident Hazards (COMAH) Regulations 2015 has been used to convert the volume effect of chemicals from volumetric scale or cubic meters into unit less scale based on COMAH classification. The purpose of the COMAH Regulations is to prevent major accidents involving dangerous substances and limit the consequences to people and the environment of any accidents, which might occur. Chemical’s substance volumes will be classified based on critical limits set by COMAH into lower and upper tier requirements. These limits creates 3 Zones or group of chemicals as the following :

- **LL zones chemicals:** chemicals volumes, which are less, than or equal to the lower limits/ tier set by COMAH schedule 1 of Dangerous substance. The impact of chemicals (nature and volume) in LL zone is 0.25 or 25%.
- **LU zones chemicals**: chemicals volumes which are higher than the lower limits or tier but less than upper tier set by COMAH schedule 1 of Dangerous substance. The impact of chemicals (nature and volume) in LU zone is 0.5 or 50%.
- **UU zones chemicals**: chemicals volumes which are higher/ more than upper limits/ tier set by COMAH schedule 1 of Dangerous substance. The impact of chemicals (nature and volume) in UU zone is 1.0 or 100%.

These chemicals inventory list and classified is based on CLP (Classification, Labelling and Packaging) regulation list published by ECHA (European chemicals agency). The CLP Regulation ensures that the hazards presented by chemicals are clearly communicated to workers and consumers in the European Union through classification and labelling of chemicals. Accordingly, before placing chemicals on the market, the industry must establish the potential risks to human health and the environment of such substances and mixtures, classifying them in line with the identified hazards. The hazardous chemicals also have to be labelled according to a standardized system so that workers and consumers know about their effects before they handle them.

- **The combined effect of Population, wind speed and location (Location index Lc) :** in LHI model, the combined effect of population (head count) , wind speed and relevant location is called location factor (Lc) which is presented in table shown in Appendix E . These elements are assumed to be linearly related in single site and accordingly location index tables or matrix has been produce to be used in LHI calculations.

- **Single incident Hazard assessment (LHI) :** hazards are transboundary phenomena which need to be analyzed in view of understanding the surrounding environments and conditions which shall be consider and reflected in the overall hazard level. Accordingly, The calculation of LHI will be done on several steps to allow integration and understanding of adjacent and surrounding conditions as the following :

- **Hazard impact of each chemicals on site**: The hazard of each chemicals will be mainly depending on properties of chemical substances available in each location and its volume. The values for toxicity, flammability, and reactivity will determined based on NFPA 704 standard. The chemical properties hazard will be ranging from 12 points (maximum value for very hazardous materials) to 0 point (which is non-hazardous materials). The values for the three properties will be summed for each chemical substance then it will be multiplied by its volume index Icv that has been calculated based on COMAH standards to reflect the effect of the available quantities of each location as shown in Table A.6.
- **Hazard impact of single clusters**: To calculated Hazard index for each cluster, we shall calculated the hazard impact of each substance (as explained in previous step) then, multiply with location factor for each cluster. The location index (Li) is determined based on each cluster location, and wind conditions relevant to the main cluster at which incident is located. Normally, each incident site is divided into 9 clusters at which main incident location is in the center as show in in Figure 4.6. The overall hazard index for single cluster will be the highest/ Max hazard for any single chemicals available in the cluster.
- **Hazard impact for single site/ incident location (LHI)**: To calculated single site hazard, we calculate the location for each cluster as explained above, then multiply it

with location factor which basically include location impact, and population or head count impact as explained in previous section. The overall LHI for single site will be maximum of any clusters at that site. The overall number is calculated and will reflect the potential hazard in the incident location which will help the emergency response team and managed to decide on the required response level and optimize available reprices based on location hazard index (LHI).

- **Overall assessment of Multiple locations incidents** : At specific moment of time, several incident/ accident might occurred, thus a simultaneous emergency response will be required especially in industrial cities where risk might aggravated rapidly and escalated to highest levels of emergency situation. LHI will provide a suitable tool to facilities decision-making process by providing quick reference for setting priorities to manage the limited resource and divert it to most critical and need locations to minimize losses. Sample multiple incident simulation is shown in Appendix G.

Table A.1 : List of chemical substances as per NFPA 704.

Compounds (A-C)	Health	Fire	React	Spec. Haz.
1,1,1-Trichloroethane	2	1	0	
1,1-Dichloroethene	2	4	2	
1,2-Dichlorobutane	2	2	0	
1,2-Dichloroethylene	2	3	2	
1-Butane	1	4	0	
1-Decene	0	2	0	
1-Dodecanethiol	2	1	0	
1-Dodecanol	0	1	0	
1-Hexene	1	3	0	
1-Methyl Piperazine	2	2	0	
1-Nitropropane	1	3	1	
1-Octene	1	3	0	

1-Pentene	1	4	0	
2,2-Dimethylbutane	1	3	0	
2,3-Dimethyloctane	0	2	0	
2,3-Dimethylpentane	0	3	0	
2,4-Dinitrotoluene	3	1	3	
2-Heptanol	0	2	0	
2-Methyl-1-Pentene	1	3	0	
2-Methylpyrazine	2	2	0	
2-Octanol	1	2	0	
2-Undecanol	1	1	0	
3-Aminopropanol	3	2	0	
3-Ethoxypropanal	2	2	0	
3-Hexanone	1	3	0	
4-Ethylmorpholine	2	3	0	
Acetal	2	3	0	
Acetaldehyde	2	4	2	
Acetic Acid (glacial)	2	2	2	
Acetic Anhydride	3	2	2	W
Acetone	1	3	0	
Acetonitrile	2	3	0	
Acetophenone	1	2	0	
Acetyl Chloride	3	3	2	W
Acetyl Peroxide	1	2	4	
Acetylene	1	4	3	
Acetylene	1	4	3	G
Acrolein	3	3	2	
Acrolein Dimer	1	2	1	

Table A.2: NFPA 704 chemicals classifications groups.

NFPA 704 **Standard System for the Identification of the Hazards of Materials for Emergency Response**

NFPA HAZARD RATING SYSTEM

Health (Blue) Detailed Description of Health Rating		
4	Danger	May be fatal on short exposure. Specialized protective equipment required
3	Warning	Corrosive or toxic. Avoid skin contact or inhalation
2	Warning	May be harmful if inhaled or absorbed
1	Caution	May be irritating
0		No unusual hazard

Flammability (Red)Detailed Description of Flammable Rating		
4	Danger	Flammable gas or extremely flammable liquid
3	Warning	Flammable liquid flash point below 100°F
2	Caution	Combustible liquid flash point of 100° to 200°F
1		Combustible if heated
0		Not combustible

Reactivity (Yellow) Detailed Description of Reactivity Rating		
4	Danger	Explosive material at room temperature
3	Danger	May be explosive if shocked, heated under confinement or mixed with water
2	Warning	Unstable or may react violently if mixed with water
1	Caution	May react if heated or mixed with water but not violently
0	Stable	Not reactive when mixed with water

Special Information Key (White) Detailed Description of Special Information Rating		
4	Oxidizing Agent	Oxy
4	Water Reactive	W
3	Compressed Gas	G
1	Liquid Nitrogen	LN2
1	Liquid Helium	LHE

Table A.3: Beaufort Wind Scale.

Force	Wind (Knots)	m/s	Km/hr		WMO Classification	Appearance of Wind Effects On the Water	On Land	effect
0	Less than 1		1.9		Calm	Sea surface smooth and mirror-like	Calm, smoke rises vertically	0.5
1	1 to 3	0.5	1.9	5.7	Light Air	Scaly ripples, no foam crests	Smoke drift indicates wind direction, still wind vanes	0.5
2	4 to 6	2.1	7.6	11.4	Light Breeze	Small wavelets, crests glassy, no breaking	Wind felt on face, leaves rustle, vanes begin to move	0.5
3	7 to 10	3.7	13.3	19	Gentle Breeze	Large wavelets, crests begin to break, scattered whitecaps	Leaves and small twigs constantly moving, light flags extended	0.5
4	11 to 16	5.8	20.9	30.4	Moderate Breeze	Small waves 1-4 ft. becoming longer, numerous whitecaps	Dust, leaves, and loose paper lifted, small tree branches move	0.85
5	17-21	9.0	32.3	39.9	Fresh Breeze	Moderate waves 4-8 ft taking longer form, many whitecaps, some spray	Small trees in leaf begin to sway	0.85
6	22-27	11.6	41.8	51.3	Strong Breeze	Larger waves 8-13 ft, whitecaps common, more spray	Larger tree branches moving, whistling in wires	0.85
7	28-33	14.8	53.2	62.7	Near Gale	Sea heaps up, waves 13-19 ft, white foam streaks off breakers	Whole trees moving, resistance felt walking against wind	0.85
8	34-40	17.9	64.6	76	Gale	Moderately high (18-25 ft) waves of greater length, edges of crests begin to break into spindrift, foam blown in streaks	Twigs breaking off trees, generally impedes progress	0.85
9	41-47	21.6	77.9	89.3	Strong Gale	High waves (23-32 ft), sea begins to roll, dense streaks of foam, spray may reduce visibility	Slight structural damage occurs, slate blows off roofs	0.85

10	48-55	25.3	91.2	104.5	Storm	Very high waves (29-41 ft) with overhanging crests, sea white with densely blown foam, heavy rolling, lowered visibility	Seldom experienced on land, trees broken or uprooted, "considerable structural damage"	0.3
11	56-63	29.6	106.4	119.7	Violent Storm	Exceptionally high (37-52 ft) waves, foam patches cover sea, visibility more reduced		0.3
12	64+	33.8	121.6		Hurricane	Air filled with foam, waves over 45 ft, sea completely white with driving spray, visibility greatly reduced		0.3

Table A.4: Population weighing factor.

No	No of staff	population	factor H
1	0	No population	0.001
2	1	low populated	0.5
3	2 to 5	Medium populated	0.8
4	more than 5	heavily populated	1

Table A.5: location weighing factor.

Location of population	factor P
Center	1
down wind	0.8
side	0.5
up wind	0.1

Table A.6: Chemical hazard calculation for cluster A1.

	chemicals hazard input			Location info. Input		
	Hazr no	**substance**	**Vc, volume, MT**	**type/ class**	**Adjacent cell location**	**head count**
Pixel/ location 1 : Terminal and LNG storage Area.						
A1	1	LNG, Methane	10,000.00	Gentle Breeze	center	1
	2	Propane	6,000.00			
	3	Butane	5,000.00			
	4	Diesel Fuel	2,000.00			
	5	Methanol	500.00			
	6	Ethane	3,000.00			

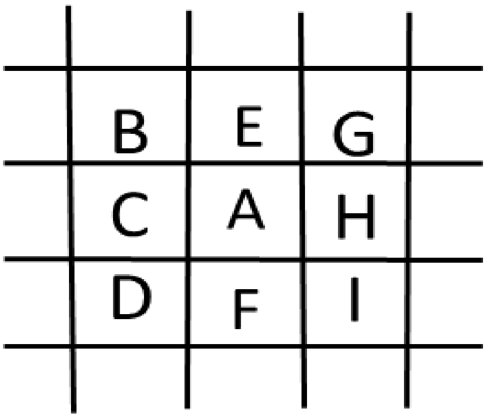


Figure A.1: Incident site division into 9 clusters.

A.2 Dispatching Model simulation using AMPL:

The dispatch model simulation is done via AMPL for the optimization formula. The basic objective function with all constraint s will be transfer into AMPL programs as the following:

A.2.1 The main program formulation:

The program needs to have 5 fundamental components to have full functions of the program. The comments are:

- **Sets**, like the emergency response centers (depot), incident locations sets.
- **Parameters**, like available resources in each emergency response center (depot), its capacity, LHI for each site, etc.
- **Variables**, whose values the solver is to determine such as dispatch truck from depot to incident location.
- **an objective**, to be maximized or minimized (to minimize overall response time for your case)
- **Constraint** that the solution must satisfy such as not exceed in the available resources capacity and fulfilling the demand in each location.

For this case, the AMPL optimization code is written as the following:

- Sets group: Which is the part that defines the main groups of resources that needs to be optimized. For this case we have 3 groups, the first one is the emergency response centers (depot) , the group of incident locations and the type of emergency response/ Firefighting trucks. The optimization will use these 3 sets to propose selected resources as solution. The sets part of three program is written as the following :

```
#SETS
set DEPOT; # Fire Depot
```

```
set LOCA; # incident location

set TRUK; # Types of FF Trucks
```

- The parameters: Five parameters are required for this model. These parameters are :
    - No of trucks in each depot.
    - Capacity of each truck.
    - Location hazard index for each incident location.
    - Demand for each incident location.
    - The travel time for each type of truck from depot to incident location.

The parameters part of the program will be written as the following:

```
#PARAMETERS

param resources{TRUK,DEPOT} >= 0; # Existing resources in each depot

param Ck{TRUK} >=0; #The capacity of each truck in Gallons

param LHI{LOCA} >= 0; #Location Hazard index (LHI) for each location

param Di{LOCA} >= 0; #Water Demand in each Location

param time {DEPOT,LOCA,TRUK} >= 0; #Travel time per route per truck
```

- The variables: It is the nomination of selected trucks from nearest depot to the selected incident location to fulfil the objectives (minimize the time) and considering the constraint s (capacity and demand). The variables part of the program are written as the following:

```
#VARIABLES
```

```
var X{LOCA,DEPOT,TRUK}binary;
```

- The Objective: This is the main part of the program in our case which cover the objective function of the mathematical optimization model. For this case, its minimizing the overall emergency response time by allocating the required Firefighting trucks capacity from nears depot to guarantee the minimum time with priority to incident location with highest LHI. The objective function is coded as the following :

```
#OBJECTIVE
```

- `minimize TTT :`

```
=  (sum{i in LOCA, j in DEPOT, k in TRUK} 1/LHI[i]* ((X[i,j,k]*Time[j,i,k])
+(X[i,j,k]*St[k])));
```

- The Constraint s: for this case, constraints represent the three conditions. The first related to the demand for each incident location, which need to be fulfilled while achieving the objective function. The second is related to limiting dispatch resources from each depot to the available capacity. The third one is related to response vehicles structure at which K1 type resource is mandated at each dispatch operation. These constraint s are coded as the following :

```
#CONSTRAINT
subj to demand {i in LOCA}: sum {j in DEPOT, k in TRUK} (X[i,j,k] * Ck[k])>=
Di[i];
```

```
subj to resource {j in DEPOT, k in TRUK}: sum {i in LOCA} X[i,j,k] <= Resources[k,j];
subj to truckusage {i in LOCA}: sum {j in DEPOT} X[i,j,'K1']>=1;
```

The full AMPL main program formulation is shown in Appendix G.

A.2.2 The input data:

The input date file will contains list of all sets and parameters mentioned in the main program.

```
set DEPOT := DEPOT1 DEPOT2 DEPOT3 DEPOT4 DEPOT5;
set LOCA := L1 L2 L3 L4 L5 L6 L7 L8 L9 L10;
set TRUK := K1 K2 K3 K4;
#existing resources in each depot
param resources: DEPOT1 DEPOT2 DEPOT3 DEPOT4 DEPOT5:=
K1 1 1 1 1 1
K2 3 2 2 1 1
K3 2 1 1 0 0
K4 2 1 1 1 1
;
#The capacity of each truck in Gallons
param Ck:=
K1 400
```

```
K2 1000
K3 4000
K4 6000
;
#Location Hazard index (LHI) for each location
param LHI:=
L1 6
L2 12
L3 0.35
L4 1
L5 0.8
L6 0.7
L7 0.6
L8 0.5
L9 0.4
L10 0.1
;
#Water Demand in each Location
param Di:=
L1 1500
L2 10000
L3 400
L4 600
```

```
L5 500
L6 400
L7 300
L8 250
L9 200
L10 100
;
#Travel time between depots and locations for each type of trcuk
param time :=
[*,*,K1]: L1 L2 L3 L4 L5 L6 L7 L8 L9 L10:=
DEPOT1 2 5 15 10 13 15 10 20 3 12
DEPOT2 4 6 10 2 4 8 10 15 6 8
DEPOT3 4 2 6 5 3 5 3 10 3 3
DEPOT4 10 6 2 10 6 4 3 6 6 2
DEPOT5 10 15 18 6 7 9 10 20 10 13

[*,*,K2]: L1 L2 L3 L4 L5 L6 L7 L8 L9 L10:=
DEPOT1 2.1 5.25 15.75 10.5 13.65 15.75 10.5 21 3.15 12.6
DEPOT2 4.2 6.3 10.5 2.1 4.2 8.4 10.5 15.75 6.3 8.4
DEPOT3 4.2 2.1 6.3 5.25 3.15 5.25 3.15 10.5 3.15 3.15
DEPOT4 10.5 6.3 2.1 10.5 6.3 4.2 3.15 6.3 6.3 2.1
DEPOT5 10.5 15.75 18.9 6.3 7.35 9.45 10.5 21 10.5 13.65
```

```
[*,*,K3]: L1 L2 L3 L4 L5 L6 L7 L8 L9 L10:=
DEPOT1 2.4 6 18 12 15.6 18 12 24 3.6 14.4
DEPOT2 4.8 7.2 12 2.4 4.8 9.6 12 18 7.2 9.6
DEPOT3 4.8 2.4 7.2 6 3.6 6 3.6 12 3.6 3.6
DEPOT4 12 7.2 2.4 12 7.2 4.8 3.6 7.2 7.2 2.4
DEPOT5 12 18 21.6 7.2 8.4 10.8 12 24 12 15.6

[*,*,K4]: L1 L2 L3 L4 L5 L6 L7 L8 L9 L10:=
DEPOT1 3 7.5 22.5 15 19.5 22.5 15 30 4.5 18
DEPOT2 6 9 15 3 6 12 15 22.5 9 12
DEPOT3 6 3 9 7.5 4.5 7.5 4.5 15 4.5 4.5
DEPOT4 15 9 3 15 9 6 4.5 9 9 3
DEPOT5 15 22.5 27 9 10.5 13.5 15 30 15 19.5
;

X [*,*,K1]
:   DEPOT1 DEPOT2 DEPOT3 DEPOT4 DEPOT5    :=
L1     0     0     0     0     0
L10    0     0     0     1     0
L2     0     0     0     0     0
L3     0     0     0     0     0
L4     0     0     0     0     0
L5     0     0     0     0     0
```

```
L6     0     0     1     0     0

L7     0     0     0     0     0

L8     0     0     0     0     0

L9     1     0     0     0     0


 [*,*,K2]

:   DEPOT1 DEPOT2 DEPOT3 DEPOT4 DEPOT5    :=

L1     0     0     0     0     0

L10    0     0     0     0     0

L2     0     0     0     0     0

L3     0     0     0     0     0

L4     0     1     0     0     0

L5     0     0     1     0     0

L6     0     0     0     0     0

L7     0     0     1     0     0

L8     0     0     0     1     0

L9     0     0     0     0     0


 [*,*,K3]

:   DEPOT1 DEPOT2 DEPOT3 DEPOT4 DEPOT5    :=

L1     1     0     0     0     0

L10    0     0     0     0     0

L2     0     0     1     0     0
```

```
L3   0   0   0   0   0

L4   0   0   0   0   0

L5   0   0   0   0   0

L6   0   0   0   0   0

L7   0   0   0   0   0

L8   0   0   0   0   0

L9   0   0   0   0   0

 [*,*,K4]

:   DEPOT1 DEPOT2 DEPOT3 DEPOT4 DEPOT5    :=

L1   0   0   0   0   0

L10   0   0   0   0   0

L2   0   0   1   0   0

L3   0   0   0   1   0

L4   0   0   0   0   0

L5   0   0   0   0   0

L6   0   0   0   0   0

L7   0   0   0   0   0

L8   0   0   0   0   0

L9   0   0   0   0   0
```

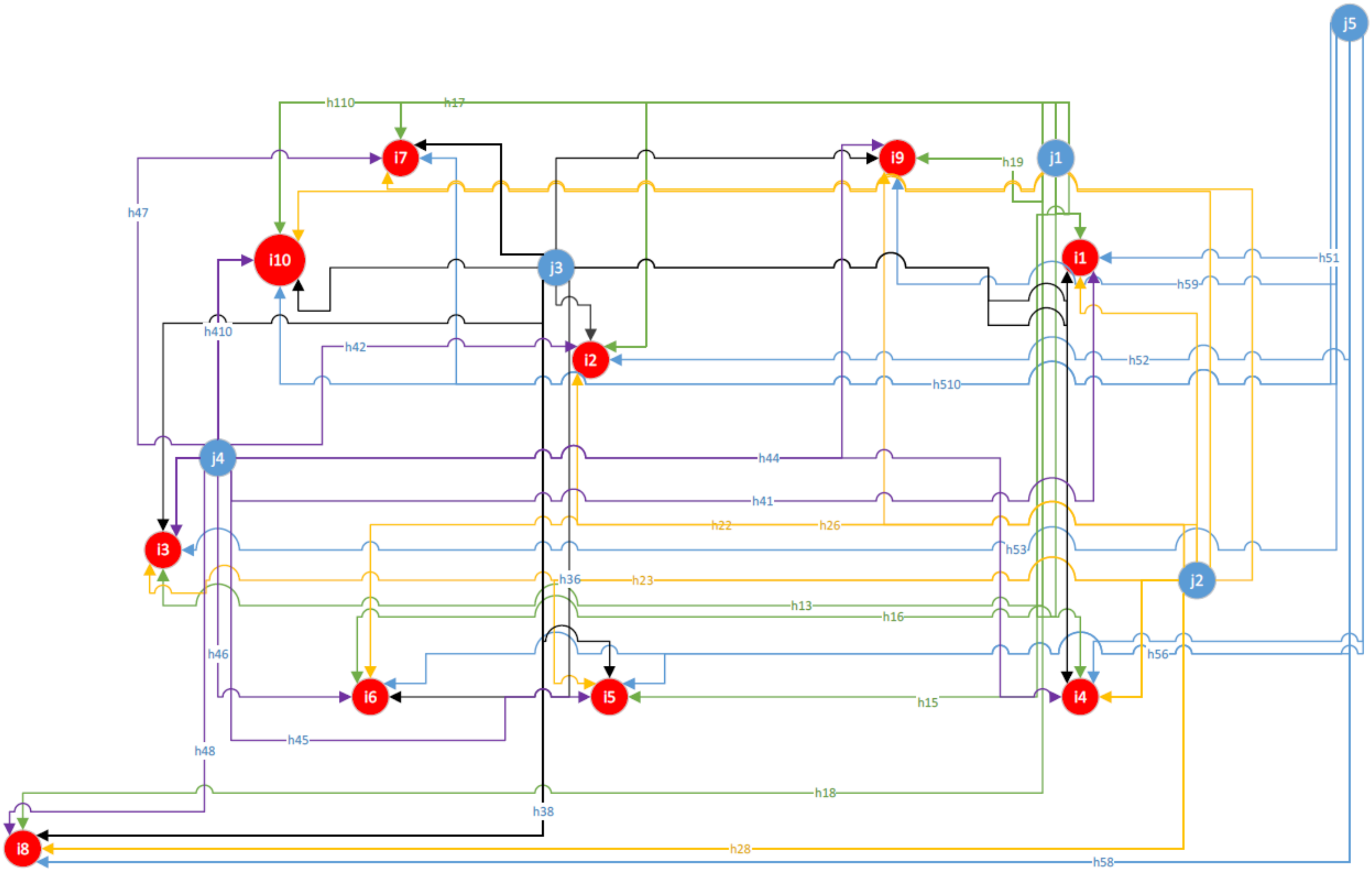
Appendix B: Travel time of emergency resources.

Estimated time for selected route h for each Truck Type			**Response time in minutes**			
	j	i	K1	K2	K3	K4
h	**1**	1	2	2.1	2.4	3
h	**1**	2	5	5.25	6	7.5
h	**1**	3	15	15.75	18	22.5
h	**1**	4	10	10.5	12	15
h	**1**	5	13	13.65	15.6	19.5
h	**1**	6	15	15.75	18	22.5
h	**1**	7	10	10.5	12	15
h	**1**	8	20	21	24	30
h	**1**	9	3	3.15	3.6	4.5
h	**1**	10	12	12.6	14.4	18
h	2	1	4	4.2	4.8	6
h	2	2	6	6.3	7.2	9
h	2	3	10	10.5	12	15
h	2	4	2	2.1	2.4	3
h	2	5	4	4.2	4.8	6
h	2	6	8	8.4	9.6	12
h	2	7	10	10.5	12	15
h	2	8	15	15.75	18	22.5
h	2	9	6	6.3	7.2	9
h	2	10	8	8.4	9.6	12
h	**3**	1	4	4.2	4.8	6
h	**3**	2	2	2.1	2.4	3
h	**3**	3	6	6.3	7.2	9
h	**3**	4	5	5.25	6	7.5
h	**3**	5	3	3.15	3.6	4.5
h	**3**	6	5	5.25	6	7.5
h	**3**	7	3	3.15	3.6	4.5
h	**3**	8	10	10.5	12	15
h	**3**	9	3	3.15	3.6	4.5
h	**3**	10	3	3.15	3.6	4.5
h	4	1	10	10.5	12	15
h	4	2	6	6.3	7.2	9
h	4	3	2	2.1	2.4	3

h	4	4	10	10.5	12	15
h	4	5	6	6.3	7.2	9
h	4	6	4	4.2	4.8	6
h	4	7	3	3.15	3.6	4.5
h	4	8	6	6.3	7.2	9
h	4	9	6	6.3	7.2	9
h	4	10	2	2.1	2.4	3
h	**5**	1	10	10.5	12	15
h	**5**	2	15	15.75	18	22.5
h	**5**	3	18	18.9	21.6	27
h	**5**	4	6	6.3	7.2	9
h	**5**	5	7	7.35	8.4	10.5
h	**5**	6	9	9.45	10.8	13.5
h	**5**	7	10	10.5	12	15
h	**5**	8	20	21	24	30
h	**5**	9	10	10.5	12	15
h	**5**	10	13	13.65	15.6	19.5

APPENDIX C: TYPICAL ROUTES OPTIONS FOR EMERGENCY VEHICLES.

Emergency Response Route options



APPENDIX D: MAP OF CASE STUDY INDUSTRIAl CITY.

Master plan

Master plan to anticipate and accommodate future growth of gas based industries.

Planning for the provision of infrastructure and marine terminals required to meet the importing and exporting needs of industries.

Ras Laffan area: 239 Sq. km
Port area: 56 Sq. km
Total Ras Laffan area
(Including port): 295 Sq. km

J = Fire station / Depo
i = Incident location

APPENDIX E: THE LOCATION INDEX TABLE.

		Location Index (Li)				
	Center	down wind	Side	up-wind		No of staff
Calm	1	0.525	0.25	0.01	No Population	0
Light Air	1	0.56	0.275	0.015		
Light Breeze	1	0.595	0.3	0.02		
Gentle Breeze	1	0.63	0.325	0.025	low populated	1
Moderate Breeze	1	0.665	0.35	0.03		
Fresh Breeze	1	0.7	0.375	0.035		
Strong Breeze	1	0.7	0.4	0.04	Medium populated	2 to 5
Near Gale	1	0.7	0.425	0.045		
Gale	1	0.7	0.45	0.05		
Strong Gale	1	0.7	0.475	0.055	heavily populated	more than 5
Storm	1	0.7	0.5	0.06		
Violent Storm	1	0.7	0.5	0.065		
Hurricane	1	0.7	0.5	0.07		
Calm	1	0.6	0.3	0.02	No Population	0
Light Air	1	0.64	0.33	0.03		
Light Breeze	1	0.68	0.36	0.04		
Gentle Breeze	1	0.72	0.39	0.05	low populated	1
Moderate Breeze	1	0.76	0.42	0.06		
Fresh Breeze	1	0.8	0.45	0.07		
Strong Breeze	1	0.8	0.48	0.08	Medium populated	2 to 5
Near Gale	1	0.8	0.51	0.09		
Gale	1	0.8	0.54	0.1		
Strong Gale	1	0.8	0.57	0.11	heavily populated	more than 5
Storm	1	0.8	0.6	0.12		
Violent Storm	1	0.8	0.6	0.13		
Hurricane	1	0.8	0.6	0.14		
Calm	1	0.675	0.4	0.06	No Population	0
Light Air	1	0.72	0.44	0.09		
Light Breeze	1	0.765	0.48	0.12		
Gentle Breeze	1	0.81	0.52	0.15	low populated	1
Moderate Breeze	1	0.855	0.56	0.18		
Fresh Breeze	1	0.9	0.6	0.21		
Strong Breeze	1	0.9	0.64	0.24	Medium populated	2 to 5
Near Gale	1	0.9	0.68	0.27		
Gale	1	0.9	0.72	0.3		
Strong Gale	1	0.9	0.76	0.33	heavily populated	more than 5

Storm	1	0.9	0.8	0.36		
Violent Storm	1	0.9	0.8	0.39		
Hurricane	1	0.9	0.8	0.42		
Calm	1	0.75	0.45	0.08		
Light Air	1	0.56	0.495	0.12	No Population	0
Light Breeze	1	0.595	0.54	0.16		
Gentle Breeze	1	0.72	0.585	0.2		
Moderate Breeze	1	0.76	0.63	0.24	low populated	1
Fresh Breeze	1	0.8	0.675	0.28		
Strong Breeze	1	0.9	0.72	0.32		
Near Gale	1	0.9	0.765	0.36	Medium populated	2 to 5
Gale	1	0.9	0.81	0.4		
Strong Gale	1	1	0.855	0.44		
Storm	1	1	0.9	0.48	heavily populated	more than 5
Violent Storm	1	1	0.9	0.52		
Hurricane	1	1	0.9	0.56		
	Center	down wind	Side	up-wind		

APPENDIX F: SAMPLE CALCULATION SHEET OF LHI.

		chemicles hazard input		Location info. Input			Out put						Volume indix							Location Indix				
	Hazr no	substance	Vc, voume, MT	type/ class	Adjacent cell location	head count	Tc, Toxisisty	Fc, flambility	Rc, reactivity	Ii	Ivc	New LHI	substance	volume	Teir	Health Hazard, Toxic	Flamability	Reactivity, Explosive	Overall	type/ class	direction	Adjacent cell location	head count	Location Factor
Pixel/ location 1 : Termial and LNG stroage Area.																								
A1	1	LNG, Methane	10,000.00	Gentle Breeze	center	1	2	4	0	1.00	1.00	6.0	LNG, Methane	10000	UU				1					
	2	Propane	6,000.00				1	4	0	1.00	1.00	5.0	Propane	6000	UU				1					
	3	Buteane	5,000.00				1	4	0	1.00	1.00	5.0	Buteane	5000	UU				1					
	4	Disel Fuel	2,000.00				1	2	0	1.00	1.00	3.0	Disel Fuel	2000	UU				1					
	5	Methanol	500.00				1	3	0	1.00	1.00	4.0	Methanol	500	UU				1					
	6	Ethane	3,000.00				1	4	0	1.00	1.00	5.0	Ethane	3000	UU				1					
												6.0	0	0						Gentle Breeze	North	center	1	1
B1	1	Propane	1,500.00	Gentle Breeze	up-wind	25	1	4	0	0.20	1.00	1.0	Propane	1500	UU				1					
													0	0										
													0	0										
												1.0	0	0						Gentle Breeze	North	up-wind	25	0.2
C1	1	Disel Fuel	500.00	Gentle Breeze	side	0	1	2	0	0.33	1.00	1.0	Disel Fuel	500	UU				1					
	2	Buteane	500.00				1	4	0	0.33	1.00	1.6	Buteane	500	UU				1					
		Propane	900.00				1	4	0	0.33	1.00	1.6	Propane	900	UU				1					
		Methanol	10.00				1	3	0	0.33	0.25	0.3	Methanol	10	LL				0.25					
	3	MethANE	1,000.00				1	4	0	0.33	1.00	1.6	MethANE	1000	UU				1					
												1.2	0	0						Gentle Breeze	North	side	0	0.325
D1	1	Disel Fuel	3,000.00	Gentle Breeze	dowin-wind	1	1	2	0	0.72	1.00	2.2	Disel Fuel	3000	UU				1					
												0.0	0	0										
												0.0	0	0										
												2.2	0	0						Gentle Breeze	North	dowin-wind	1	0.72

E1	1	Methane/ LNG	10,000.00	Gentle Breeze	up-wind	5	1	4	0	0.15	1.00	0.8	Methane/ LNG	10000	UU				1					
	2	Propane	6,000.00				1	4	0	0.15	1.00	0.8	Propane	6000	UU				1					
												0.0	0	0										
												0.8	0	0						Gentle Breeze	North	up-wind	5	0.15
F1	1	Disel Fuel	200.00	Gentle Breeze	down-wind	0	1	2	0	0.63	1.00	1.9	Disel Fuel	200	UU				1					
	2	NA	-									0.0	NA	0										
	3	NA	-									0.0	NA	0										
												1.9	0	0						Gentle Breeze	North	down-wind	0	0.63
G1	1	Methane / LNG	8,000.00	Gentle Breeze	down-wind	0	1	4	0	0.63	1.00	3.2	Methane / LNG	8000	UU				1					
	2	Methanol	10.00				1	3	0	0.63	0.25	0.6	Methanol	10	LL				0.25					
	3											0.0	0	0										
												3.2	0	0						Gentle Breeze	North	down-wind	0	0.63
H1	1	NA	-	Gentle Breeze	side	1				0.39	0.25	0.0	NA	0					0.25					
	2	NA	-							0.39	1.00	0.0	NA	0					1					
	3	NA	-							0.39	1.00	0.0	NA	0					1					
												0.0	0	0						Gentle Breeze	North	side	1	0.39
I 1	1	NA	-	Gentle Breeze	down-wind	0				0.25	0.63	0.0	NA	0					0.25					
	2	NA	-							1.00	0.63	0.0	NA	0					1					
	3	NA	-							1.00	0.63	0.0	NA	0					1					
												0.0	0							Gentle Breeze	North	down-wind	0	0.63
												6.0												
												MAX												
										variance	1.8	6.0	4.81828125	Out of 12										
										1.875563249	Average	MAX	Weighted											

Appendix G: AMPL mathematical optimization program.

```
#IERMS Formulation
#SETS
set DEPOT; # Fire Depot
set LOCA; # incident location
set TRUK; # Types of FF Trucks
#PARAMETERS
param resources{TRUK,DEPOT} >= 0; # Existing resources in each depot
param Ck{TRUK} >=0; #The capacity of each truck in Gallons
param LHI{LOCA} >= 0; #Location Hazard index (LHI) for each location
param Di{LOCA} >= 0; #Water Demand in each Location
param time {DEPOT,LOCA,TRUK} >= 0; #Travel time per route per truck
#VARIABLES
var X{LOCA,DEPOT,TRUK}binary;
#OBJECTIVE
minimize TTT : sum{i in LOCA, j in DEPOT, k in TRUK}(1/LHI[i])*X[i,j,k]*time[j,i,k];
#CONSTRAINT S
subject to demand {i in LOCA}: sum {j in DEPOT, k in TRUK} X[i,j,k] * Ck[k]>= Di[i];
subj to resource {j in DEPOT, k in TRUK}: sum {i in LOCA} X[i,j,k] <= resources[k,j];
```

APPENDIX H: AMPL DATA FILE.

```
set DEPOT := DEPOT1 DEPOT2 DEPOT3 DEPOT4 DEPOT5;
set LOCA := L1 L2 L3 L4 L5 L6 L7 L8 L9 L10;
set TRUK := K1 K2 K3 K4;
#Existing resources in each depot
param resources: DEPOT1 DEPOT2 DEPOT3 DEPOT4 DEPOT5:=
K1 1 1 1 1 1
K2 3 2 2 1 1
K3 2 1 1 0 0
K4 2 1 1 1 1
;

#The capacity of each truck in Gallons
param Ck:=
K1 400
K2 1000
K3 4000
K4 6000
;

#Location Hazard index (LHI) for each location
```

```
param LHI:=
L1 6
L2 12
L3 0.35
L4 1
L5 0.8
L6 0.7
L7 0.6
L8 0.5
L9 0.4
L10 0.1
;

#Water Demand in each Location
param Di:=
L1 1500
L2 10000
L3 400
L4 600
L5 500
L6 400
L7 300
```

```
L8 250
L9 200
L10 100
;

#Travel time between depots and locations for each type of truck
param time :=
[*,*,K1]: L1 L2 L3 L4 L5 L6 L7 L8 L9 L10:=
DEPOT1 2 5 15 10 13 15 10 20 3 12
DEPOT2 4 6 10 2 4 8 10 15 6 8
DEPOT3 4 2 6 5 3 5 3 10 3 3
DEPOT4 10 6 2 10 6 4 3 6 6 2
DEPOT5 10 15 18 6 7 9 10 20 10 13

[*,*,K2]: L1 L2 L3 L4 L5 L6 L7 L8 L9 L10:=
DEPOT1 2.1 5.25 15.75 10.5 13.65 15.75 10.5 21 3.15 12.6
DEPOT2 4.2 6.3 10.5 2.1 4.2 8.4 10.5 15.75 6.3 8.4
DEPOT3 4.2 2.1 6.3 5.25 3.15 5.25 3.15 10.5 3.15 3.15
DEPOT4 10.5 6.3 2.1 10.5 6.3 4.2 3.15 6.3 6.3 2.1
DEPOT5 10.5 15.75 18.9 6.3 7.35 9.45 10.5 21 10.5 13.65

[*,*,K3]: L1 L2 L3 L4 L5 L6 L7 L8 L9 L10:=
```

```
DEPOT1 2.4 6 18 12 15.6 18 12 24 3.6 14.4
DEPOT2 4.8 7.2 12 2.4 4.8 9.6 12 18 7.2 9.6
DEPOT3 4.8 2.4 7.2 6 3.6 6 3.6 12 3.6 3.6
DEPOT4 12 7.2 2.4 12 7.2 4.8 3.6 7.2 7.2 2.4
DEPOT5 12 18 21.6 7.2 8.4 10.8 12 24 12 15.6

[*,*,K4]: L1 L2 L3 L4 L5 L6 L7 L8 L9 L10:=
DEPOT1 3 7.5 22.5 15 19.5 22.5 15 30 4.5 18
DEPOT2 6 9 15 3 6 12 15 22.5 9 12
DEPOT3 6 3 9 7.5 4.5 7.5 4.5 15 4.5 4.5
DEPOT4 15 9 3 15 9 6 4.5 9 9 3
DEPOT5 15 22.5 27 9 10.5 13.5 15 30 15 19.5  ;
```

APPENDIX I : LHI CALCULATION FOR LOCATION A IN SCENARIO S1 (CHAPTER 4) .

		chemicles hazard input		Location info. Input			Out put						Volume indix							Location Indix				
	Hazr no	substance	Vc, voume, MT	type/ class	Adjacent cell location	head count	Tc, Toxisisty	Fc, flambility	Rc, reactivity	Ii	Ivc	New LHI	substance	volume	Teir	Health Hazard, Toxic	Flamability	Reactivity, Explosive	Overall	type/ class	direction	Adjacent cell location	head count	Location Factor
Pixel/ location 1 : Termial and LNG stroage Area.				Gentle Breeze	center	1																		
A1	1	LNG, Methane	10,000.00				4	4	0	1.00	1.00	8.0	LNG, Methane	10000	UU				1					
	2	Propane	6,000.00				1	4	0	1.00	1.00	5.0	Propane	6000	UU				1					
	3	Buteane	5,000.00				1	4	0	1.00	1.00	5.0	Buteane	5000	UU				1					
	4	Trinitro benzene	2,000.00				4	4	4	1.00	1.00	12.0	Trinitrobenzene	2000	UU				1					
	5	Methanol	500.00				1	3	0	1.00	1.00	4.0	Methanol	500	UU				1					
	6	Ethane	3,000.00				1	4	0	1.00	1.00	5.0	Ethane	3000	UU				1					
												12.0	0	0						Gentle Breeze	North	center	1	1
A2	1	Propane	1,500.00	Gentle Breeze	up-wind	25	1	4	0	0.20	1.00	1.0	Propane	1500	UU				1					
													0	0										
													0	0										
												1.0	0	0						Gentle Breeze	North	up-wind	25	0.2
A3	1	Disel Fuel	500.00	Gentle Breeze	side	0	1	2	0	0.33	1.00	1.0	Disel Fuel	500	UU				1					
	2	Buteane	500.00				1	4	0	0.33	1.00	1.6	Buteane	500	UU				1					
		Propane	900.00				1	4	0	0.33	1.00	1.6	Propane	900	UU				1					
		Methanol	10.00				1	3	0	0.33	0.25	0.3	Methanol	10	LL				0.25					
	3	MethANE	1,000.00				1	4	0	0.33	1.00	1.6	MethANE	1000	UU				1					
												1.2	0	0						Gentle Breeze	North	side	0	0.325
A4	1	Disel Fuel	3,000.00	Gentle Breeze	dowin-wind	1	1	2	0	0.72	1.00	2.2	Disel Fuel	3000	UU				1					
												0.0	0	0										
												0.0	0	0										
												2.2	0	0						Gentle Breeze	North	dowin-wind	1	0.72

A5	1	Methane/ LNG	10,000.00	Gentle Breeze	up-wind	5	1	4	0	0.15	1.00	0.8	Methane/ LNG	10000	UU				1					
	2	Propane	6,000.00				1	4	0	0.15	1.00	0.8	Propane	6000	UU				1					
												0.0	0	0										
												0.8	0	0						Gentle Breeze	North	up-wind	5	0.15
A6	1	Disel Fuel	200.00	Gentle Breeze	down-wind	0	1	2	0	0.63	1.00	1.9	Disel Fuel	200	UU				1					
	2	NA	-									0.0	NA	0										
	3	NA	-									0.0	NA	0										
												1.9	0	0						Gentle Breeze	North	down-wind	0	0.63
A7	1	Methane / LNG	8,000.00	Gentle Breeze	down-wind	0	1	4	0	0.63	1.00	3.2	Methane / LNG	8000	UU				1					
	2	Methanol	10.00				1	3	0	0.63	0.25	0.6	Methanol	10	LL				0.25					
	3											0.0	0	0										
												3.2	0	0						Gentle Breeze	North	down-wind	0	0.63
A8	1	NA	-	Gentle Breeze	side	1				0.39	0.25	0.0	NA	0					0.25					
	2	NA	-							0.39	1.00	0.0	NA	0					1					
	3	NA	-							0.39	1.00	0.0	NA	0					1					
												0.0	0	0						Gentle Breeze	North	side	1	0.39
A9	1	NA	-	Gentle Breeze	down-wind	0				0.25	0.63	0.0	NA	0					0.25					
	2	NA	-							1.00	0.63	0.0	NA	0					1					
	3	NA	-							1.00	0.63	0.0	NA	0					1					
												0.0	0							Gentle Breeze	North	down-wind	0	0.63
												12.0												
												MAX												
										variance	2.5	12.0	9.31828125	Out of 12										
										3.717558002	Average	MAX	Weighted											