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# Construction Site Layout Optimization, Considering Risk of Natural or Technological Hazard Utilizing GIS

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## **Thèse**

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## **Construction Site Layout Optimization, Considering Risk of Natural or Technological Hazard Utilizing GIS**

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**Soutenu** le 24 Mai 2017

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prayers and encouragement led to this  
accomplishment*



# Abstract

## Construction Site Layout Optimization, Considering Risk of Natural or Technological Hazard Utilizing GIS

Construction sites contain several supporting facilities that are required to complete construction activities. These facilities are susceptible to damage due to the occurrence of natural or technological hazards such as fire, explosion, blast wave, and so on. These may cause adverse consequences for the whole construction process, which in turn lead to fatal accidents that have a major impact on worker and employee productivity, project completion time, project quality and project budget. Therefore, project planners must adopt and develop innovative approaches able to face the occurrence of potential hazards, minimize their consequences, and facilitate the evacuation of the site in case of their occurrence. One of these approaches is optimizing construction site layout. In general, generating construction site layout able minimizing risk resulting from natural or technological hazards is still a scientific challenge.

In the present research, two proposed model (deterministic and probabilistic) are developed to minimize the risks within a construction site. The common methodology adopted to develop these two models consists of:

- Modeling construction site components, for instance; electric generator, offices and material storages, in a 2D layout, to act as either hazardous source or potential target or both at the same time.
- Modeling hazard: it shows the hazard interaction among site components and the attenuation of hazard.
- Modeling vulnerability: it represents the potential weakness of whole targets to the hazard generated from each source.
- Defining the utility function: it aims to afford an optimized site layout with minimum total risk in the construction site. The differential evolution algorithm is adopted to run optimization process.

Particularly, in the deterministic model, we use space syntax principle in order to realize the impact of space configurations in evaluating the risk in the construction site. Therefore, as the

evacuation process is considered in estimating the risk, the actual risk is amplified by utilizing penalty factor called mean depth. Furthermore, Dijkstra's algorithm is run on deterministic model to find the safest paths (least risk paths) for evacuating sites from any position on the construction site towards the safe places in order to diminish losses and fatalities. On the other hand, the framework utilized to develop a probabilistic model assumed that the risk is combined of the individual failure of each facility within a construction site. Moreover, the numerical simulation is performed to find the probabilistic distribution of failure for the whole site.

Geographic information system (GIS) capabilities were exploited, in this research, to present data in maps format, generate the spatial risk map in the construction site, and implement the Dijkstra's algorithm and least-cost path analysis.

For illustration purposes, the proposed models are employed in a case study consisting of several facilities. In the deterministic model, all of these facilities act as hazardous sources and potential targets, at the same time, while, in a probabilistic model, only some of these facilities act as fire hazardous sources, whereas, all of them are potential targets. The results revealed that the proposed models are efficient due to their capability of generating site layout with the safer work environment. In addition, the model is capable of highlighting the riskiest areas within a construction site. Moreover, the proposed models are able to generate paths through least-risk zones, which will minimize the serious injuries and victims in cases of emergencies.

**Keywords:** Construction site layout, risk analysis, vulnerability, optimization algorithm, optimal paths, GIS

# Résumé

## **Optimisation de l'aménagement d'un chantier de construction en fonction des risques naturels et technologiques, utilisation du SIG.**

Les chantiers de construction contiennent plusieurs installations. Celles-ci sont susceptibles d'être endommagées par des incidents liés aux risques naturels ou technologiques comme les incendies, les explosions, les ondes de souffles, etc. Ces incidents peuvent avoir des conséquences néfastes sur l'ensemble du processus de construction, ce qui pourrait entraîner des accidents graves ayant un impact majeur sur la productivité des employés, le temps global du projet, sa qualité et son budget. Par conséquent les gestionnaires et les planificateurs du projet doivent adopter et développer des approches novatrices capables de faire face aux risques naturels potentiels, de minimiser leurs conséquences et de faciliter l'évacuation du site en cas de danger. Une de ces approches consiste à optimiser l'aménagement des chantiers de construction. En général, la réduction des dommages résultants de risques naturels ou technologiques est encore un défi scientifique.

Dans cette thèse, deux modèles (déterministe et probabiliste) sont développés pour minimiser les risques au sein d'un chantier. La méthode adoptée pour le développement de ces deux modèles consiste en :

- La modélisation des éléments du chantier, par exemple : le générateur électrique, les bureaux et les entrepôts de matériaux, sont modélisés en 2D, pour agir en tant que source d'aléa et/ou cible vulnérable potentielle.
- La modélisation de l'aléa : elle montre l'interaction des aléas entre les composants du chantier.
- La modélisation de la vulnérabilité : elle représente la faiblesse potentielle des cibles sur l'aléa généré par chaque source.
- La définition de la fonction d'utilité : elle vise à offrir une disposition optimisée avec un minimum de risque total sur le chantier. L'algorithme à évolution différentielle est adopté pour exécuter le processus d'optimisation.

D'une part, dans le modèle déterministe, nous utilisons le principe de la syntaxe spatiale pour étudier l'impact des configurations spatiales dans l'évaluation du risque sur le chantier. Par conséquent, comme le processus d'évacuation est pris en compte dans l'estimation du risque, le risque réel est amplifié en utilisant le facteur de pénalité appelé « profondeur moyenne ». L'algorithme de Dijkstra est appliqué sur un modèle déterministe afin de trouver les chemins les plus sûrs (chemins de moindre risque) pour évacuer les sites à partir de chaque position sur le chantier vers les lieux sûrs afin de diminuer les pertes humaines et matérielles.

D'autre part, le modèle probabiliste suppose que le risque est composé de la défaillance individuelle de chaque installation sur le chantier de construction. La simulation numérique est utilisée pour trouver la distribution de probabilités des défaillances pour l'ensemble du site.

Les fonctionnalités d'un SIG (Système d'Information Géographique) ont été utilisées pour présenter les données sous forme de cartes, pour produire des cartes spatiales de risque sur le chantier de construction, pour mettre en œuvre l'algorithme de Dijkstra et pour l'analyse du coût le plus faible.

A titre indicatif, les modèles proposés sont utilisés dans un cas d'étude comprenant plusieurs installations. Dans le modèle déterministe, toutes ces installations agissent comme des sources d'aléa et des cibles vulnérables, en même temps, dans le modèle probabiliste, quelques-unes de ces installations agissent comme des sources d'aléa et toutes comme des cibles vulnérables. Les résultats obtenus montrent que les modèles proposés sont efficaces en raison de leur capacité à générer une disposition optimale du site avec un environnement de travail plus sûr. En outre, les modèles obtenus sont capables de mettre en évidence les zones les plus risquées d'un chantier, de générer les chemins d'évacuation les moins risqués, ce qui permettra de minimiser les blessures graves et les victimes en cas d'urgence.

**Mots clés:** Aménagement du site de construction, l'analyse des risques, vulnérabilité, algorithme d'optimisation, chemin optimal, SIG





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# CHAPTER 1

## General Introduction

This chapter involves presenting general introduction about construction site layout planning; the statement of the problem, justifications and objectives of conducting this research, the significance of this study, and finally the research outline.

### 1.1 Background

At the beginning of the twentieth century, a lot of the changes and evolutions happened in the construction industry. It becomes a fundamental criterion to measure countries' growth and development. Consequently, a lot of money were spent and will be spent in this sector to construct many projects; highways, tunnels, bridges, schools, hospitals, water networks, and sewer treatment systems, for instance.

Unfortunately, the construction industry is distinguished from other industries by a lot of risks occurring during the execution of construction projects (Zhang et al. 2013). Moreover, one main feature of the construction industry is the frequent occurrence of uncertain extreme events, such as fire, explosion, blast waves, thermal flux, and leakage of hazardous material. They may lead to failure and/or adverse effect on the project schedule, project budget, and project quality. They also threaten lives of workers. Furthermore, they may lead to catastrophic consequences if they propagate from one area to another within a construction site.

Teo et al. (2005) and Tam et al. (2004) indicated that fire hazard is one kind of accidents that may occur at construction sites that may lead to construction schedule disturbance. Hui et al. (2012) designated that due to rapid development in the construction industries, the fire hazard is frequently occurring at construction sites. U.S. Fire Administration (2001) found that about



4,800 construction site fires occur every year, resulting in more than \$ 35 million losses in property. It is obvious from these data; there is an urgent need to adopt creative ways to minimize these losses. Site layout planning, for instance, is one of these options that can be used for this purpose.

Construction managers and project site planners always aim to keep the consequences of these accidents events to a minimum level, and usually, they exert considerable effort to minimize injuries and fatalities that might be caused by these events. Therefore, it is necessary for the construction managers and project site planners to properly manage a construction site in order to maintain the integrity of the site, provide a safe working environment, and facilitate the evacuation process during the emergency cases. All of these will be positively reflected in workers' morale and productivity (Huang and Wong 2015).

In fact, construction site contains several supporting temporary facilities (concrete plant, tower crane, materials storage area, fabrication lot, electrical generator, fuel storage, offices, and so on). These supporting facilities are necessary to execute and complete construction activities. In addition, these facilities must be accommodated in a proper position within a site to be helpful in minimizing consequences of the potential hazard and achieve project intents.

Actually, minimizing risk resulting from natural or technological hazards is still a scientific challenge. Referring to El-Rayes and Said (2009) the construction site space is considered as one of the project resources that require management, like any other resources, in order to accomplish the project objectives.

Site layout planning can be defined as the accommodation of supporting temporary facilities at a suitable location within the available site space. Hence, to consider a site layout plan as efficient, it is essential to benefit from the work areas provided to minimize hazard consequences and alleviate the catastrophic cascading effects. Zolfagharian and Irizarry (2014) stated that for each construction project, the site layout planning is distinctive from any other projects and depends entirely on the work areas and the location of different facilities.

According to that, this research aims to enhance site layout planning by developing new models that generate optimal site layout aims to minimize the catastrophic consequences of the potential hazard. Moreover, this research seeks identification of the shortest and safest paths to help evacuate the construction site quickly and safely during the occurrence of uncertain accidental

events. The advanced technology like; genetic algorithms (GA) and geographic information system (GIS) were used in this study to run optimization technique and to generate a site spatial risk map respectively.

## **1.2 Statement of the problem**

Planning a construction site is a multi-objective task. In fact, it is very rare to complete a construction project without accidents. In addition, construction projects are not exempt from exposure to the occurrence of natural or technological hazards (fire, thermal flux, and explosions, for instance) that may lead to catastrophic consequences. The use of hazardous materials and the use of advanced technology in performing construction (production) activities are the main sources of these hazards' occurrence. Fire hazard, for instance, may occur in one or more of the temporary supporting facilities assigned in a construction site. It may lead to damage construction site completely or partly. Whatever the damage level occurs, the work in the site will be suspended.

The current site layout planning models focus entirely on reducing the travel cost distance between facilities (El-Rayes and Khalafallah 2005). They ignored the potential hazards that may lead to infeasible or non-effectual solutions. They believe that minimizing the travel distance will help save time and money. This is not always true, because sometimes if the site layout is organized by focusing only on travel distance and the potential occurrence of fire hazard is overlooked, this may lead to the occurrence of fatal accidents. This may, in turn, lead to the suspension of work for a period of time, impacts on workers' morale, and finally and more crucially, difficulties in evacuating the construction site. In addition to this, the parties involved in construction tend to make decisions regarding site layout plans based on their own experience. Sometimes these decisions may be incomplete and/or incorrect, which in turn leads to unsafe site layouts. Even though there are numerous researchers dealing with site space management to smooth arrangement of conducting construction activities, some of the construction site managers and planners still give less attention to site space management which still relies on the concept "first come first serve".

Moreover, only a few efforts have been devoted to organizing site layout for avoiding or at least minimizing the risk of potential hazards. El-Rayes and Khalafallah (2005); Sanad et al. (2008)

developed an optimization site layout model which aims to maximize construction safety. However, these models did not take into account the potential hazards such as fire and blast waves during optimization as they rather focus on the facilities containing hazardous materials.

Furthermore, one of the most important issues that are often overlooked during site planning is the identification of the shortest and safest path to help evacuate the construction site quickly and safely during the occurrence of uncertain events. Evacuation is highly significant in construction site safety planning. If any hazard occurs within a site, the workers need to be evacuated safely, through crossing areas with least risk, to minimize casualties. According to [Mahdjoubi and Yang \(2001\)](#), finding the best paths can minimize the number of injuries and fatalities. [Soltani et al. \(2002\)](#) stated that the best route does not necessarily have to be the shortest distance path but must be the one with the lowest risk. The travel cost of moving along the shortest physical distance route within a construction site can be higher than that for other routes if there are limited visibility and a high risk along that route.

Therefore, this research aims to develop optimal site layout based on minimizing the risk of potential hazard. In addition, it aims to find the best paths to facilitate evacuation within a construction site, readily and without panic, from any position on the site to the external exit safe gate.

### **1.3 Research justifications**

The site layout planning is one of the major tasks that should be performed by site managers and it is distinctive from one project to another. Most of the current site layout planning methods are ineffective because they primarily emphasized only on minimizing travel cost distance among facilities. In addition, they disregarded the expected risk of fire hazard. Moreover, construction site managers and planners give less attention to site space management due to complexity, great effort and time needed. Also, the rules and regulations for site layout planning have not been created. Also, there is a scarcity of studies aimed at identifying the lowest risk path for evacuating a construction site during emergencies.

Generally, implementing inefficient site layouts result in generating unsafe working environments, damage one or more of supporting facilities, project performance becomes poor, owner attitudes will not be met, price changes and cost overruns, and delay in project completion

date. These, in turn, lead to failure of the whole project. The present research addresses two main issues:

- The loss of life as a result of construction accidents every year should be reduced. According to (Banaitiene and Banaitis, 2012), about 1300 people are being killed every year in Europe due to construction accidents. Furthermore, construction workers are about three times more likely to be killed and twice as likely to be injured compared to other industries.
- The hazards such as fire may take place at any facilities on a construction site. It can then disseminate to other facilities or positions within the site, causing what is called domino-effect phenomena, which lead to catastrophic damages and losses in property and life. Even though this rarely happens in construction sites, the high dependence on advanced technology, which depends highly on electrical and fuel energy usage, may increase the probability of technological hazards occurrence. It is then worth to consider technological and natural hazard as one of other usual hazards happened during construction of the project.

Since few efforts have been devoted to considering the impact of natural and technological hazards and their risks on construction sites, the current research is conducted to improve site layout planning in order to alleviate most of the problems associated with ineffective site layout plan.

## **1.4 Research objectives**

This research aims to improve construction site layout planning in order to avoid or at least minimize the natural or technological hazard consequences during constructability process. Therefore, the objectives of this research can be summarized as follows:

1. Developing a new model that takes into account the hazard and vulnerability interactions among facilities. The model capable of avoiding, or at least diminishing the risk of natural or technological hazard and subsequent disasters.
2. Analyzing and identifying the influence of space configurations on spatial variability of risk within a construction site.
3. Visualizing the site spatial risk map (generated from potential hazards) within a construction site utilizing geographic information system (GIS).

4. Finding the best paths to facilitate evacuation within a construction site, readily and without panic, from any position on the site to the external exit safe gate. This will minimize the number of injuries and fatalities.
5. Developing a probabilistic optimization model aims to minimize the risk of failure of the whole site.

## 1.5 Significance of study

Indeed, performing efficient site layout planning considering the risk of natural or technological hazards will afford optimum safe working environments and minimize undesirable impacts of these hazards. In addition, construction companies that conducting site layout planning efficiently will benefit from greater productivity, financial savings, enhanced decision making and success rates of new projects. So, it is important to properly manage a site in order to minimize the number of accidents and injuries and maintain the integrity of the construction workers before, after and during emergency cases.

Foremost, this research draws inspiration from [Dagan and Issac \(2015\)](#) where the interaction between facilities is considered as a source of the hazardous situation within a construction site.

However, up to now, only a few studies have been devoted to the generation of efficient models for site layout planning. The proposed model in this research overcomes the deficiencies of the existing optimization models, as the layout optimization now depends on the hazard and the vulnerability of the facilities, instead of transportation cost. The present research will focus on:

1. The implementing of an interaction matrix technique to determine the potential global impact for each construction facility in the project.
2. The use of an optimization technique to optimize site layout facilities based on interaction matrices
3. The effect of space configuration in understanding, accommodating and modeling spatial analysis problems.
4. The use of geographic information system (GIS) capabilities to analyze spatial datasets and generate a site spatial risk map for the construction site. It will assist in identifying the most at-risk positions within the site, which will play a primary role in finding the safest paths for site evacuation to minimize injuries and fatalities. Generally, understanding and visualizing

the spatial variability of risk at the construction site will assist site managers in making and adopting proper decisions. This will be able to avoid or at least reduce the domino effect of a threat.

5. Develop a probabilistic model that consider the risk of failure of the whole site is a combined of individual failure of each facility presents in the construction site. It shows how optimizing site layout reduces the probability of failure for the whole site.

The proposed model will assist construction managers and planners in the hierarchy the existing facilities in the construction site based on their potential global impact. This hierarchy will lead to determining the facilities that required more attention (highest risk facilities) during the construction phase to enhance the constructability and safety of workspaces in the project site. Moreover, the risk is visualized within a construction site by considering the space configuration and visibility in estimating the risk at each position within a site

## **1.6 Thesis organization and contribution**

Since the current site layout planning models focus only on travel cost distance, therefore, in this study, we are interested in developing site layout optimization model that takes into account the risk of natural or technological hazard within a construction site as the main utility function. Two models have been developed: deterministic and probabilistic. Both models consist of: (1) modeling construction site components, for instance; electric generator, fuel storage, offices, equipment and material storages, in the 2D layout. These components act as hazardous sources and potential targets at the same time; (2) modeling hazard interaction matrix: it shows the hazard interaction among site components and the attenuation of hazard with distance; (3) modeling vulnerability interaction matrix: it represents the potential weakness of whole targets to the hazard generated from each source; (4) defining the utility function: it aims to afford an optimized site layout with minimum total risk in the construction site; and (5) performing spatial analysis technique, utilizing space syntax principle, to realize space configurations in the construction site. As the evacuation process is considered in evaluating and visualizing the risk, the actual risk is amplified by utilizing penalty factor, took from space syntax analysis, called mean depth.

This study will be presented in five chapters as illustrated below:

1. Chapter one: include an introduction to the study, the objective of the study, the reason behind performing this study, and the significance of it.
2. Chapter two: literature review that involves information about a current site layout planning methods, the criteria utilized for site layout planning, the optimization technique, the hazard, vulnerability and risk in a construction site, space syntax explanation, GIS capabilities, and Dijkstra's and least cost path algorithm.
3. Chapter three: research methodology designates how the objectives of the study will be attained. Also, the model developments that display the mathematical formulas to formulate site layout planning problems and run optimization technique.
4. Chapter four: case studies that display the model implementation on a case project that consists of several facilities acting as hazardous sources and potential vulnerability targets at the same time. It involves discussion on the obtained results.
5. Chapter five: conclusion and perspective of the study.

## **1.7 Résumé du chapitre 1**

Ce chapitre contient une introduction générale sur l'aménagement d'un chantier de construction, la problématique, l'importance ainsi que les objectifs de cette recherche.

En général, le secteur de la construction se distingue des autres secteurs par la présence des risques pendant le processus de la construction (Zhang et al. 2013). Une caractéristique principale en est la présence fréquente d'événements extrêmes incertains, comme le feu, l'explosion, les ondes de souffle, le flux thermique et la fuite de matériaux dangereux. Ces événements pourraient jouer sur le calendrier d'un projet, sur son budget et sur sa qualité. Ils peuvent aussi mettre en danger la vie des ouvriers. En outre, ils peuvent mener à des conséquences catastrophiques s'ils se propagent d'une zone à une autre dans un chantier. Les chefs de projets de construction ont toujours comme objectif de minimiser les conséquences de ces événements accidentels et font un effort considérable pour réduire les blessures et les victimes sur les chantiers et pour faciliter le processus d'évacuation en cas d'urgence.

En fait, le chantier contient plusieurs installations provisoires nécessaires pour exécuter les travaux de construction. Elles doivent être situées dans une position appropriée afin de minimiser les conséquences du danger potentiel et de réaliser les objectifs du projet. Les modèles actuels de

planification des chantiers de construction se concentrent entièrement sur la réduction des coûts de déplacement entre les installations (El-Rayes and Khalafallah 2005). Ces modèles ne prennent pas en compte les aléas potentiels qui peuvent menacer les résultats attendus du projet.

Ils considèrent que la minimisation de la distance de déplacement aidera à économiser du temps et de l'argent. Ce n'est pas toujours vrai : si la disposition du chantier est organisée en prenant en compte seulement la distance des déplacements et en ignorant la présence potentielle des aléas naturels ou technologiques, elle peut mener à des accidents mortels. Ceci peut conduire à son tour à la suspension du travail pour une certaine période, à des impacts sur le moral des ouvriers et finalement à des difficultés dans l'avancement du chantier. De plus, les parties impliquées dans la construction ont tendance à prendre des décisions quant aux plans d'aménagement d'un chantier basés sur leur propre expérience. Certains chefs de projets de construction donnent peu d'attention à la gestion spatiale du site qui est toujours basée sur le concept « premier arrivé, premier servi ». Parfois, ces décisions peuvent être mauvaises et entraînent une disposition risquée du chantier.

Une autre question importante souvent oubliée pendant la planification du chantier est l'identification du chemin le plus court et le plus sûr pour évacuer le chantier rapidement et sans risque pendant la présence des aléas. Cette recherche vise à améliorer l'aménagement du chantier en développant des modèles capables de minimiser le risque de l'aléa potentiel. De plus, elle aide à trouver les meilleurs chemins pour faciliter l'évacuation sur un chantier, sans panique et à partir de n'importe quelle position sur le chantier. Cette recherche vise à étudier et à analyser l'influence de configurations spatiales sur la variabilité spatiale de risque dans un chantier.

Le modèle proposé aidera les chefs de projets de construction dans l'identification des installations et des positions qui nécessitent plus d'attention (installations à haut risque) pendant la phase de construction, qui se traduira par l'amélioration de la constructibilité et de la sécurité des espaces de travail sur le site du projet.

Cette recherche sera présentée dans cinq chapitres comme illustré ci-dessous :

1. Chapitre un : il contient une introduction générale de la thèse, les objectifs, l'importance de la réalisation de cette recherche.
2. Chapitre deux : il présente une étude bibliographique concernant les modèles actuels pour l'aménagement des chantiers, les données générales sur l'aléa, la vulnérabilité, le risque, la



matrice d'interaction, les capacités des SIG, l'implémentation de l'algorithme de Dijkstra, l'impact de la configuration de l'espace sur le risque et la façon dont la technique d'analyse spatiale est appropriée pour cela, le mécanisme de travail de l'algorithme d'évolution de l'optimisation et finalement le principe d'analyse de l'incertitude.

3. Chapitre trois : il traite la méthodologie adoptée pour réaliser les objectifs de la thèse. Il illustre les étapes nécessaires pour développer deux modèles d'aménagement de chantier (déterministe et probabiliste). Il présente les formules mathématiques utilisées pour réaliser la modélisation de l'aléa, de la vulnérabilité et du risque, nécessaire pour développer des modèles d'aménagement de chantier. Il démontre la procédure adoptée pour générer une carte de risque spatial et pour déterminer les chemins optimaux à partir de n'importe quelle position jusqu'à la sortie de secours sécurisée extérieure.
4. Chapitre quatre : il décrit le cas pratique utilisé pour mettre en œuvre les modèles proposés. Il contient des commentaires et l'analyse des résultats obtenus.
5. Chapitre cinq : il contient un résumé de la recherche, il présente une conclusion de la thèse, et fournit des perspectives pour les développements futurs de la recherche en cours.

# CHAPTER 2

## Related Work

This chapter involves presenting general information about life cycle of construction project, site layout planning, interaction matrix, kinds of hazards, vulnerability definition and types, previous studies conducted and dealt with a site layout planning, optimization technique explanation, space syntax principle, Dijkstra’s algorithm, GIS datasets analysis and capabilities, and the benefit of simulation for risk analysis.

### 2.1 Project life cycle

Project life cycle can be defined as “the whole process needed for producing a new system, new plant or another specified result” Archibald (2003). The life cycle for any kind of project has start and end points accompanying with a time scale. Moreover, the construction project can be defined as a set of activities linked together to form a task and get a specific product through various phases called project life cycle.

The life cycle of a construction project involves exerting many efforts from all parties participating in the project in order to accomplish owner desires, purposes, and requirements. The life cycle of construction project consists of several phases that are common to anyone having experience in construction industry. Figure 2.1 displays all of these phases.



Figure 2.1. Life cycle of construction project

### **2.1.1 Feasibility study**

In this phase, most of the analysis and assessments have been done by the owner or occasionally with the involvement of consultants. The parties participated, in this phase; conduct the feasibility study of proposed constructing project, evaluate the economic feasibility of the project assess the scope of the work, determining the suitable location of the project from possible available options, and perform environmental and social impact assessment of the project.

### **2.1.2 Design phase**

Design phase can be separated into two sub-phases: preliminary design and detailed design. The initial design of the project is made during a preliminary design stage. It also involves: evaluating different alternatives, preparing preliminary plans, drawings, specifications, preparing preliminary cost estimates, and preliminary landscape of the project that will be evaluated by the owner before generating detailed drawings. The preliminary design stage needs a significant coordination and cooperation among different specialists in geology, civil, architecture, electric, and mechanic works.

On the other hand, the detailed design stage involves: investigation and design of project items, refining the preliminary design, developing detailed plans and specifications, doing cost estimates, and determining construction materials and construction methods, and finally identifying the required temporary supporting facilities and equipment.

### **2.1.3 Procurement phase**

The construction documents prepared during design phase are assembled together in order to start procurement phase. The procurement phase involves: conducting a bid advertisement to attract contractors to bid, provide contractors with bid documents, conduct meetings with interested bidders, and evaluating the interested contractors to select one of them to construct the project.

#### **2.1.4 Construction phase**

The construction phase is the most important and vital phase of a project life cycle since the plans and specification will be translated into a physical product. Most of the construction problems will appear during this phase. In addition, most of the project budget will be spent on this phase. Therefore, the selected contractor will exert all of his efforts to minimize accidents, injuries, fatalities and provide a safe working environment to achieve and complete project within specified time, budget, and quality. Site layout planning is one of the essential tasks that must be conducted during this phase.

#### **2.1.5 Operation and maintenance phase**

In this phase, the constructed project is evaluated to determine if it meets the planned objectives or not. This phase involves the operation and maintenance of the constructed project. In addition, it involves transferring the responsibility of project operation to the initial occupants.

### **2.2 Site layout planning**

Site layout planning techniques perform to all projects where numerous physical means have to be located in a certain space. In general, the layout means an arrangement of everything required to complete production of any product. Really, the main purpose of site layout planning involves organizing work areas in the most efficient manners to be safe for personnel carrying out the work.

Site layout planning can be defined as accommodation, in advance, of supporting temporary facilities, such as an electric generator, fuel storage, office trailers, fabrication areas, construction equipment, and warehouses and so on, at the proper location within the available site space. Even though all of these facilities are temporary, but they are great crucial to conduct and complete construction and production activities. In addition, any accidental event occurs in at least one of these facilities may be sufficient to endanger the workers' life, escalate the occurrence of domino effect phenomenon, hinder and suspend work in the project for a period of time and even failure of the whole project. The purposes of conducting site layout planning allow a more active

workflow at the site and make workers and equipment being more productive. [Andayesh and Sadeghpour \(2014\)](#) indicated that site layout models can be categorized into two classes. One is the static model, i.e. changes over time are not considered. The other is the dynamic model, i.e. changes over time are considered. The dynamic models focus on assigning an appropriate location of each temporary facility taking into account the dynamic changes in the requirements and site space availability. [Huang and Wong \(2015\)](#) stated that the site layout planning should be optimized taking into account multiple construction stages to avoid the excessive cost associated with the relocation of facilities and enhance efficiency.

The available construction site space should be exploited efficiently in order to minimize threats' impacts, provide the safe working environment, and enhance workers' productivity. There are many shortcomings associated with ineffective site layout plans:

1. Bad use of the available space.
2. Move long distances to carry out any operations on a construction site.
3. Skilled and qualified labors perform a lot of simple works.
4. The occurrence of various accidents on the site.
5. Suspension of work for a period of times.
6. The discomfort of labor when executing construction activities.
7. The complexity of monitoring and controlling the construction process

However, there is a consensus among most researchers that site layout planning is still a complex and challenging task ([Zolfagharian and Irizarry 2014](#); [Sanad et al. 2008](#); [Zouein and Tommelein 1999](#)). [Sanad et al. \(2008\)](#) indicated that site layout planning is a complex problem, due to the existence of several large tasks that need to be performed. [Zouein and Tommelein \(1999\)](#) demonstrated that utilizing site space efficiently to locate resources and facilities over the duration of a project is a complicated dilemma. In general, to develop and attain an efficient site layout plans, the construction managers and site planners must recognize the followings:

1. The facilities needed to be located on a construction site
2. The available space and the size of the space required for each facility.
3. The best position that each facility should be located at within a construction site
4. The reduction of failure risk due to natural or technological hazards.
5. The increase in workers' satisfaction and safety.
6. The reduction of material handling

7. The reduction of travel distance and unnecessary movements to minimize total transportation cost.

Unfortunately, all of these realizations cannot be achieved simultaneously, so the final site layout should take into account a balance among all factors affecting on it in order to acquire optimal site layout plan. Up until now, there is no regulation adopted to organize and manage site layout planning for avoiding or at least minimizing the risk of natural and/or technological hazards. Furthermore, the current site layout planning models consider a travel distance as a sole criterion in generating site layout plans (El-Rayes and Khalafallah 2005). Therefore, it is significant to develop a new model aims to minimize the risk of natural and/or technological hazard.

### 2.3 Temporary facilities

Construction managers, based on their experience, have to identify the temporary facilities required to facilitate construction operations. Table 2.1 displays some of the common temporary facilities utilized over construction phase of the project. According to Elbeltagi et al. (2001), the size of temporary facilities can be determined according to estimated quantity of the work, site space availability, resources' production rate, labors requirements, and the allocated project budget considerations.

Table 2.1. Some of the temporary facilities utilized over construction phase

	<b>Temporary Facility</b>
1	Labor services
2	Carpentry fabrication
3	Carpentry storage
4	Material storage
5	Offices
6	Parking lots
7	Concrete plant
8	Guard office
9	Electric generator
10	Fuel storage
11	Steel reinforcement rebar shop
12	Reinforcement rebar fabrication area
13	Cement storage
14	Welding area
15	Construction equipments

## 2.4 Optimal path

Occasionally, construction managers encounter difficulties in finding the safest routes for movement within a construction site. The ability to find the optimal path between two points is very important in all fields of life: in industry, commerce, urban planning, and evacuation, for instance. It has great importance in reducing cost, speeding up production, and facilitating communication.

Unfortunately, there is a scarcity of studies aimed at identifying the lowest risk path for evacuating a construction site during emergencies. [Soltani et al. \(2002\)](#) stated that the best route does not necessarily have to be the shortest distance path but must be the one with the lowest risk.

The optimal distance and the straight line distance between any two points are not necessarily the same. The straight line distance always overlooks the existence of obstacles, the cost of route construction, the time needed to navigate along the route, and the riskiness of the route. On the other hand, optimal path analysis leads to finding the most effective and shortest path from one location to another, considering all of these criteria and/or any other criteria defined by the planners and construction managers.

The travel cost of moving along the shortest physical distance route within a construction site can be higher than that for other routes if there are limited visibility and a high risk along that route. Therefore, finding the best paths that facilitate evacuation within a construction site, without panic, from any position on the site to the external exit safe gate is one of the crucial issues that haunt construction site managers.

## 2.5 Previous studies

Several studies have been conducted for construction site layout planning and to find optimal paths. [Zolfagharian and Irizarry \(2014\)](#) confirmed that site planning is unique for each construction project. They also stated that optimizing the cost, safety, and productivity of a project relies on the adequate planning of the construction site layout.

Really, based on the broad literature review, the studies interested in site management and planning can be categorized into three parts: (1) the criteria that have been utilized for

conducting optimization; (2) optimal path determination; and (3) risk analysis and quantification studies.

### **2.5.1 Criteria consideration for site layout planning**

Site layout planning can be categorized according to the criteria that have been utilized for conducting optimization into:

#### **2.5.1.1 Optimization models based on travel cost distance**

In general, there are a lot of efforts have been exerted by the researchers to enhance construction site layout planning. Most of these efforts consider the travel cost distance as the most significant utility function and they aim to minimize it (Andayesh and Sadeghpour 2013, 2014; Astour and Franz 2014; Cheng and O'Connor 1994, 1996; Hegazy and Elbeltagi 1999; Zouein et al. 2002; Said and El-Rayes 2013; Zouein and Tommelein 1999; Huang and Wong 2015). They also applied several optimization algorithms to accommodate construction facilities at suitable positions within a construction site.

Hegazy and Elbeltagi (1999) developed an evolution-based site layout planning model called EvoSite. It is based on the implementation of a genetic algorithm (GA) to search for the optimum layout. El-Rayes and Said (2009) presented a model based on approximate dynamic programming (ADP) aiming to minimize the overall site layout costs in order to get optimal dynamic site layout of construction projects. Zouein and Tommelein (1999) developed a linear programming model to generate dynamic site layout, endeavoring to minimize the travel distance and relocation costs among all facilities. Andayesh and Sadeghpour (2013) developed an innovative dynamic model that is capable of producing optimized layouts over the project's duration. The model is derived from the principles of an energy dominating physical system. The model is effectual due to its ability to assign space to facilities when they are required on the site and allows for the reuse of the space over time. Huang and Wong (2015) used the branch and bound algorithm to develop optimal site layout aims to minimize total cost. They indicated that the total cost consist of material transportation cost between facilities, set up cost of facilities and relocation cost for all facilities in each construction stage.



Furthermore, several researchers have used advanced technologies for site management. **Cheng and O'Connor (1994, 1996)** developed an automated site layout system called ArcSite. The proposed model uses the search by elimination principle available in the geographic information system (GIS) to identify the best position for each supporting temporary facility and generate the optimal layout. **Andoh et al. (2012)** presented a framework for the continuous tracking of the 4D status of a dynamic construction site, utilizing radio frequency identification (RFID), the global positioning system (GPS) and the GIS, in order to achieve project objectives. **Astour and Franz (2014)** described the problems associated with site layout planning and developed a model utilizing building information modeling (BIM) to generate a 3D site layout plan. **Kang and Seo (2012)** utilized GIS for determining the optimal layout of a haul route for large earthmoving projects.

### **2.5.1.2 Optimization models for consideration of safety issues**

Other researchers concerned with maximizing safety conditions by considering the safety operation of some supporting facilities, crane, and facilities containing hazardous material for instance. They asked construction managers to give them higher priority of controlling over construction phase (**Elbeltagi and Hegazy 2003; El-Rayes and Khalafallah 2005; Sanad et al. 2008; Dagan and Isac 2015**).

**Elbeltagi and Hegazy (2003)** proposed site layout planning optimization model that considers other relevant criteria, in addition to the travel distance, such as site safety and productivity. They presented the construction site and facilities as a multi-unit. The GA was used to achieve an optimal site layout. **Sanad et al. (2008)** developed an optimization site layout model by utilizing a GA and considering safety aspects and the actual route between facilities as the main criteria in generating optimal site layout. **El-Rayes and Khalafallah (2005)** presented a model capable of maximizing construction site safety and minimizing travel cost distance within a construction site. They suggested providing an adequate distance between hazardous facilities and any other potential targets. The safety criteria that were considered in this model are (1) crane safety operation and (2) control of hazardous materials. Although the model did not take into account hazards from all other construction facilities, but it is still vital because it illustrated the trade-off between safety and travel costs. **Dagan and Isaac (2015)** proposed a planning method in order to protect workers from injuries and keep them at a safe distance from each

other. The proposed method depends on the assumption that the hazardous situation is a result of the interaction between the reinforcing and counteracting characteristics of the workers. Moreover, they embedded the definition of a minimum safe distance between workers. In addition, 3D time-space diagram is embraced in the methodology to analyze the dynamic movement of workers on the construction site.

### **2.5.2 Determining the optimal path**

Finding the safest routes for movement within a construction site is also still a scientific challenge. [Soltani and Fernando \(2004\)](#) developed a framework for construction site path planning analysis, considering travel cost, visibility, and safety as multi-criteria for path evaluation. [Choi et al. \(2009\)](#) developed software called (dump traveler) to determine the optimal haulage routes from mines for dump trucks. The software is based on a combination of multi-criteria evaluation and least-cost path analysis. [Choi and Nieto \(2011\)](#) created a software application called the Google Earth Based Optimal Haulage Routing System (GEOHARTS) to find the optimal route for dump trucks in construction and mining sites. It is based on the capability of Google Earth and the least-cost path algorithm. Moreover, the software has the ability to generate the optimal haulage routes that ensure the shortest travel time and lowest fuel cost between loading and dumping areas.

There is a frequent trend among most researchers to use GA to find the optimal path. [las Mercedes Gómez-Albarrán et al. \(1997\)](#) created an algorithm called GALO, which integrated GA and Lee's algorithm in order to find the shortest path between nodes in circuit routing. [Gen et al. \(2001\)](#) utilized GA for solving problems associated with network analysis, especially those related to finding the shortest path. [Soltani et al. \(2002\)](#) conducted a comparison among three optimization techniques to evaluate their efficiency in finding the optimal paths on construction sites. These algorithms are GA, Dijkstra's algorithm, and the A\* algorithm. [Saha et al. \(2005\)](#) utilized Dijkstra's algorithm and least-cost path analysis in route planning of areas susceptible to landslide. [Xu and Lathrop \(1994\)](#) improved the cost simulation model. They enhanced the cost-path tracking by recording path information using two layers. [Feldman et al. \(1995\)](#) used remotely sensed data, GIS, and least-cost analysis to carry out pipeline routing.

**Collischonn and Pilar (2000)** developed a least-cost path algorithm to determine the best path for linear features such as roads and canals. The algorithm is highly dependent on the raster structure, which is usually utilized in GIS. **Yu et al. (2003)** upgraded traditional algorithms for practical roadway planning. They took into consideration the spatial distances and the existence of tunnels and bridges, in finding the least-cost paths for roadway planning. **Rees (2004)** utilized Dijkstra's algorithm to calculate the least-cost paths on a Digital Elevation Model (DEM) to find footpaths in a mountainous area in Wales. The results showed that the existing footpaths did not coincide with the calculated least-cost paths and did not follow the route that took the least time. **Akkanen and Nurminen (2001)** conducted a review study to demonstrate the evolution of routing algorithms. They concluded that algorithms have improved over time. They also indicated that the engineering attitude should be considered when utilizing any of these algorithms. **Kang and Seo (2012)** elaborated a GIS-based method for determining the optimal haul route for earthmoving. They implemented a least-cost path analysis to calculate the route with the shortest weighted distance between cut and fill areas. **Mahdjoubi and Yang (2001)** created Virtual Construction Material Router (VCMR) software. It is composed of GIS, computer-aided design, and fuzzy logic. It enables the simulation of several potential scenarios, where site managers can select the best routes for transferring materials within a construction site. **Modesti and Sciomachen (1998)** performed a study to find the shortest path in urban transportation networks considering travel time, travel cost, and user preferences as main criteria to identify the optimal path. **Sung et al. (2000)** identified the shortest path for time-dependent networks based on Dijkstra's algorithm. In these networks, the time interval is the basic unit to determine the flow speed for each link. **Gao et al. (2007)** indicated that evacuation is very crucial in emergency management. They developed a model to minimize the evacuation time through performing a simulation of a route/time swapping process utilizing a heuristic algorithm to get the optimal routes.

### **2.5.3 Risk management studies**

Several studies have tackled the subject of construction risks and injuries occurring during the construction process, proposed methods to facilitate evacuation and reduce losses and casualties in cases of emergency, and the economic cost of implementing risk management while ignoring the impact of site layout on minimizing these losses.

Raz and Michael (2001) developed a questionnaire to identify the tools that are most frequently utilized and contributed by enhancing project risk management. Akintoye and MacLeod (1997) found that risk management during construction is very significant in reducing losses and increasing profitability, and also conclude that the risk analysis and management depend entirely on experience, judgment, and intuition. They found that risk management techniques are rarely utilized due to a lack of knowledge and suspicion about the appropriateness of these techniques in giving the best results. Kim et al. (2013) stated that the repetitive occurrence of similar accidents in the construction industry is a prevalent feature. They proposed an accident automated information retrieval system that composes a query set that combines building information modeling (BIM) objects with a project management information system. Users can noticeably reduce query generation and can easily avoid risks by receiving similar past accident cases that may happen while they work. Carr and Tah (2001) proposed a model for qualitative risk assessment based on a hierarchical risk breakdown structure. In this model, the relationship between project sources and consequences on project performance can be quantified utilizing a fuzzy approach.

Charrière et al. (2012) talked about the importance of risk communication as one of the procedures that should be conducted to enhance the preparedness of inhabitants in order to minimize risk disaster. They proposed a visualization utilizing GIS as one of the best ways of propagating information about spatial phenomena. Belinfante et al. (2012) conducted a study to propose a way of determining the economic value of geospatial information in risk management. They claimed that the probable value of geo-information in risk management is high due to its ability to enhance the speed and quality of decision-making in disaster and risk management. This, in turn, enhances the possibility to minimize losses and damage. Kang et al. (2013) developed a risk management visualization model that has the capability to analyze the degree of risk in construction projects by collecting risk information utilizing quantifying methodologies like the Analytical Hierarchy Process (AHP) and fuzzy techniques.

Jannadi and Almishari (2003) developed a computerized model called risk assessor model (RAM), to identify the risk associated with specific construction activities. It is helpful for contractors in determining the highest risk of major construction activities and enhancing the safety precaution arrangements. Mitropoulos and Namboodiri (2010) proposed new safety risk assessment technique for construction activities called task demand assessment (TDA). It depends on the activity characteristics, the level of observable task demand factors and exposure

to the hazard. However, the method elucidated how the potential of accidents are highly impacted by the changes in the operation parameters of construction activities. Also, it reveals the complexity to conduct activity safely.

Rozenfeld et al. (2010) developed a construction job safety analysis (CJSA) framework to assess the hazard of construction activities. The framework aims to enhance safety precautions and planning at the affected locations, through identifying the probable loss of control events for common construction activities, and their probability of occurrence. They found that the events related to exterior work at height are the most common. Sousa et al. (2015) indicated that the rate of construction accidents is still very high, even with the resort to utilizing advanced technology in performing construction activities. They referred this to the financial rise of applying additional safety precautions in a competitive market. Therefore, they offered a model that displays the cost- beneficial of conducting occupational safety and health risk management on construction projects. Although all of the previous models are efficient, they focused only on hazard generated by construction activities operation. They did not consider the consequences of natural or technological hazards that may lead to catastrophic destruction.

However, other researchers devoted their attention in developing frameworks deal with the technological or natural hazards and cascading effects that may occur due to these hazards. Most of these frameworks aim to quantify the vulnerability, the incurred losses, and the probability of failure for the system (Douglas 2007; Roberts et al. 2009; Nguyen et al. 2009; Antonioni et al. 2009; Mebarki et al. 2012a, 2012b, 2014, 2016; López-Molina et al. 2013, Kadri et al. 2013, Leone et al. 2011; Eckert et al. 2012;; Marchand et al. 2009).

Roberts et al. (2009) stated that there is a difference in recognizing, evaluating, defining and measuring the risk, hazard, and vulnerability between natural and social sciences. They indicated that the risk is quantitatively measured in physical science, whereas in social sciences risk is qualitatively measured

Mebarki et al. (2012a; 2012b; 2014a; 2014b) performed a study considering the accidents that may be expected to happen in industrial plants. They stated that if the initial accident or hazard occurs at industrial plants, and then starts to propagate to other objects and facilities within the plants, it will cause damages to the targets erected in the vicinity of the hazard sources. It may also cause a new sequence of damages and cascading effect called “domino effect”. Mebarki et al. (2012a) made comparisons between the risk of structure fragments and blast wave that may

take place in industrial plants. They proposed simplified mechanical models to describe global failure (overturning, sliding, buckling, shear effects, excessive bending, for instance) of tanks in the plant. [Mebarki et al. \(2012b\)](#) studied the failure risk of masonry construction resulted from flood hazards. They analyzed the relation between flood hazard intensity, represented by flood water level, and the probability of failure of masonry construction. Moreover, they developed a probabilistic risk framework considering the failure of masonry construction is a combined of a set of governing parameters having different individual weighted contribution. [Mebarki et al. \(2014, 2016\)](#) studied the risk of a tsunami on the coastal industrial tanks and evaluated its resilience after the occurrence of a tsunami event.

[Abdolhamidzadeh et al. 2010](#) indicated that explosions and fires are the primary incidents for domino effects happening. [Nguyen et al. \(2009\)](#) studied the accidents and the domino effect analysis for the industrial plants. They developed a probabilistic approach to quantify the probability of domino effect due to explosions. [Kadri et al. \(2013\)](#) presented a methodology to quantify the individual and societal risk of domino effects triggered by fire and explosion in an industrial site. [Antonioni et al. \(2009\)](#) developed a methodology to assess the risk due to a domino effect in order to identify the potential escalation hazard events in industrial areas. [López-Molina et al. \(2013\)](#) proposed a procedure to minimize the probability of occurrence of a domino effect in industrial areas. It is based on the assumption that the layout should be adequately designed to maximize safety distributions and diminish escalation probability of a hazard.

[Marchand et al. \(2009\)](#) developed a GIS-based model capable of quantifying and visualizing variability of potential damages and casualties of coastal areas apt to tsunami hazard. [Eckert et al. \(2012\)](#) studied the hazard, vulnerability and risk analysis for building prone to tsunami hazard in Alexandria. They utilized GIS to analyze the data obtained from remote sensing and field surveying. [Douglas \(2007\)](#) discussed the reasons behind poorly modeling of physical vulnerability of most of the natural hazards (volcanoes, mass movements, for instance), which will lead to poor quantitative risk estimations. [Leone et al. \(2011\)](#) developed a fragility curves that show the relationship between tsunami wave height and mean damage intensities for buildings-prone tsunami hazard at the Indian Ocean. These curves are a benefit to quantify the tsunami potential losses. [Aguilar et al. \(2008\)](#) generated a stochastic approach to estimate the expected damages of buildings located in urban areas due to seismic hazard. [Fuchs et al. \(2007\)](#) derived the vulnerability curve for the brick masonry and concrete buildings resulting from the

debris-flow hazard. They found that the vulnerability is highly dependent on the type of construction material utilized in buildings. Rosset et al. (2005) investigated the vulnerability of typical buildings due to the earthquake and generated maps showing the variation of damage rate of buildings. Lantada et al. (2009) evaluated the seismic risk for buildings using two methods: vulnerability index method and capacity spectrum based method. They generate detailed risk maps utilizing GIS to enhance emergency planning in urban areas. Dunand et al. (2014) assessed the seismic risk (human and economic losses) in a probabilistic manner. Cardona et al. (2012) developed a scientific platform model called CAPRA (comprehensive approach to probabilistic risk assessment) to assist countries in establishing risk management planning options to minimize the potential damages of hazard. The model capable assesses the probability of losses for elements at risk. Hollenstein (2005) suggested a conceptual extension to the scope of existing risk assessment models in order to standardize the consequence of the hazard evaluations.

However, up to now, only a few studies have been devoted to the generation of efficient models for site layout planning capable of avoiding or at least diminishing, consequences of natural or technological hazard (fire for instance) and subsequent disasters on the failure of the site. Moreover, most of the previous studies did not identify the effect of space configurations on the severity of the risks within the site. In addition, there is a scarcity of studies aimed at identifying the lowest risk path for evacuating a construction site during emergencies. Furthermore, the previous studies tackled the risk management supposed performing proactive protection systems to minimize the losses and enhance the resilient of the community. They rarely concern about the layout optimization as one of proactive protection systems that reduce the probability of losses or failure.

Therefore, it is vital to propose model capable of overcoming the deficiencies of the existing optimization models, where the layout optimization, in this research, depends on the hazard and the vulnerability of the facilities, instead of travel distance transportation cost. Generally, the correct assessment of hazard and the vulnerability are highly essential for the success of the risk estimation. Moreover, in this research, the spatial variability of risk at a construction site is visualized considering the impact of space configuration in estimating the risk at each position within a site.

Generally, in this research, two optimization layout models have been developed. One is deterministic and the other is probabilistic. The latter one has been developed since most of the



existing optimization layout models (especially those considering travel cost distance as the main utility function) are deterministic in nature, they are not reflecting the reality. In addition, there are a lot of uncertainties associated with the hazard and the vulnerability of elements at risk (temporary supporting facilities in our case). These uncertainties will be reflected on the risk of failure for each facility in the construction site as well as on the whole site. In general, the two models aim to minimize the risk due to potential identified hazards (natural or technological).

Therefore, the present research will focus on:

1. The implementation of an interaction matrix technique, which has been attempted in environmental impact assessments and structural risk for informal masonry construction [Mebarki et al., \(2012b\)](#), to develop hazard and vulnerability interaction matrices. In addition, to determine the potential global impact for each construction facility in the project.
2. The application of a space syntax concept that deals with space configuration, proving that it is an efficient method for understanding, accommodating and modeling spatial analysis problems [\(Bin et al. 2000\)](#).
3. The use of a differential evolution optimization technique to optimize site layout facilities based on interaction matrices.
4. The use of GIS capabilities to analyze the spatial datasets and generate a spatial risk map for the construction site. This map will assist in identifying the most at-risk positions within the site, and play primary cornerstone to finding the best routes with minimum risk that should be followed to minimize injuries and fatalities.
5. The utilization of Dijkstra's and least-cost path algorithm to find the optimal path for evacuating construction site in case of emergencies.
6. The identification of the probability of failure of the whole site and find suitable probability distribution function for the failure.

Whatever the case, the proposed two models will show how optimizing site layout reduces the probability of failure for the whole site. Moreover, they will assist construction managers and planners in the arrangement of the existing facilities in the construction site based on their risk. This hierarchy will lead to determining the facilities that required more attention (highest risk facilities) during the construction phase in order to enhance the constructability and safe working environment at a construction site.



## 2.6 Hazard

Regarding the United Nations Office for Disaster Risk Reduction (**UN-ISDR**), hazard can be defined as “a dangerous phenomenon, substance, human activity or condition that may cause loss of life, injury or other health impacts, property damage, loss of livelihoods and services, social and economic disruption, or environmental damage”. The hazardous events may be potentially harmful to the humans, buildings, technical and essential facilities (hospitals, universities, schools, etc.), infrastructures (highways, bridges, communication, electricity, water systems, etc.), environment, and economy. All of these can be assembled together under term elements at risk. Usually, the hazard can be expressed quantitatively as the exceedance probability of occurrence of an event with specific intensity value during a specific period of time utilizing historical data or scientific analysis. The hazard is also frequently described in terms of the likelihood of a measurable physical parameter or parameters exceeding a certain threshold value during a period of time.

Generally, the hazard can be classified into three categories:

1. Natural hazards which can be attributed to the occurrence of natural processes or physical phenomena that causing damage to the elements at risk. It can be divided into five classes:
  - a. Geophysical such as; earthquake, tsunami, volcanic, and landslides
  - b. Hydrological such as; flood and avalanches.
  - c. Meteorological such as; extreme temperatures (cold wave, heat wave, and severe winter conditions), storms and cyclones.
  - d. Climatological such as; drought and wildfire.
  - e. Biological such as; disease epidemics, and insect or animal plagues.
2. Human-induced or technological hazards which are a result of humans’ activities such as; industrial accidents (collapse, explosion, fire, gas leak, and chemical spills), and transportation accidents (air, rail, roads, and water).
3. Mixed hazards are combined of both natural and man-made hazard. They are considered as natural but triggered by human actions.

Usually, no one can predict or totally stop the occurrence of potential hazards, but it is possible to adopt proactive actions to reduce their consequences and cascading effects. In fact, in order to model any kind of hazard phenomenon, it is essential to recognize that the most catastrophic

events have not happened yet and the hazard modeling process requires experience. In addition, it is important to know the characteristics of each hazard phenomenon, which involves:

1. Type of hazard: since each kind of hazard has different input values and different analysis techniques.
2. Hazard intensity: since the hazard damaging effects is spatially distributed. The hazard levels are different with locations. This represents how hazard attenuates with distance. It is too high at the origin position of occurrence, and it reduces as keep away from its origin.
3. The area that may be affected by the potential hazard, which is called hazard footprints.
4. The frequency of occurrence: it is used to identify the frequency of occurrence of events. Usually, the large events are seldom occurring, whereas the small events are often occurring.

Furthermore, diverse modeling methods are needed for analyzing hazard scenarios; they depend on kind of hazard, the availability of input data, and scale of analysis (international, provincial, municipality, local, and site specific).

Briefly, hazard analysis involves the identification of hazard that could lead to harmful situations, analyzing several hazard scenarios especially those related to the occurrence of high consequences, and designing and adopting proactive measures and barriers that reduce assets damage to an acceptable level.

## **2.7 Vulnerability**

The vulnerability concept involved in the quantification of risk since the 1970s. Several definitions for vulnerability were developed due to the existence of different disciplines that having different own views and concepts on vulnerability.

According to (UN-ISDR), the vulnerability can be defined as the features and circumstances of a system or asset that make it prone to hazard and lead to negative consequences and losses. It changes continuously over time. In addition, the vulnerability can be expressed at different scale levels from human to municipality to provincial to global. Moreover, it is specific for each area, where each location might need its own method. The vulnerability is also a function of a number of physical, social, economic and environmental parameters that could effect on the potential damage to the elements at risk. The vulnerability measures the extent to which elements at risk

(structures, populations, services, or geographic area) are prone to be destroyed or disrupted in the case of particular hazard occurrence.

The vulnerability can also be defined as a combined result of exposure, resistance (susceptibility) and resilience. Where exposure is related to elements at risk (people, property, etc.), resistance is the measures taken to minimize losses, and resilience is the ability of system or community to adapt, cope, and recover when such kind of hazard occur in order to restore and continue providing services and basic functions after the threat occurrence. Susceptibility reflects the weakness, preparedness, and lack of strength of the system. In fact, poor predisposition, and lack of resilience increase the vulnerability of the system. In particular, the parameter of vulnerability signifies the conditional probability that the threat is finally successful to damage the potential target (i.e. elements at risk).

In fact, the aim of all efforts devoted in conducting vulnerability and risk assessments is to enhance the scientific knowledge of the community and people about the consequences of accidental events (natural and technological hazards) and decreasing the vulnerability of disaster-prone elements at risk.

According to type of losses, the vulnerability can be grouped into four distinct types:(1) physical related to the potential impact of hazard on a physical environment (building damage, infrastructures damage, and damage to contents); (2) social is related to the potential impact of hazard on humans and groups (injuries, fatalities, diseases, homelessness, political unrest); (3) economic is related to the potential impact of hazard on the economic properties and business (loss of skilled labors due to injuries and fatalities, suspension of providing services due to damage of buildings and infrastructures, and insurance losses); and (4) environmental is related to the potential impact of hazard on the environment (pollution, damage of ecological zone, and endangered species). When a physical vulnerability is only considered, it can be defined as the degree of damage to an element at risk (e.g. supporting facilities, infrastructure, buildings, etc.) prone to a given level of hazard intensity. Actually, the vulnerability can be measured in various ways:

1. Vulnerability indices that are commonly used to perform a holistic assessment of various aspects of vulnerability.
2. Vulnerability tables that show the relation between hazard intensity and the level of damage of the elements at risk in the table form.

3. Vulnerability curves relate the expected degree of damage of a particular type of elements at risk with the hazard intensity as shown in figure 2.2. It ranges from 0 (if the elements at risk are completely protected and hardened, i.e. no damage), to 1 (if elements at risk are not protected nor strengthened, i.e. completely collapse). These curves display the damage level either in a relative or absolute values. Actually, at the same hazard intensity value, the vulnerability value for various types of elements at risk is different. The vulnerability curves express the vulnerability in a continuous form as a function of a certain hazard intensity parameter. Establishing of vulnerability curves is a complex task. They can be developed either empirical using historical damage events for which hazard intensity and damage level is existing for various elements at risk, or through numerical modeling.
4. Fragility curves that display the likelihood for a specific type of elements at risk to be in or exceeding certain damage state (slight, moderate, high, extremely high destruction; for instance). They represent the capability of an engineered system to withstand a specified accidental event.
5. Damage probability matrices (DPM) show the conditional probability that particular elements at risk will be in a given damage state level for a given hazard intensity value. They express the conditional probability in a discrete form ( $P [D = k|j]$ ) to get damage level  $k$  due to the occurrence of hazard with intensity  $j$ .

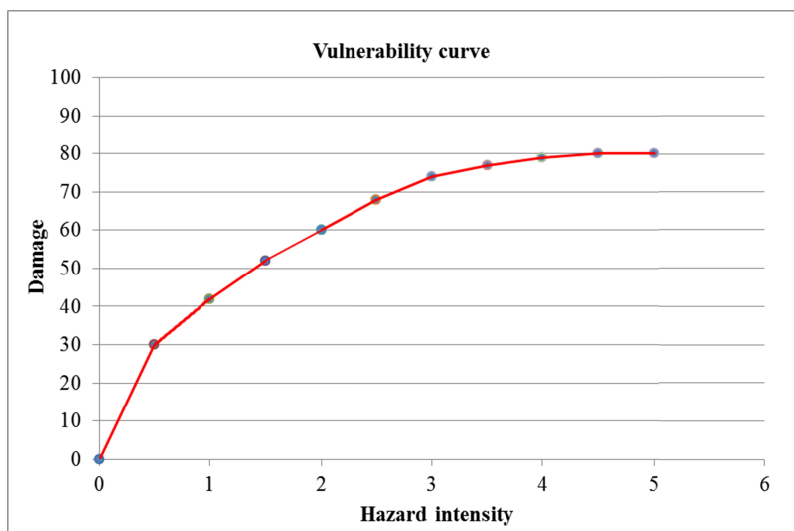


Figure 2.2. General vulnerability curve

Really, there are no simple or standard generic methodologies can be used to estimate vulnerability of elements at risk. Therefore, vulnerability assessment is a complicated process.

### **2.7.1 Physical vulnerability**

The physical vulnerability is the degree of damage of a particular type of assets resulting from the occurrence of an accidental event of a given intensity. It is expressed on a scale from 0 (no destruction) to 1 (completely collapse). Actually, vulnerability assessment is conditional to the occurrence of threat. Really, determining a physical vulnerability value is a complex process. It can be generated utilizing either empirical or analytical method. Empirical methods are based on historical data or expert judgment. The resort to using historical data is suitable for events that occurred frequently like earthquake and floods, where it is easy to develop a relation between hazard intensity and the degree of damage for a particular type of elements at risk. Since it is not easy to conduct data collection for large areas after an accidental event occurs, therefore represented elements at risk can be designated. On the other hand, the expert judgment is suitable in the case where the events rarely happen or the historical data are not available.

However, the analytical method involves structural analysis of the buildings based on engineering design criteria utilizing computer simulation techniques to determine the failure behavior and estimate the probability of the failure of the structures.

For risk assessments in a construction site, there is a lack of studies on the vulnerability of temporary facilities, and therefore the vulnerability curves are not available. Moreover, the fire hazard may attack the temporary facilities and construction site at any time. Hence it is essential to enhance the awareness of construction managers about the fire risk in a construction site and develop a proper way to minimize its losses. Really, in the current research, the physical vulnerability has been considered in estimating the risk in a construction site.

## **2.8 Risk**

The risk is the result of the exposure of elements at risk to threats, and the vulnerability of these elements. Therefore, the risk is defined as the measure of the expected probability of losses or harmful consequences in elements at risk (injuries, deaths, economic, physical, assets, environmental and social) as a consequence of the occurrence of a particular hazard event in a specified area over a specific period of time. The risk is a result of interactions between natural or human-induced hazard with vulnerable circumstances. Generally, it is possible to say that the

community is at risk if a particular hazard attacks the community and left adverse effects. Risk estimation is not an easy task; it requires participation from multidiscipline in order to conduct a holistic evaluation of the losses.

One of the most common, simple, widespread, accepted and applied mathematical model for evaluating the risk quantitatively can be represented by the relationship shown in equation 2.1. It is a convolution between hazard and vulnerability.

$$R = H * V \tag{2.1}$$

Where:

R: quantitative risk or expected losses

H: particular threat event (hazard)

V: vulnerability of specified type of elements at risk with respect to the hazard (i.e. the probability that a given threat is successful)

As shown in equation 2.1, the level of risk depends on: kind and nature of the threat and the vulnerability of elements at risk. The hazard is the first parameter that must be considered in risk estimation. Therefore, modeling and analyzing a potential hazard and its impacts on the elements at risk is essential to get an accurate estimation of losses. A foremost dilemma in the risk quantification model is related to the difficulty in evaluating the second component of risk analysis which is the vulnerability. The vulnerability (V) is a non-dimensional parameter because it displays the conditional probability of the successful of a threat to influence on the element at risk.

Generally, the models used to analyze the risk and demonstrate the influence of protective measures on the risk can be categorized into: (1) quantitative approaches such as; quantitative risk assessment and event tree analysis; (2) qualitative approaches such as risk matrix approach and indicator-based approach. The accuracy of risk model depends on the availability of data and the accuracy of the assumptions in modeling both hazard and vulnerability. Usually, quantitative ways are complex and they are suitable for small areas due to huge detailed data needed that can be attained through (1) expert judgment, (2) historical data of damage records, and (3) numerical statistical models and computer simulation techniques.

Actually, the aim of risk management is to amend the initial vulnerability circumstances or threats in order to create efficient protection able to reduce the risk to a tolerable level. So, minimizing either the threats or the vulnerability of elements at risk has a positive consequence on the reduction of overall risk and cascading effects. These will also be reflected on the resilience and recovery of the system. Whatever the case, awareness, and predisposition are the most significant factors that must be considered to minimize the potential losses resulted from the occurrence of any kind of potential hazard.

## **2.9 Interaction matrix**

Interaction matrices were used in environmental impact assessment, where the features of the environment were recorded vertically, and the actions were listed horizontally (Mavroulidou et al. 2004). The interaction matrices can be utilized in order to identify the impact of one component on another within the system, the effect of the system on each component, and determine the total impact of each component within the whole system considering both the impact of the component on the system and the effect of the system on the component. Therefore, this kind of matrix is used in this study to identify the impact of each construction facility (site offices, batch plant, fabrication areas, etc.) within a construction site on another, and the potential global impact of that facility on the construction site as a whole. However, the size of the matrix varies from one construction site to another, depending on the number of construction facilities existing within the site (Mebarki et al., 2012a, 2012b, 2014a; Mebarki and Barroca, 2014).

Moreover, this kind of interaction matrix has been utilized in this research for modeling and generating the hazard and vulnerability interaction matrices. These two matrices are essential to quantify the losses in a construction site.

In general, the framework for generating the hazard and vulnerability interaction matrices consists of several steps. It aims to evaluate the hazard generated by each facility compared to the other facilities. It can be adapted to consider different kind of natural or technological hazards that may happen on a construction site, i.e. fire, explosions, thermal flux and blast waves, for instance. Moreover, it is possible to identify the vulnerability of targets within a site with respect to the hazards generated from each source. The vulnerability of each target depends

on its capacity to resist various hazard values generated by surrounding sources. In the framework, the global risk for each facility can be identified by the convolution between hazards generated by the sources and the vulnerability of the targets.

### 2.9.1 Generating the interaction matrix

Several steps should be followed in order to create an interaction matrix ( [Mebarki et al., 2012a, 2012b, 2014a; Mebarki and Barroca, 2014](#)):

- Identify the objects that exist or will be erected within a specific area (i.e. construction site in our case).
- Identify the nature of hazard that may arise in that area (fire, explosions, blast waves, malicious acts, etc.).
- Based on kind of hazard, evaluate the hazard intensity at each object compared to other objects using specified relative scale measurement categories such displayed in table 2.2, where 0 represents the lowest hazard, and 4 represents the highest hazard, in order to fill the diagonal of the interaction matrix. These diagonal values represent the highest hazard from each object existing in a construction site. In fact, while these diagonal values seem such as the object interacting with itself, this just indicates that the intensity and consequence of the hazard is the highest at the object itself and it will attenuate with distance (i.e. the hazard intensity and consequence on the source of hazard occurrence is the highest and it attenuate as it becomes far away from the hazard source).
- The remaining values of the interaction matrix can be estimated based on the specified hazard attenuation model. It is generated based on kind of hazard and the available historical data about that hazard. Figure 2.3 displays the interaction matrix, where  $h_{11}, h_{22}, \dots, h_{nn}$  represent the hazard intensity generated and initiated at objects 1, 2... n respectively (i.e. the highest hazard from each source i), and  $h_{ij}$  represents the hazard intensity at object j resulted from the hazard occurred initially at object (i), it represent the attenuation of hazard with distance.



Table 2.2. Example of interaction scale measurements categories (Hazard interaction scale)

Hazard level	Details
0	No hazard
1	Low hazard
2	Moderate hazard
3	High hazard
4	Very high hazard

$$\begin{bmatrix} h_{11} & \dots & h_{1n} \\ \vdots & h_{ij} & \vdots \\ h_{n1} & \dots & h_{nn} \end{bmatrix}$$

Figure 2.3. Example of interaction matrix

### 2.9.2 Mathematical operations on interaction matrix

This section explains the application of mathematical operations on the interaction matrix adopted for this study. Consider the interaction matrix between objects  $\mathcal{M} \in \mathcal{M}_n$  where (n) is the total number of objects that exists or will be erected within a specific area. Hence (n x n) matrix will be developed as shown in equation 2.2, where  $m_{ij}$  represents the interaction value between objects (i) and (j)

$$\mathcal{M} = \begin{bmatrix} m_{11} & \dots & m_{1n} \\ \vdots & m_{ij} & \vdots \\ m_{n1} & \dots & m_{nn} \end{bmatrix} \quad 2.2$$

The overall potential global impact of each object can be determined through implementing the following matrix algebra. It is also presented by equations (2.3-2.6).

- Find the summation of each individual row ( $\bar{\mathcal{M}}_i$ ) and the summation for each individual column ( $\bar{\mathcal{M}}_j$ ) in the developed interaction matrix (i.e. the row summation expresses the object influence on the system, while the column summation represents the system impact on the object)
- Then, find the summation of ( $\bar{\mathcal{M}}_i$ ) and ( $\bar{\mathcal{M}}_j$ ) for all (i = j) to determine the global potential impact of each object (i) on the whole system ( $\mathfrak{X}_i$ ).

$$\bar{\mathcal{M}}_i = \sum_{j=1}^n \mathcal{M}_{ij} \quad , \forall i \in \{1, 2, \dots, n\} \quad 2.3$$

$$\bar{\mathcal{M}}_j = \sum_{i=1}^n \mathcal{M}_{ij} \quad , \forall j \in \{1,2, \dots, n\} \quad 2.4$$

$$\kappa_i = \bar{\mathcal{M}}_i + \bar{\mathcal{M}}_j \quad , \forall i, j \in \{1,2, \dots, n\} \quad 2.5$$

$$\psi_i = \frac{\kappa_i^*}{\sum_{i=1}^n \kappa_i^*} \quad , \forall i \in \{1,2, \dots, n\} \quad 2.6$$

Where:

$\bar{\mathcal{M}}_i$  : is the potential impact of each object (i) on the system.

$\bar{\mathcal{M}}_j$  : is the potential impact of the system on each object (j).

$\kappa_i^*$ : is the global potential impact of each object (i) within the system.

$\psi_i$ : is the normalized global potential impact of each object (i) within the system

The implementation of mathematical operations on interaction matrix can be demonstrated through the example presented in table 2.3. It displays interaction matrix consists of four objects.

Table 2.3. Implementation of mathematical operations on (4 x4) interaction matrix

Object No.	OB 1	OB 2	OB 3	OB 4	$\bar{\mathcal{M}}_i$	$\kappa_i$	$\psi_i$
OB 1	4	1	1	3	9	13	0.295
OB 2	0	2	1	1	4	9	0.205
OB 3	0	2	4	3	9	15	0.341
OB 4	0	0	0	0	0	7	0.159
$\bar{\mathcal{M}}_j$	4	5	6	7		44	1.0

It is clear that from table 2.3, the object (OB 3) has the highest global potential impact (34.1%) within the system compared with other objects, followed by an object (OB 1) with a relative potential global impact equal to 29.5%. In addition, table 2.3 presents that the object (OB 4) has no influence on the system. In contrast, the objects (OB 1 and OB 3) have the greatest influence on the system ( $\bar{\mathcal{M}}_i = 9$ ).

The table also displays that, the most dominant object within the system is (OB 1), where the difference between the influence of the object on the system ( $\bar{\mathcal{M}}_i$ ) and the influence of the system on the object ( $\bar{\mathcal{M}}_j$ ) is the highest. This means that object (OB 1) influences on the system more

than impacted by the system. Furthermore, object (OB 4) is strongly impacted by the system and has no influence on the system.

## 2.10 Space syntax

Space syntax is a spatial analysis technique that was developed to understand and realize the spatial patterns and space configurations of modern cities based on connectivity graph representation (Hillier 2007). It shows the interactions between space and society or correlation between different spaces. Also, it consists of a set of theories and tools utilized for spatial morphological analysis (Jiang et al. 2000).

The notion in space syntax lies in dividing large-scale space (free space) into a limited number of small spaces, which in turn are subject to analysis based on their interconnection and integration. The awareness of small-scale spaces affords prequalification to the awareness of large-scale space. From this analysis, it is possible to obtain a set of parameters that assist in understanding the urban structure properties and basic functions.

Referring to Jiang et al. 2000, space syntax model computations depend on two fundamental steps. The first is the splitting of the large scale environment into small scale spaces and the second is the connecting of the small spaces together to a create connectivity graph which constitutes the basis for spatial property computations such as the connectivity of each node with direct nearby nodes and the connectivity with all other nodes.

There are three approaches for achieving space syntax analysis, based on the linearity of space:

- The first is directed to environments that are considered approximately linear such as roadways. In this approach, space is represented as an axial map with the least number of longest straight lines.
- The second is directed to environments that are considered nonlinear in nature like the layout of internal premises. In this approach, the spaces are represented by convex polygons with the least number of them that cover the whole space.
- The third is used for environments that are also considered nonlinear. In this approach, an isovist map that shows the visible field from each point in the whole space is created. The plan from isovist analysis is divided into a small grid, where each cell represents a single

point in the space and its related isovist. The connectivity graph can be generated based on the overlapping of each isovist with all other isovists.

Space syntax analysis technique affords several of significant spatial property parameters, which are derived from and computed based on connectivity graph. The followings are a brief summary of some of these parameters.

- Connectivity (C): is the spatial property that shows the number of nodes, which are directly connected to each of individual node in the connectivity graph, it can be determined using equation 2.7 where k in the equation related to the number of nodes that are directly connected to the individual node (i).

$$C_i = k \quad 2.7$$

- The control value is the spatial parameter that shows the degree to which each node controls its immediate neighborhood nodes. It is determined by the sum of inverse connectivity values of the immediate neighborhood nodes.
- The depth and mean depth: is a spatial parameter expresses the integration or segregation of a node within a system. It can be defined as the number of steps from a considered node to all other nodes. A node can be considered either deep or shallow based on the number of steps separating it from all other nodes. The depth ( $\delta$ ) and mean depth ( $\bar{\delta}$ ) of a node can be computed using equations (2.8) and (2.9) respectively, obtained from [Jiang et al. 2000](#).

$$\delta_k = \sum_{j=1}^N S_{kj} \quad 2.8$$

$$\bar{\delta}_k = \frac{\delta_k}{N - 1} \quad 2.9$$

Where:

$S_{kj}$ : is the shortest distance (steps) between two nodes (k and j) in a connectivity graph, then the total depth of node (k) is the sum of the steps.

$\delta_k$  : is the depth of node (k).

$\bar{\delta}_k$  : is the mean depth of node (k)

N: is the total number of nodes

- Integration is another spatial parameter that gives an indication about the segregation or integration of a node within a whole system. Space can be considered highly integrated if all other spaces are accessed with traversing a minimum number of concerned spaces. Referring

to [Jiang et al. 2000](#), the integration value can be measured with relative asymmetry value (RA) as shown in equation (2.10). As the RA is high the location is deep, whereas if the RA value is low, the location is shallow. It is evident that the low integration location is deep (segregated) with respect to all other locations, while the high integration location is shallow. Hence, the global risk for location is high when the location is deep (low integration value) and is low when the location is shallow (high integration value).

$$RA_k = \frac{2(\bar{\delta}_k - 1)}{N - 2} \quad 2.10$$

Where:

$RA_k$ : is a relative asymmetry value of the node (k).

## 2.11 Optimization algorithm

[Kusiak and Heragu \(1987\)](#); [Heragu and Kusiak \(1991\)](#) classified the algorithms used to solve facility layout problem into four categories: construction algorithms, improvement algorithms, hybrid algorithms, and graph theoretic algorithms. [Kusiak and Heragu \(1987\)](#) made comparison among twelve algorithms to examine their efficiency based on computation time and the accuracy of the solution. [Patil and Joshi \(2013\)](#) noted that the meta-heuristic methods such as genetic algorithms (GAs), simulated annealing technique, and ant colony optimization are most common algorithms used for site layout planning. [Lam et al. \(2009\)](#) developed a hybrid model that integrates genetic algorithm with max-min ant system. The results of this hybrid model provide a better optimal solution than utilizing traditional genetic algorithm.

[Zouein et al. \(2002\)](#) investigated the capabilities of a GA in finding the optimal solution for site layout problems. They found that when the ratio between the area of total facilities and the site area did not exceed 60%, the algorithm produces a solution that is considered very close to the optimal solution. [Said and El-Rayes \(2013\)](#) made a comparison between a GA model and ADP by considering two criteria: the effectiveness of optimal solution attainment and the efficiency of minimizing the computation time. They found that ADP was more efficient than the GA. However, GAs will continue to be a valuable optimization method due to their simplicity

### 2.11.1 Evolutionary algorithm

Evolutionary algorithms are search algorithms. They are useful methods for solving complex optimization problems that are not suitable for gradient based algorithms. The idea behind evolutionary algorithms is derived from Darwin's principle which relies on the survival of the fittest. These algorithms imitate the optimization process in nature. The biological species are optimized in order to maximize the survival of the fittest, which leads to an enhancement in the quality of that generation. As the evolutionary algorithm (Genetic Algorithm) is a very common technique for solving optimization problems (Sanad et al. 2008; Hegazy and Elbeltagi 1999; Zouein et al. 2002; Pourvaziri and Naderi 2014; El Ansary and Shalaby 2014), it is adopted in the present research.

### 2.11.2 Evolutionary approach technique

The first step to implementing the evolutionary optimization technique is to design particular chromosomes containing genes of the problem decision variables as shown in Figure 2.4. It is obvious from this figure that each successive genes pair represents the x and y coordinates for the facility (i). Moreover, the number of decision variables are equal to the number of facilities (n) multiplied by two (the number of variables = 2n). In the present research, the decision variables (genes) are set as numerical values (real numbers).

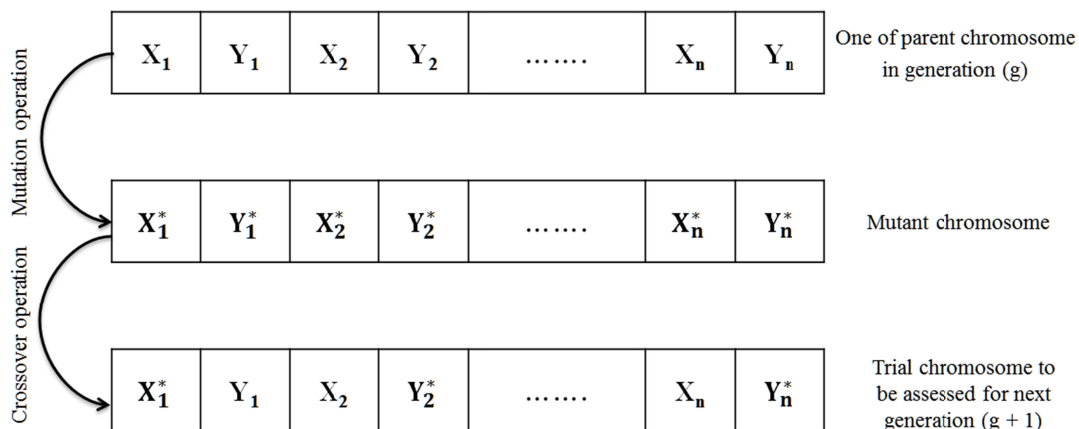


Figure 2.4. Illustration of the decision variable chromosomes.

Generally, GAs work with a collection of chromosomes called population. The chromosomes are evaluated through a process called fitness function to examine the convenient of the solution. The genetic operators called “crossover and mutation” are applied. In the crossover, some chromosomes in the population are mate to generate new chromosomes called offspring. Offspring inherit merits from their parents. In mutation, few chromosomes are mutating in their genes. The chromosomes undergo to crossover and mutation operations are randomly selected and controlled through crossover rate and mutation rate. The probability of chromosome in the current population, to be appearing again in the next generation is directly proportional to the fitness value. After several generations, the optimal solution will be obtained. In the current research, the differential evolution algorithm is adopted to perform optimization process. It is available at Science Python (SciPy) library. According to (Storn and Price 1997; Pedersen 2010; Mezura-Montes et al. 2010), for each generation, the mutation operation is conducted for each candidate solution through mixing it with other candidate solutions to create trial chromosome as shown in Figure 2.4. In mutation operation, two chromosomes are randomly selected from the population, and then the difference between them is determined (i.e. difference chromosome is created). The resulted difference chromosome is scaled based on user defined parameter called mutation parameter. Afterward, the scaled difference chromosome is added to the best chromosome in the population to generate new chromosome called mutant chromosome. This later is subjected to discrete recombination with the parent chromosome to create trial chromosome using crossover parameter. This trial chromosome is undergoing to fitness evaluation. If it is better than the parent, it will occupy its position. In addition, if the trial chromosome is better than the best chromosome in the generation, it will take its place too.

## **2.12 Dijkstra’s algorithm and least cost path analysis**

Dijkstra’s algorithm (Dijkstra 1959) is an optimization algorithm that conducts least-cost path analysis. It is widely utilized to find the optimal route between an origin and destination points. The algorithm relies on graph and network theory: a graph consists of nodes connected by weighted links. It is also designed to trace the least-cost route between source nodes (starting point) and any other nodes. The general cost may concern any utility function such as time, slope, risk, or any other criteria defined by the user. The procedure used to run Dijkstra’s algorithm involves the following steps: (1) the network consisting of nodes and their weighted

links is created. The weight of each link represents the cost between the two connected nodes. (2) The source node (starting point) is identified as the currently visited node and is assigned a zero value. Meanwhile, all other nodes are considered as unvisited nodes and are assigned a value of infinity. (3) The cumulative cost from the unvisited nodes to the source node is calculated, taking into account that all nodes must be visited once. (4) The unvisited nodes are selected, with the lowest accumulated cost to the source node as the current node, and step 3 is repeated. In the case where the cumulative calculated cost is less than the current one, it is overwritten by the new one. Checking the visited node again is not allowed, and therefore the accumulated cost of the visited node is final and is the lowest. (5) The process continues until all nodes have been visited.

Least-cost path analysis is a distance analysis technique used to determine the most effective path between two locations that costs the least. The least-cost distance and the Euclidean distance (the straight line distance between any two points) are not necessarily the same. The Euclidean distance always overlooks the existence of obstacles, the cost of route construction, the time needed to navigate along the route, and the riskiness of the route. On the other hand, least-cost path analysis assists in finding the most effective and shortest path from one location to another, considering all of these criteria and/or any other criteria defined by the planner. Moreover, the cost distance is calculated based on cost units, which are not geographic units.

It is very important to note that the map consists of the grid. Each cell in the map has a value that represents both the cost criteria defined by the planner. From the cell perspective, the cost assigned per cell is the per unit distance measure for the cell. Thus, the cell size will be used to calculate the accumulated cost for each cell to reach a source cell. The total cost of traveling through the cell horizontally or vertically can be determined using Equation (2.11). If the movement through the cell is diagonal, the total accumulated cost can be determined using Equation (2.12).

$$\text{Total}_{\text{cost}} = \text{cost}_{\text{cell}} * \text{cell}_{\text{size}} \quad 2.11$$

$$\text{Total}_{\text{cost}} = \sqrt{2} * \text{cost}_{\text{cell}} * \text{cell}_{\text{size}} \quad 2.12$$

As mentioned previously, the cost surface is a graph consisting of nodes and links, with the center of each cell being considered as a node. It is connected to other nodes by links; each link has an associated cost value that is equal to the average cost of two end connected cells. Figure



2.5 displays the total path cost of traveling between cell 1 and cell 2 horizontally. The total path cost from any cell to the source cell is equal to the cumulative cost of all connected links along the path.

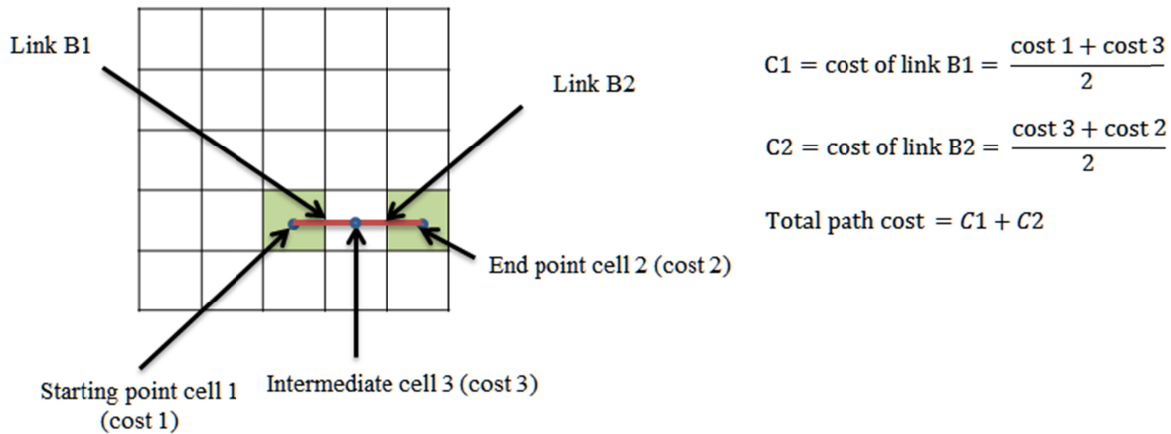


Figure 2.5. Total path cost between two cells

The least-cost path has the smallest cost distance among all possible paths from the cell to the source cell. Usually, there are many possible paths along which one can move from the cell to reach the source cell, but one of these paths has the least cost compared to the others.

### 2.13 Geographic information system (GIS)

Geographic information system (GIS) becomes the most common modern technology applied to solving a lot of engineering problems. It assists decision makers in adopting and making proper decisions through its ability to analyze, visualize, and processing a large amount of data. It is very flexible and it can be simply automated to carry out specific assignments. Moreover, it is an efficient tool to prepare maps, conduct modeling operations, and quick information retrieval. In general, the efficient utilization and exploitation of GIS generate great economic benefits and income. According to Kamal (2008), GIS has a significant role in local developments of cities where many governments adding it to be part of their administrative management system.

In particular, the word geographic concerns the spatial nature of given and specific features, whereas, the information is related to the possibility of creating information to conduct analysis and decision making. In addition, systems word refers to staff, computer hardware, and procedures adopted for data collection, data processing, and visualizing.

Recently, the advanced developments in computer technology contribute to rapid and widespread utilization of GIS in all aspects of life; economic, physical, social, environments, urban planning, land use planning, industrial, and disaster management for instance. GIS can be used to conduct multi-criteria decision making (MCDM) evaluation and perform intelligent decisions. Additionally, GIS is a computerized system able to store, manage, manipulate, acquire, analyze, display, interpret, generate maps, and present information in a digital form based on spatial data. Spatial data concerns with the location, it is not essentially for the location to be on the earth surface.

Generally, GIS offers efficient tools and functions for modeling, analysis, and visualization of maps spatially. In addition, it has the ability to conduct searching through information and combining text search with the geographic search to facilitate finding and presenting the relevant data faster. GIS allows then to share these data with other users. Usually, the data in GIS is organized in layers to be overlaid based on analysis requirements as presented in figure 2.6.

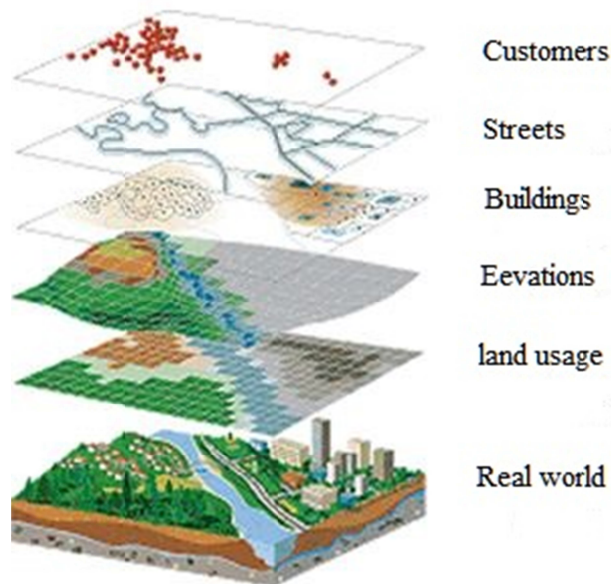


Figure 2.6. GIS data layers (Source: GIS LOUNGE)

Data in GIS can also be stored and presented either in tabular format (attribute data) or map format (spatial data), where the data in the tables encompasses information related to the map. Usually, GIS systems deal with the spatial and attribute data separately, then connect them for analysis and/or display.

In the current research, GIS has been utilized to assist construction site managers and planners in visualizing and understanding the importance of site layout planning in minimizing the potential risk resulted from specific kind of natural or technological hazard, displaying the map of spatial variability of risk within a construction site, identifying the most at-risk position in a construction site, identifying the most risky facility on a construction site, assigning the best position for exit/entrance gate(s), and finding the optimal paths for evacuating construction site in case of emergencies. All of these visualizations and the consequent decisions are essential to achieving project pledges and minimize the negative consequences of the potential hazard.

## **2.14 Simulation technique and uncertainty analysis**

Simulation is applied to conduct a quantitative analysis of problems that cannot be expressed in the analytical form (deterministic manner). It is also applied to model and represent, as close as possible, the real system. In general, the idea behind simulation is to build up and run a mathematical numerical experiment over a large number of trials to realize what happens on average in order to imitate the real world situation. In general, performing a large number of trials on the same experiment offers a good understanding and realizing on what will occur. In addition, the average of all of these trials will be close to the expected value. The accuracy of the models output directly proportional to the number of trials. As the number of trials increases, the accuracy will increase too.

The recent advanced in modern computers make simulation models very flexible and easy to generate. It is widely spread since modern computers accelerate repetitive numerical computations

Specifically, Monte-Carlo technique is one of the most common and widely used simulation tools. It is a computational method utilizing repeated random sampling to attain numerical results. Monte Carlo method is suitable when the components of the system exhibit chance in their behavior. The steps needed to apply Monte-Carlo simulation involve: (1) define the problem under consideration; (2) identify the input variables associated with the problem; (3) establish a probability distribution for these inputs based on historical data or expert judgments; (4) set up a cumulative probability distribution for each of these variables; (5) set up an interval

of random numbers for each of input variables; (5) Generating a random numbers utilizing computer program; and (6) perform experiment many times to simulate the output of interest.

Monte-Carlo simulation is also appropriate for uncertainty analysis, where the uncertainty is propagated on the input variables through the models to get a probability distribution for the outcome(s) of interest. Specifically, the uncertainty on each input variable can be characterized by assigning suitable probability density function for each of them. When the model runs, the random numbers are drawn randomly from the assigned probability density function. After running the model a large number of trials, aggregate the outcome(s) of interest to generate a probability distribution. Figure 2.7, displays the way of modeling of uncertainty analysis problems.

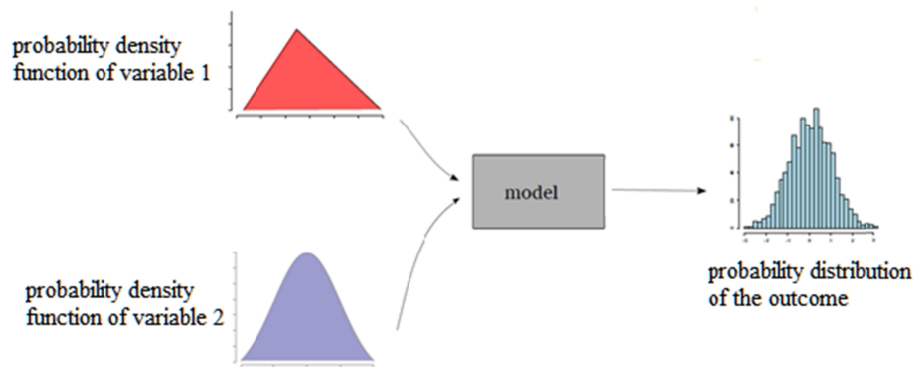


Figure 2.7. Uncertainty analysis modeling

In the current research, the probabilistic framework has taken into account the uncertainties in developing the model. The model aims to develop proper level of confidence on the probability of failure of the whole construction site.

## 2.15 Résumé du chapitre 2

Ce chapitre contient une présentation générale du cycle de vie d'un projet de construction, le plan d'aménagement du site, la matrice d'interaction, les aléas, la définition de la vulnérabilité, les études antérieures autour de plan d'aménagement de site, les techniques d'optimisation, le principe de syntaxe spatiale, l'algorithme de Dijkstra, les capacités des SIG et de l'analyse spatiale et les bénéfices de la simulation pour l'analyse des risques.

## **CHAPTER 3**

### **Research Methodology and Model Development**

In this chapter, the methodology adopted to accomplish the objectives of the current research and develop optimization models for site layout planning has been discussed. It includes: modeling the hazard, modeling vulnerability, risk modeling, the importance of space syntax analysis and its impact on the global risk within a construction site, and the role of GIS in generating spatial risk map and finding the optimal paths. Generally, two optimization models have been developed: (1) generic deterministic model; and (2) probabilistic model for fire hazard. The mathematical formulas used to develop these two models have also been illustrated in this chapter.

#### **3.1 Methodology**

In general, to develop a framework for site layout planning able to minimize the risk due to natural or technological hazards, the general methodology shown in figure 3.1 is undertaken. It consists of the following major phases:

##### **3.1.1 Meticulous literature review**

The literature review is very significant for all researchers due to huge benefits and data obtained through reviewing previous research and studies conducted in the same field of interest. It should be the initial point for any research. It assists the researcher in understanding the research topic and finds the gap between what he wants to do and what are the current and previous orientations

of the researchers applied on the same field. Basically, the importance of this phase lies in: understanding the current model adopted for site layout planning, defining the construction site components, identifying the process used to make risk analysis, propose approach to create hazard and vulnerability interaction matrix, identifying the utility function, realizing the benefit of optimization techniques in conducting site layout planning, recognizing the effect of space configuration on spatial risk within a construction site, and perceive the capability of GIS in enhancing decision making especially those related to spatial risk in a construction site.

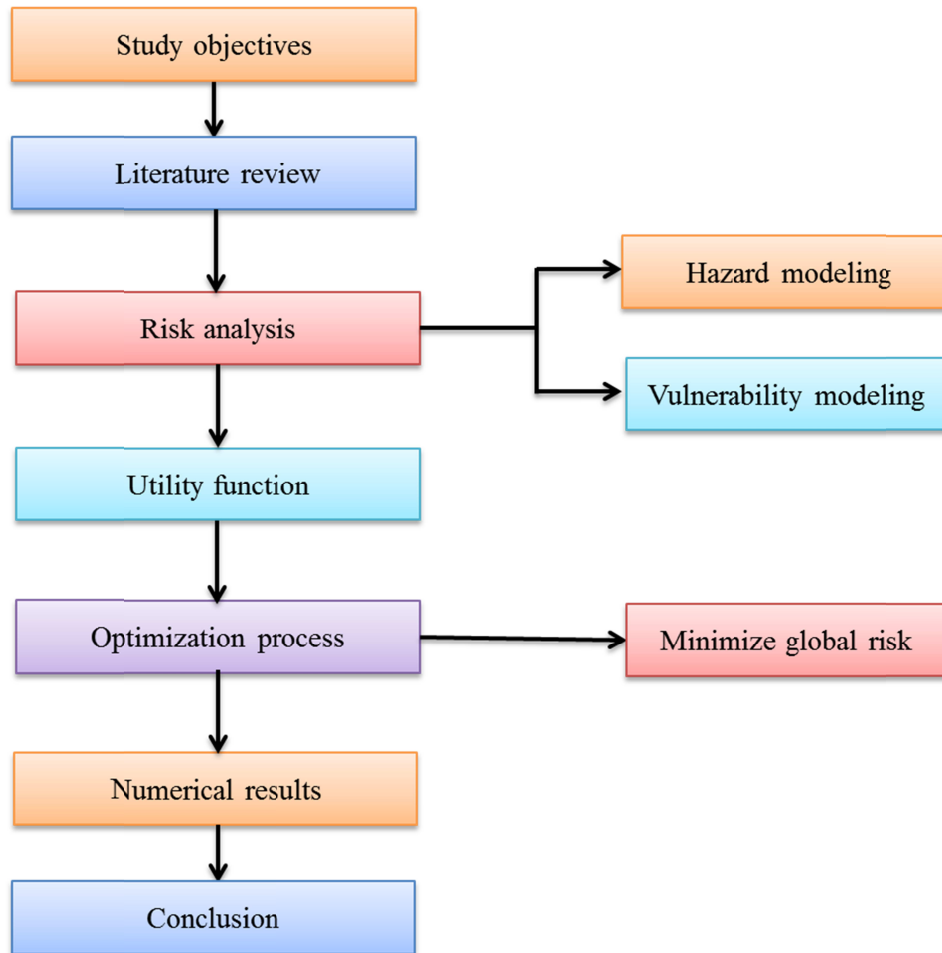


Figure 3.1. Research modeling methodology

### 3.1.2 Risk analysis

Risk analysis involves identifying the most frequent hazard happened on a construction site such as; fires, blast waves, explosions, thermal flux, and so on. In addition, defining the effect of a potential hazard on the construction process, for instance, hazardous construction material may

burn and cause a fire. The fire occurrence slows down the construction process, endanger the human life and can cause damage to surrounding properties and facilities. Moreover, it is required to define the system components in order to define their vulnerability and determine the risk of the potential hazard.

### **3.1.3 Utility function and optimization**

Basically, to conduct optimization process for any problem, it is necessary to establish and define the utility function. It aims either to minimize losses or maximize profitability. Furthermore, identifying the constraints that should be considered to complete optimization process successfully is another crucial issue. The current research aims to minimize the global risk or probability of failure of the construction site in order to provide safe working environments. Accommodating facilities in a proper position within a construction site is one way to achieve the declared utility function (minimizing risk).

### **3.1.4 Numerical results**

The proposed developed model is implemented in a case study to determine the validity and efficiency of the model. The information about one of construction projects has been acquired in order to identify project components, and carry out the proposed optimization model on it to see numerically how the global risk minimize based on the spatial relation among the project components.

## **3.2 Developing deterministic model**

As shown in figure 3.2, the framework utilized to develop deterministic model is divided into two phases: (1) finding the optimal layout aims to minimize global risk; and (2) finding optimal paths from any position in a construction site to the external exit gate.

### **3.2.1 Generating optimal layout of construction site (phase 1)**

Phase (1) in the specified deterministic model to generate optimal site layout consists of several steps as presented in figure 3.2: (1) identifying the characteristics of facilities required to perform construction activities and the way to present site and facilities; (2) identifying kind of hazard and modeling hazards and vulnerability interaction matrices among facilities; (3) identifying decision variables, constraints and the objective function for optimization utilizing the differential evolution technique algorithm; (4) implementing space syntax principles to determine the influence of space configuration and (5) importing the data from previous steps to the GIS to generate a construction site risk map.

The proposed model aims to find the best position for each facility, within a construction site, in order to minimize the risk. It is based entirely on identifying the nature of hazard that may happen on potential sources in a construction site, determining the hazard attenuation value in order to model hazard interaction matrix and modeling interaction matrix for the vulnerability of the potential targets.

The decision variables are represented by the  $(x, y)$  coordinates of each facility. The evolutionary algorithm is run to commence searching for the best  $(x, y)$  coordinates for each facility, considering both the boundary and overlapping constraints. Once the coordinates are identified, the optimal risk matrix and optimal site layout can be generated. The optimal risk matrix is utilized to find the potential global impact for each facility. Afterward, the space syntax analysis is conducted on the optimal site layout to determine the visibility mean depth value for each position within a construction site, to be used as a penalty factor to amplify the risk. Finally, the optimal site layout, potential global impact for each facility and visual mean depth are integrated together, utilizing the GIS to create a spatial risk map, as illustrated in the following sections.

#### **3.2.1.1 Site and facility representation**

In the proposed model, the construction site is represented as a rectangle with length ( $L$ ) and width ( $W$ ). The coordinate system  $(x, y)$  is created. The boundaries of the construction site along the  $x$ -axis are  $x_1$  and  $x_2$ , while the boundaries along the  $y$ -axis are  $y_1$  and  $y_2$ , as displayed in figure 3.3. Also, let the number of construction facilities to be located in construction sites be  $(n)$ .



The construction facilities have different sizes and are represented as rectangles too, with length ( $\ell_i$ ) and width ( $w_i$ ), where  $i = 1, 2, \dots, n$ . The coordinates of the centroid of the facility ( $i$ ) are ( $x_i, y_i$ ). These coordinates are the decision variables of the problem (Easa and Hossain 2008). Figure 3.3 displays the model components representation that involve: site boundaries and its dimensions, construction facilities and their dimensions, and the decision variables ( $x_i, y_i$ ) for the facility ( $i$ ).

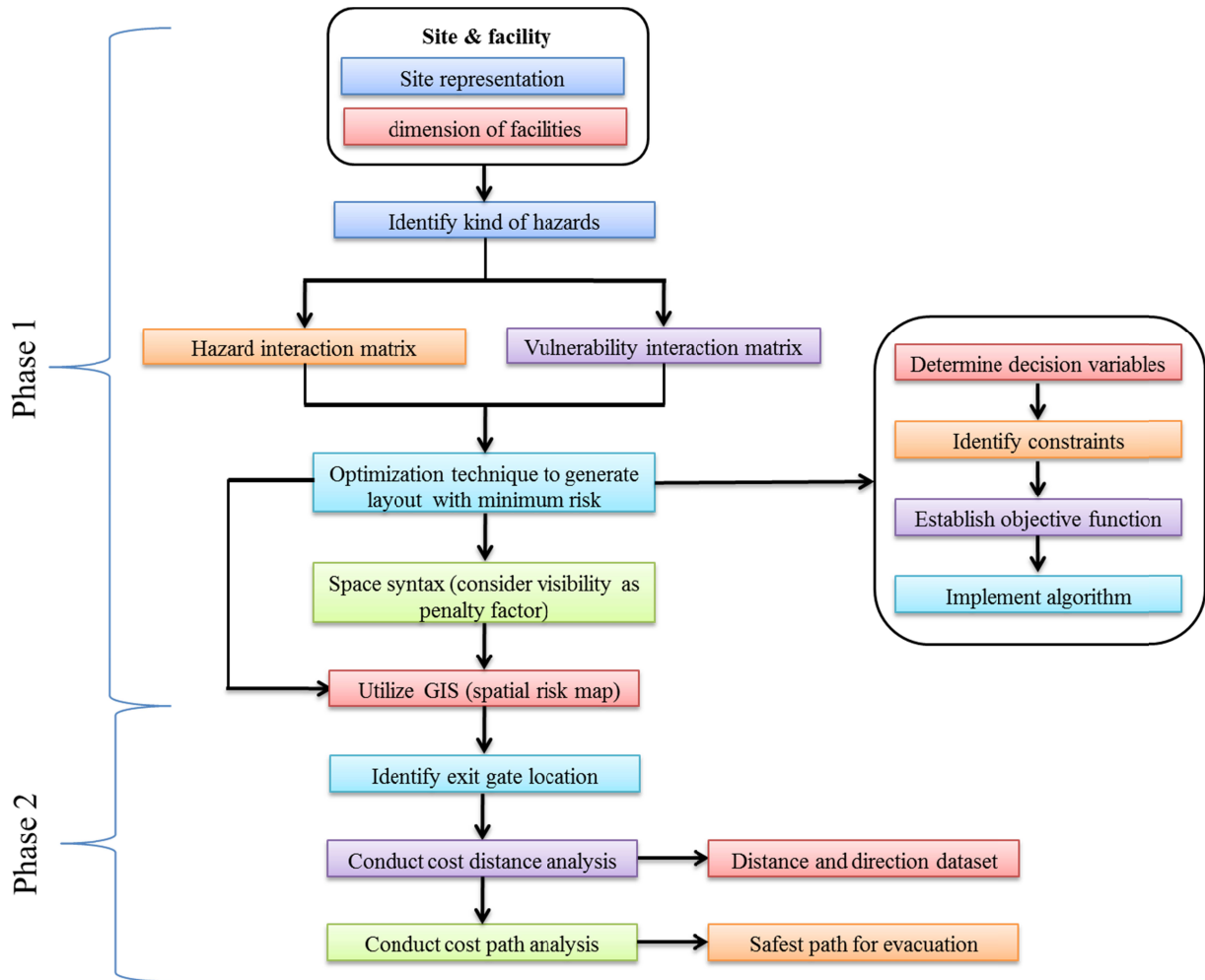


Figure 3.2. Deterministic model to generate optimal site layout and optimal paths for evacuation

### 3.2.1.2 Hazard and vulnerability interaction matrix

The framework for generating the hazard and vulnerability interaction matrices consists of several steps. It aims to evaluate the hazard generated by each facility compared to the other facilities. It can be adapted to consider different natural or technological hazards that may happen on a construction site, i.e. fire, explosions, thermal flux and blast waves, for instance.

Moreover, it is possible to identify the vulnerability of targets within a site with respect to the hazards generated from each source. The vulnerability of each target depends on its capacity to resist various hazard values generated by surrounding sources. In the framework, the global risk for each facility can be identified by the convolution between hazards generated by the sources and the vulnerability of the targets.

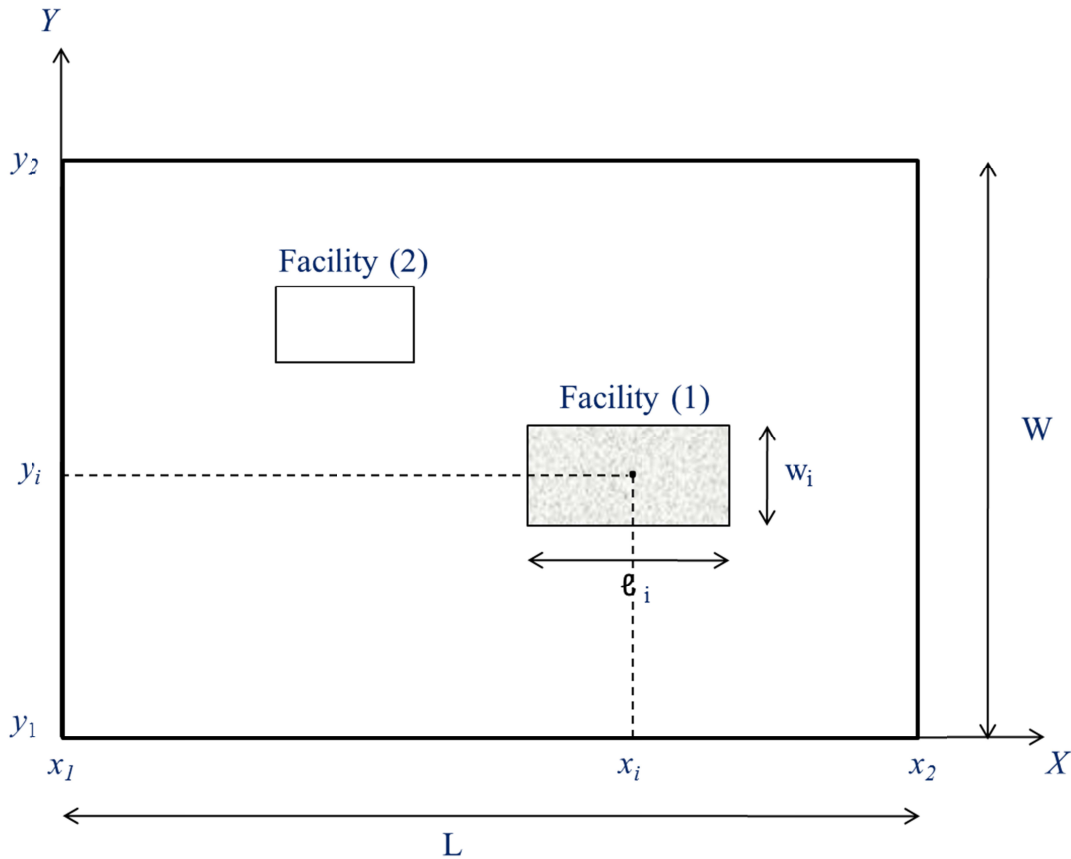


Figure 3.3. Representation of the construction site and facilities

### 3.2.1.2.1 Modeling hazard interaction matrix

Suppose hazard interaction matrix between construction facilities  $\mathbf{H}$ , and  $n$  is the total number of construction facilities that must be accommodated within a construction site. Hence, an  $(n \times n)$  matrix must be developed. Several steps should be followed in order to model hazard interaction matrix (Mebarki et al. 2012a, 2012b, 2014a; Mebarki & Barroca 2014b):

1. Identify the construction components that will be erected on the construction site.

2. Identify the kind of hazards that may happen on a construction site. It is assumed that there is the same kind of hazard effect generated from all sources.
3. Evaluate the hazard generated by each facility (i) using arbitrary relative scale measurement categories specified in Table 2.2, where 0 represents the lowest hazard level, while 4 represents the highest hazard level. In addition, the diagonal of the matrix is filled with these values as shown in equation 3.1, where  $h_{11}$  represents the hazard generated from source 1,  $h_{ii}$  represents the hazard generated from the source (i) and so on. In fact, while this value seems such as the source (i) interacting with itself, this just indicates that the intensity of the hazard is the highest at the source itself and declines as it becomes far away from the hazard source.

$$\mathbf{H} = \begin{bmatrix} h_{11} & \dots & \\ \vdots & h_{ii} & \vdots \\ & \dots & h_{nn} \end{bmatrix} \quad 3.1$$

4. To find the remaining values of the hazard interaction matrix, for the sake of simplicity, it is assumed that there is a linear attenuation law between hazard decay and distance, i.e. a linear relationship between the hazard interaction values ( $h_{ij}$ ) and the distance ( $d_{ij}$ ) to the target, therefore, the hazard from source (i) on target (j) decreases as a target (j) is located far away from the source (i). The distance between two facilities has been expressed as the Euclidean distance (the shortest straight line distance between facilities). Thus, the hazard decay, which is represented by the slope of linearity decreasing ( $\tan \alpha$ ) should be identified, as shown in figure 3.4, based on the nature of hazards, whether is it thermal flux, heat pressure or any other natural hazards effect. Furthermore, specific studies of the attenuation can be adopted depending on the nature of the hazard (Mebarki et al. 2012a, 2012b, 2014a; Mebarki & Barroca 2014b). Equations (3.2 – 3.5) explain the linear attenuation of hazard, whereas equation (3.6) displays the completed hazard interaction matrix. In addition, equations (3.7 – 3.9) are utilized to normalize the hazard interaction matrix.

$$h_{ij} = \max \left\{ \begin{array}{l} h_i^0 + \frac{\Delta H}{\Delta d} * d_{ij} * \beta \\ 0 \end{array} \right. \quad 3.2$$

$$h_i^0 = h_i |_{d=0} = h_{ii} \quad 3.3$$

$$d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2} \quad 3.4$$

$$\beta_{ij} = \begin{cases} 1, & \text{if } i \neq j \\ 0, & \text{otherwise} \end{cases}$$

3.5

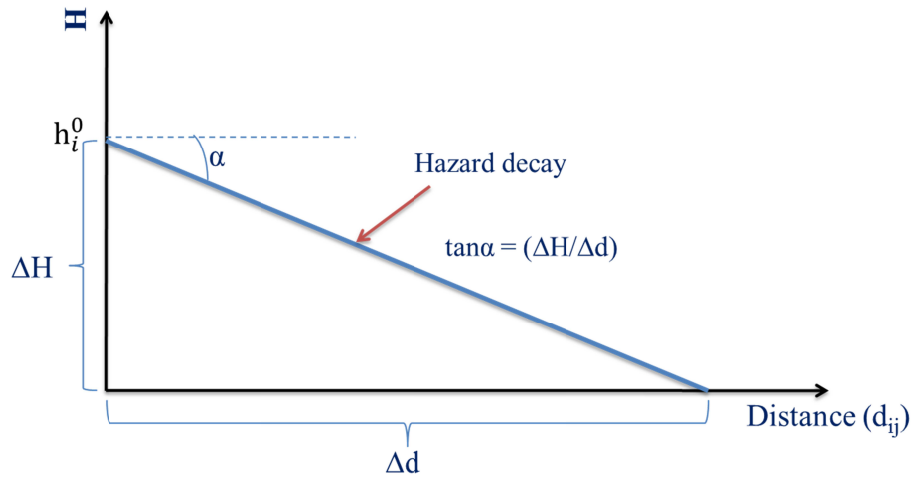


Figure 3.4. Hazard decay as a linear function of distance

$$\mathbf{H} = \begin{bmatrix} h_{11} & \dots & h_{1n} \\ \vdots & h_{ij} & \vdots \\ h_{n1} & \dots & h_{nn} \end{bmatrix} \quad 3.6$$

$$\mathbf{H}^* = \begin{bmatrix} h_{11}^* & \dots & h_{1n}^* \\ \vdots & h_{ij}^* & \vdots \\ h_{n1}^* & \dots & h_{nn}^* \end{bmatrix} \quad 3.7$$

$$h_{ij}^* = \frac{h_{ij}}{\max[h_i^0]} \quad 3.8$$

$$\mathbf{H} = \max[h_i^0] \cdot \mathbf{H}^* = \max[h_i^0] \cdot \begin{bmatrix} h_{11}^* & \dots & h_{1n}^* \\ \vdots & h_{ij}^* & \vdots \\ h_{n1}^* & \dots & h_{nn}^* \end{bmatrix} \quad 3.9$$

Where:

$\mathbf{H}$ : is the hazard interaction matrix

$h_{ii}$  : is the potential hazard of source (i) on the target (i), i.e the effect of source on itself.

$h_i|_{d=0} = h_i^0$  : is the potential hazard generated from facility (i) at distance (d = 0)

$h_{ij}$  : is the hazard interactions value between facilities (i) and (j), i.e the effect of source (i) on the target (j)

$\frac{\Delta H}{\Delta d}$ : is the amount of hazard attenuation with distance (hazard decay).

$\beta$ : is a factor utilized to consider the case when the hazard evaluation value is maximum at  $d = 0$  (i.e. to consider the case when  $i = j$ ).

$d_{ij}$ : is the Euclidean distance between facilities (i) and (j).

$x_i, y_i, x_j, y_j$ : is the coordinates of facilities (i) and (j).

$n$ : is the total number of facilities in the construction site

$\mathbf{H}^*$ : is the normalized hazard interaction matrix

$h_{ij}^*$ : is the normalized hazard interaction value between facilities (i) and (j),  $\forall h_{ij}^* \in [0,1]$

$\max[h_i^0]$ : is the maximum value of potential hazard generated from facility (i) at distance 0 among all facilities, i.e. the maximum value among all diagonal values in the hazard interaction matrix.

### 3.2.1.2.2 Modeling vulnerability interaction matrix

In order to develop the vulnerability modeling of whole targets within a site to the hazards generated from each source, suppose vulnerability interaction matrix between construction facilities  $\mathbf{V}$ . The vulnerability of each target depends on its ability to resist various hazard values generated by surrounding sources. However, as the hazards are physical phenomena and are not explicitly chosen due to general validity requirements, it is assumed that the conditional vulnerability is a linear function of hazard value, as shown in figure 3.5. According to (Mebarki et al. 2012b) the main shortcomings of the previous studies in evaluating construction vulnerability attributed to the inability of these studies in providing the practical and effective value of structural vulnerability; furthermore, the vulnerability does not evolve with the hazard level. Therefore, (Mebarki et al. 2012b) expressed the vulnerability as damage functions, which are considered as a function of hazard intensity. More sophisticated variations of the conditional vulnerability, according to the hazard intensity, can be collected from investigations on specific systems such as masonry under floods or earthquakes, or industrial metal tanks under tsunamis (Mebarki et al. 2012a, 2012b, 2014a; Mebarki & Barroca 2014b). Equations (3.10 – 3.12) illustrate the conditional vulnerability.

$$\mathbf{V} = \begin{bmatrix} V_{11} & \dots & V_{1n} \\ \vdots & V_{ji} & \vdots \\ V_{n1} & \dots & V_{nn} \end{bmatrix} \quad 3.10$$

Since the vulnerability is assumed to be a function of hazard as displayed in figure 3.5, then:

$$v_{ji} = h_{ij} \quad 3.11$$

$$\mathbf{V} = \mathbf{H}^T \quad 3.12$$

Where:

$\mathbf{V}$ : is the vulnerability interaction matrix

$\mathbf{H}^T$ : is the hazard transpose interaction matrix

$v_{ji}$  : is the vulnerability of target (j) to the hazard generated by source (i).

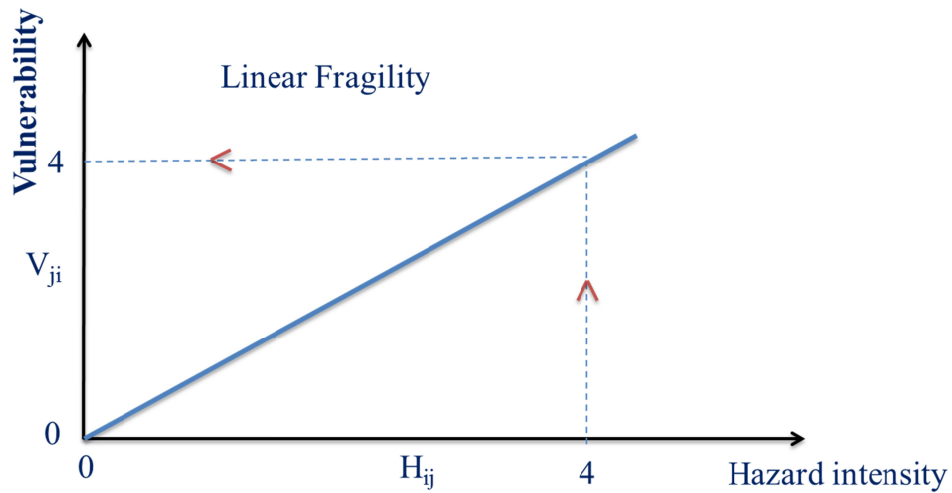


Figure 3.5. Vulnerability as a linear function of hazard value

### 3.2.1.3 Optimization technique (evolutionary algorithm)

The first step to carry out evolutionary optimization technique is to set up particular chromosomes encompassing genes of the problem decision variables and positioned alongside each other as demonstrated in figure 3.6.

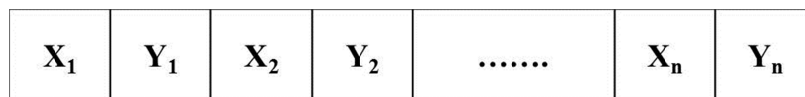


Figure 3.6. Decision variables chromosome

It is apparent from this figure that each successive genes pair represents the x and y coordinates for the facility (i). Moreover, the total number of genes in the designed chromosome are equal to

the number of facilities (n) multiplied by two (the number of variables = 2n). In the current model, the decision variables (genes) are set as numerical values (real numbers).

The evolutionary algorithm is searching algorithm. It works with generations. Based on that, it is required to determine the size of each generation (i.e. the total number of chromosomes in each generation). The genes values in each chromosome within the same generation are randomly generated. The chromosomes are subject to a sequence of operators (mutation and crossover) to generate offspring that inherit characteristics from their parents' chromosomes. Afterward, all chromosomes and offspring are subject to evaluation through a process called fitness function to check the aptness of the solution. The convenient chromosomes (passing the fitness function examination) are selected to continue in the next generation, according to the rule the survival of the best. The process continues until the best solution is found.

### 3.2.1.3.1 Utility function

It is important to develop a model able to minimize risks within a construction site and identify the best layout plan that shows the spatial variability of the global impact of each facility within the whole site. For this purpose, an optimization technique such as a differential evolution algorithm, which is one of the GA, is adopted to use in this study.

The objective function aims to minimize the risk due to potential natural or technological hazards. Therefore, it is required to minimize the global potential impact of each facility within the construction site. This is reached by identifying the best position for each facility, where the potential global impact of that facility and the total risk on the site is at the minimum value. The workflow of objective function derivation is shown in equations (3.13-3.16):

$$\mathbf{Risk} = \mathbf{H} * \mathbf{V} \quad 3.13$$

As presented previously, the conditional vulnerability is considered as a damage function and expressed as a function of hazard intensity. Since  $\mathbf{V} = \mathbf{H}^T$  as shown in equation (3.12), therefore:

$$\mathbf{Risk} = \mathbf{H} * \mathbf{H}^T \quad 3.14$$

For sake of simplicity, it is assumed that the objects hazards are not happening simultaneously. Therefore, the total risk from all objects is a cumulative risk generated from each object as

shown in equation (3.15). Moreover, equation (3.16) displays the objective function of the site layout optimization problem.

$$Total\ Risk = \sum_{i=1}^n \sum_{j=1}^n (\mathcal{R}_{ij}) \quad 3.15$$

$$Minimize \sum_{i=1}^n \sum_{j=1}^n (\mathcal{R}_{ij}) \quad 3.16$$

Where:

**Risk:** is the risk interaction matrix among facilities.

$\mathcal{R}_{ij}$ : is the risk interaction value due to the hazard generated from source (i) and vulnerability of the target (j).

### 3.2.1.3.2 Model layout constraints

Usually, it is not possible to accommodate facilities in any arbitrary location on a construction site. In fact, there are some constraints that should be considered to avoid infeasible solutions. The constraints that are considered herein are construction site boundary and overlapping constraints.

- A boundary constraint is used to guarantee that all facilities are located within the construction site, as shown in figure 3.7. For instance, facility (1) satisfies the boundary constraint, whereas facilities (2) and (3) violate that constraint. However, the facilities are not considered violating the boundary constraints if conditions in equations (3.17-3.20) are satisfied (Easa and Hossain 2008).

$$x_1 + \frac{\ell_i}{2} - x_i \leq 0.0 \quad 3.17$$

$$x_i + \frac{\ell_i}{2} - x_2 \leq 0.0 \quad 3.18$$

$$y_1 + \frac{w_i}{2} - y_i \leq 0.0 \quad 3.19$$



$$y_i + \frac{w_i}{2} - y_2 \leq 0.0$$

3.20

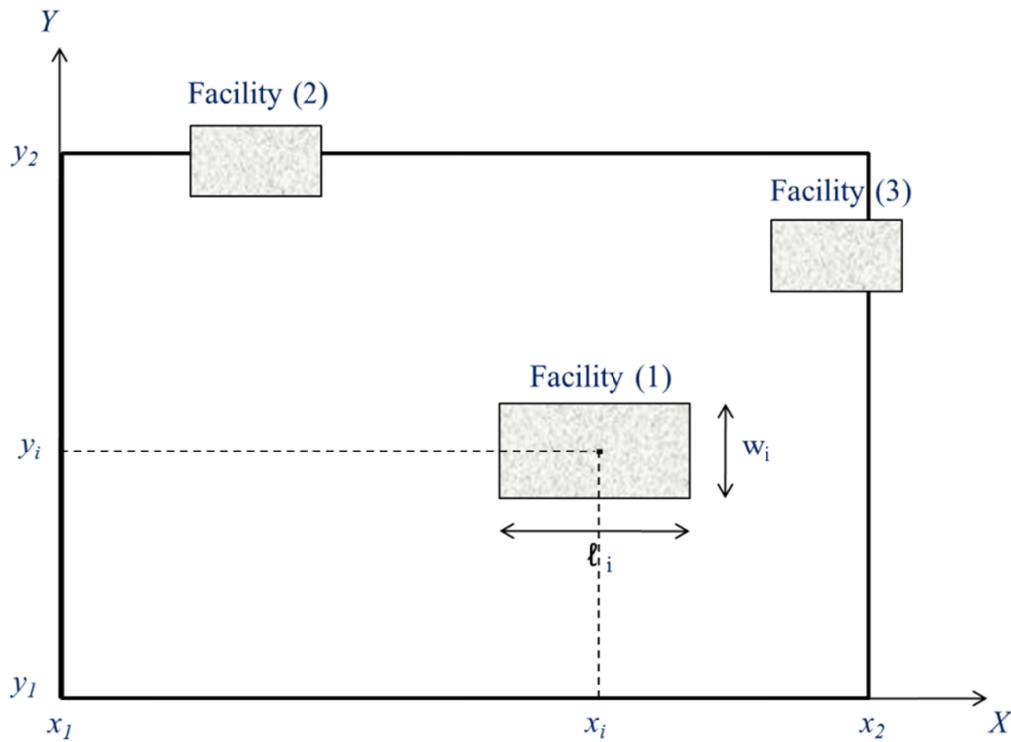


Figure 3.7. Illustration of the boundary constraint

- An overlap constraint is enforced to guarantee that there is no overlapping between any pair of facilities. As shown in figure 3.8, facility (1) satisfies the constraint, whereas facilities (2) and (3) violate the constraint. No overlapping is achieved if at least one of the conditions in both equations (3.21) and (3.22) are satisfied (Easa and Hossain 2008).

$$-|x_i - x_j| + \frac{l_i}{2} + \frac{l_j}{2} \leq 0.0 \quad 3.21$$

$$-|y_i - y_j| + \frac{w_i}{2} + \frac{w_j}{2} \leq 0.0 \quad 3.22$$

Where:

$x_i, x_j, y_i$  and  $y_j$  : are the coordinates for facilities (i) and (j).

$l_i, l_j, w_i, w_j$ : are the lengths and widths of facilities (i) and (j).

Through implementing the optimization evolutionary technique, each facility will start being located at a position inside the construction site. Once the optimization has achieved the described utility function and constraints, the optimal risk matrix can be generated. From this

matrix, the overall potential global impact of each facility can be determined through utilizing equations (3.23-3.27) that are related to mathematical operations on interaction matrix.

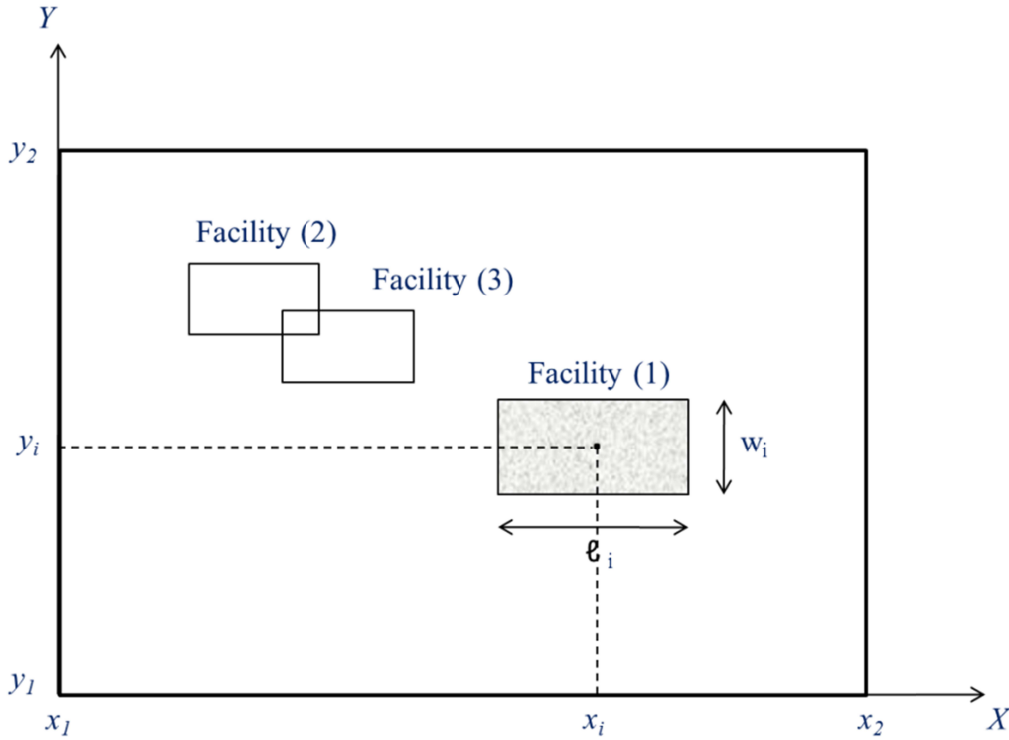


Figure 3.8. Illustration of the overlapping constraint

$$\mathbf{Risk}_{opt} = \begin{bmatrix} \mathcal{R}_{11} & \dots & \mathcal{R}_{1n} \\ \vdots & \mathcal{R}_{ij} & \vdots \\ \mathcal{R}_{n1} & \dots & \mathcal{R}_{nn} \end{bmatrix} \quad 3.23$$

$$\bar{\mathcal{R}}_j = \sum_{i=1}^n \mathcal{R}_{ij} \quad , \forall j \in \{1, 2, \dots, n\} \quad 3.24$$

$$\bar{\mathcal{R}}_i = \sum_{j=1}^n \mathcal{R}_{ij} \quad , \forall i \in \{1, 2, \dots, n\} \quad 3.25$$

$$\boldsymbol{\kappa}_i^* = \bar{\mathcal{R}}_j + \bar{\mathcal{R}}_i \quad , \forall i, j \in \{1, 2, \dots, n\} \quad 3.26$$

$$\psi_i = \frac{\boldsymbol{\kappa}_i^*}{\sum_{i=1}^n \boldsymbol{\kappa}_i^*} \quad , \forall i \in \{1, 2, \dots, n\} \quad 3.27$$

Where:

$Risk_{opt}$ : is the optimal interaction risk matrix

$\bar{R}_i$  : is the potential risk resulted from the hazard of each source (i) in the site.

$\bar{R}_j$  : is potential sensitivity of each target (j) to the hazards sources.

$\kappa_i^*$ : is the potential global impact of each object (i) on the whole site.

$\psi_i$ : is the relative potential global impact of each object (i) on the whole site

#### 3.2.1.4 Effect of space configuration (mean depth parameter)

Once the optimal position for each facility has been identified, the next step is to examine the space configuration of the optimal construction site (visibility analysis). A spatial analysis technique called space syntax was utilized to understand and realize the spatial patterns and space configurations of the site.

Space syntax shows the interactions and correlations between different spaces (Hillier 2007). The spatial analysis, in this research, relies on the delineation of least-risk paths. These paths will have high visibility and connectivity in order to facilitate site evacuation in the case of hazard occurrence. In space syntax, an isovist map that shows the visible field from each point in the whole space is established. The plan obtained from the isovist analysis is divided into a small grid, where each cell represents a single point in the space and its related isovist. The connectivity graph can be generated based on the overlapping of each isovist with all other isovists.

The mean depth is the most significant parameter that reflects the visibility from each point in the whole space. Its evaluation is based on a connectivity graph. A node can be considered either deep or shallow based on the number of steps separating it from all other nodes. As the evacuation process has been considered in evaluating and visualizing the risk within a construction site, it is revealed that the deep positions will have a higher risk compared to shallow ones due to the limited connectivity and visibility with other locations, which in turn will hinder the evacuation process. Furthermore, the actual risk is amplified by utilizing mean depth as a penalty factor. Mean depth is high for deeper positions and low for integrated or shallow positions. In particular, the depth and mean depth of a node can be computed utilizing equations (2.8) and (2.9) respectively.

Depth map analysis software has used in the current study to develop isovist map and to determine mean depth values to be used in generating a spatial risk map within a construction site.

### 3.2.1.5 Developing spatial risk map utilizing GIS

The normalize potential global impact for each facility obtained from the risk interaction matrix and mean depth values obtained from the space syntax analysis are imported to GIS in order to perform a spatial analysis and generate a spatial risk map within the construction site. For sake of simplicity, we assume that the spaces on the site are subjected to the same vulnerability and they are affected by their surrounding objects.

The construction site and facilities have been converted to raster. Cells representing facilities have values equal to relative potential global impact of that facility ( $z_i$ ). These cells are used to determine the potential global risk for each unknown node ( $Z_k$ ) in the site and generate the spatial risk map. To do so, one common interpolation techniques called inverse distance weighting (IDW), already included in the GIS, has utilized. The interpolation technique is based on the concept that spatially distributed elements are spatially correlated. In order to guarantee that we determine the best estimated cell values and reliable results, the maximum number of points is used and their distribution within the site space has been considered

The IDW technique assumes that the weight of each interpolated sample point vanishes with distance. Therefore, if the sample point is too close to the unknown cell, then it will have higher weight in determining ( $Z_k$ ), as shown in equation (3.28). It appears from this equation that the diminution of the weight (the influence of the sampled point) will be greater at remote points than at nearby ones as the power value increases. Therefore, when the node becomes too close to the facilities with the highest potential global impact, the potential global risk at that node will be high compared to those located far away from these facilities. Moreover, equation (3.29) represent the computation of the average of the interpolated sample points, it is utilized to estimate the potential global risk ( $Z_k$ ) for unknown cells. Figure 3.9 illustrates both equations (3.28 and 3.29) utilized for the interpolation process.

$$w_i = \frac{1}{d_{ik}^p} \tag{3.28}$$

$$Z_k = \frac{\sum_{i=1}^m z_i w_i}{\sum_{i=1}^m w_i} \quad 3.29$$

Where:

$Z_k$ : is the potential global risk for cell (k) in the site. It is estimated based on normalized potential global impact of facilities

$z_i$  : is a relative potential global impact value for cell (i) used as sample interpolated point.

$w_i$  : is the weight of sample point (i)

$d_{ik}$  : is the distance between the sample interpolated point (i) and the unknown node (k)

$p$ : is the power value parameter ( $p \geq 1$ ).

$m$ : is the number of sample interpolated points used to estimate unknown node (k).

The mean depth ( $\bar{\delta}_k$ ) results are imported to the GIS in order to perform spatial analysis and generate the visual map for amplified risk within a construction site. As the evacuation process will be considered in evaluating and visualizing the risk within a construction site, the actual risk is amplified by utilizing a penalty factor that has a high value for deeper locations and a low value for integrated or shallow locations. Therefore, equation (3.30) can be used to express and determine the amplified risk ( $\mathcal{R}_{af_k}$ )

$$\mathcal{R}_{af_k} = Z_k * \bar{\delta}_k \quad 3.30$$

Where

$\mathcal{R}_{af_k}$ : is amplified risk of node (k)

$\bar{\delta}_k$ : is the mean depth of node (k), acting as a penalty factor.

The spatial analyst tools in ArcGIS were utilized to find amplified risk for each node (k) within a construction site. As noted in equation (3.30), the amplified risk for any point within a construction site depends on two values, the potential global risk of the node and the mean depth of the node. Therefore, when the node becomes too close to the facilities with highest global potential impact, the potential global risk at that node will be high compared to those located far away from these facilities. Moreover, as the node is too segregated (i.e. has a high mean depth value), it will have a higher risk, since the visibility from this node is very limited, which in turn will impact the identification of the developed actual route for evacuation in the case of emergency compared to those having good visibility and low mean depth value. In addition, the

risk can also be expressed as the probability of occurrence of a limit state function. In that case, the risk (equation 3.30) should be normalized and take values within [0-1]. Otherwise, equation (3.30) can be considered as a risk index that could be used for comparative purposes, i.e. to compare various solutions and find the optimal one.

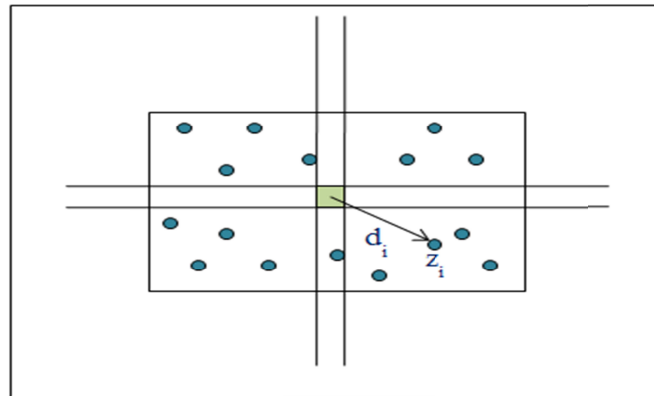


Figure 3.9. Inverse distance weighted (IDW) interpolation process

### 3.2.2 Finding optimal paths (phase 2)

The work to find optimal paths in the current research is similar to that conducted by **Soltani and Fernando (2004)** in that it (1) utilizes Dijkstra's algorithm and the least-cost path algorithm and (2) considers the same criteria (risk, distance, and visibility) for finding the shortest path. Despite the existence of similarities, the work in this research is advanced and differentiated by: (1) creating a site layout able to minimize risk of potential hazards (phase 1); (2) considering the space configuration, represented by visibility, as a penalty factor in determining the amplified risk at each position within a site (phase 1); (3) generating one cost surface that combines all the above-mentioned criteria for finding the shortest path without resorting to the use of weighting approaches like fuzzy or analytical hierarchy processes. The strengthening of this model will assist site managers in identifying the safest paths for site evacuation in case of emergency.

Foremost, once the optimal layout and spatial risk map of construction site generated (i.e. phase 1 is completed), now the time to apply the second phase of the proposed developed model is initiated. It is the moment of the implementation of Dijkstra's and the least-cost path algorithm to

find optimal paths to facilitate evacuation from any position on the site to the external exit safe gate.

As mentioned previously, phase (1) aims to visualize the variation of risk resulted from technological or natural hazard within a construction site (i.e. generating amplified spatial risk map). The amplified spatial risk map forms the cornerstone for performing the second phase of the model. Furthermore, it plays a primary role in allocating the safest position for the exit gate(s) on the site (destination). It also sets up the cost surface for running Dijkstra's algorithm and the least-cost path analysis in order to determine the least-risk path between any point on a construction site and the exit gate. Dijkstra's algorithm and the least-cost path algorithm calculate the accumulated cost for each cell in accordance with the nearness of the exit gate as shown in figure 2.5 and equations (2.11, 2.12).

GIS provides a spatial analysis tool to calculate the cost distance for each cell. Since cost distance analysis depends on iterative allocation, this guarantees that the least cost path between the cell and the source cell will be determined. The outputs of the cost distance analysis are two datasets: the lowest cumulative cost distance and the back-link direction. These datasets are highly important for performing cost path analysis, for creating the safest path that has the lowest risk, and for facilitating evacuation from any position within the construction site to the exit gate in the case of any emergency. The back-link direction dataset identifies, for each cell, the route with the least-cost path that must be taken to move back to reach the source. Furthermore, each cell in the back-link direction dataset is assigned a value from 0 to 8 depending on the convention shown in figure 3.10, where 0 is assigned to the source cell, and the remaining values from 1 to 8 are encoding clockwise starting from the east. For instance, based on figure 3.10, if a cell is assigned a value equal to 6, this means that the path from this cell must go to the upper left neighboring cell, whereas if the cell receives a value of 7, this indicates that the path must cross the north neighboring cell, and so on.

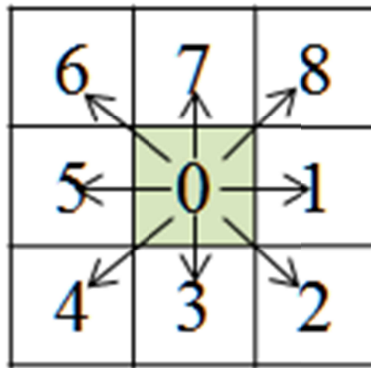


Figure 3.10. Back-link convention

### 3.3 Developing a probabilistic model

Foremost, this research draws inspiration from [Dagan and Issac \(2015\)](#). They stated that the hazardous situation is a result of the interaction between the reinforcing and counteracting characteristics of the workers. In this study, the interaction between facilities is considered as a source of a hazardous situation.

However, it is obvious from previous sections in this research that, the correct assessment of hazard and the vulnerability are highly essential for the success of the risk quantification. Since, the previous proposed deterministic model is not reflecting the reality due to many uncertainties associated with the hazard sources and the vulnerability of potential targets (temporary supporting facilities in our case), therefore, this part of research aims to develop a probabilistic optimization model to get optimal site layout able minimizing the risk of failure of the whole site due to potential fire hazard occurrence. The risk of fire hazard represents the probability of failure for each facility as well as the whole site. The failure of each facility results from a combined individual impact of all facilities exists at a construction site on that facility. Moreover, the failure of the whole site is a combined of individual failure of each facility exists on a construction site during the fire hazard occurrence. The proposed model assists construction managers and planners to identify the facilities with the highest probability of failure, in order to give them more attention to enhance the constructability and safe working environment.

Figure 3.11 displays the methodology adopted to generate optimal site layout. It consists of several steps: (1) identify the characteristics of facilities required to perform construction



activities; (2) hazard modeling; (3) vulnerability modeling; (4) risk modeling; (5) optimization technique; (6) generate spatial risk map utilizing GIS. The first step and also the last two steps are similar to that utilized in the deterministic model.

In general, fire hazard modeling consists of (a) identifying the hazard sources, i.e. the facilities triggering the occurrence of fire; (b) identifying the fire hazard intensity for hazardous sources through probabilistic distribution function; (c) developing the attenuation model that displays the propagation of the fire hazard and its intensity on the impacted targets. On the other hand, the vulnerability modeling involves: (a) identifying the targets that may be impacted by the hazard (i.e. all facilities erected in the vicinity of the hazard sources); (b) identify the vulnerability status for each target facility; (c) estimating the vulnerability value utilizing proposed vulnerability curve, or vulnerability damage functions which express the vulnerability as function of fire hazard intensity.

Risk modeling represents the probability of damage or loss for each facility as well as for the whole site. This probability of loss is obtained by concatenating probability distribution of hazard and vulnerability of elements at risk (i.e. facilities in a construction site). The probability of failure for the whole site results from the combined of individual failure of each existing facility on the site. The purpose of the optimization technique algorithm is to minimize the probability of failure for the whole site through finding the best position (x, y coordinates) for each facility, within a construction site considering the boundary and overlapping constraints. Once the optimal site layout generated, it is imported to GIS in order to develop spatial fire risk map on a construction site.

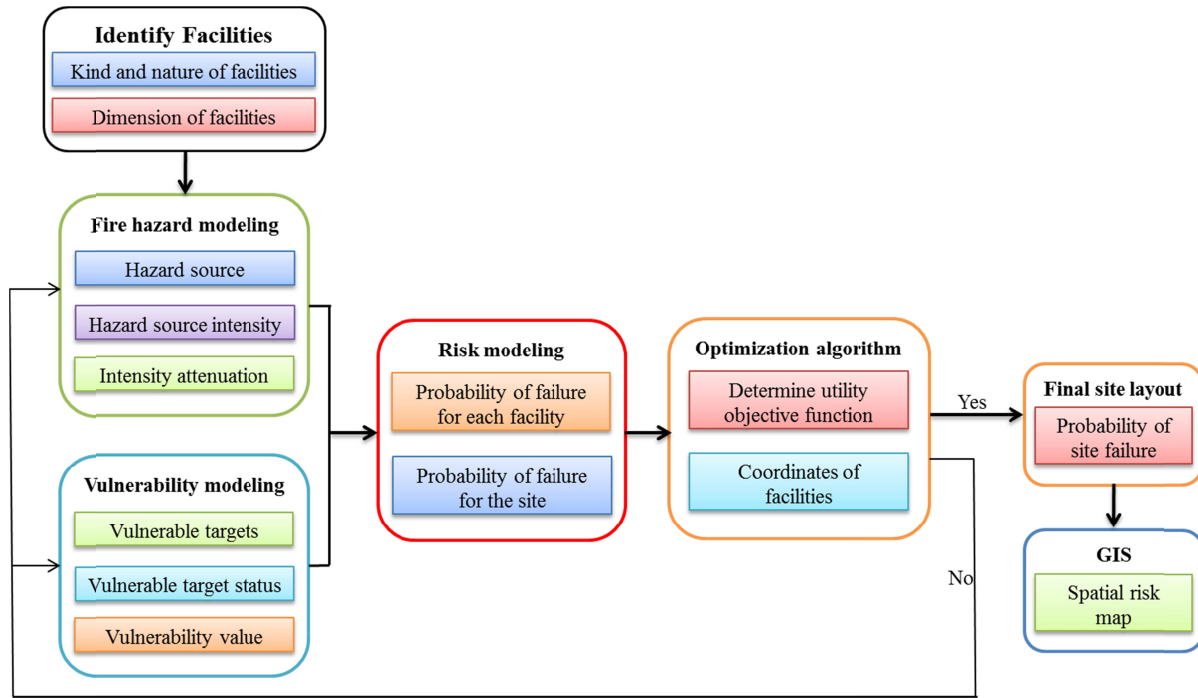


Figure 3.11. Probabilistic model to generate optimal site layout

### 3.3.1 Hazard modeling

Fire hazard is one kind of threats that could damage the construction project. Similar to any other kind of hazards, modeling fire hazard involves several uncertainties; one of these uncertainties starts through identifying the potential facilities in a construction site that trigger the initial spark of fire hazard accident. These facilities are considered most hazardous compared to other existing one. Usually, the electrical generator, the fuel storage, and the chemical materials used in the construction process are considered the most sources of fire occurrence. As the initial accident may happen in any of the existing facilities in the construction site, and it is not easy to anticipate them, it is assumed that, in this study, the fire hazard will occur in all of these hazardous facilities at the same time. This assumption considers the probable worst case scenario and guaranteed obtaining the best site layout that prevents occurring catastrophic and detrimental levels of damage from an accident. Another uncertainty associated with fire hazard modeling is estimating the fire intensity at the initial hazard sources. Fire intensity can be defined as the amount of energy emanating from each meter of head fire edge; it can be expressed in kilowatt per meter (kW/m). It depends on the amount of flaming material and the speed of burning.

Generally, the fire hazard intensity is classified into four categories, ranging from low scale grade to very high grade, as specified in table 3.1.

The expected fire hazard level for each facility is identified based on historical data or expert judgment. Thus, in case if the historical data is not available, it is required from the subject matter experts to identify the fire hazard level for each hazardous facility depending on the categories displayed in table 3.1. It is obvious from this table that, each fire hazard level falls within a range of fire intensity values (minimum and maximum value for each hazard level). Therefore, it is assumed that, for each fire hazard level, the fire intensity is a random variable, it also follows a uniform probability distribution function (i.e. if the fire hazard level for one facility is specified to be medium, then the fire intensity value for that facility is a random value falls between 400 and 1000 kW/m).

Table 3.1. Categories of fire hazard intensity

<b>Fire intensity (kW/m)</b>	<b>Fire flame height (m)</b>	<b>Fire hazard level</b>
Less than 400	0 – 1.5	Low hazard
400 – less than 1000	1.5 – 7	Medium hazard
1000 – less than 2000	7 – 14	High hazard
Greater than 2000	> 14	Very high hazard

Whatever the case, as a result of wind motion and other fire phenomena characteristics, the fire propagates to influence on other erected vicinity facilities with intensity values less than that at the initial hazard sources due to attenuate of hazard with distance. Figure 3.12 shows that the fire hazard initiates at object (i) with intensity ( $h_i^0$ ), afterwards the fire propagates to impact on objects (j) and (k) with intensities ( $h_{ij}$ ) and ( $h_{ik}$ ) respectively. Surely, these two hazard intensity values are less than the initial fire intensity value at object (i) due to attenuation law. For sake of simplicity and due to lack of historical information, it is assumed that, the attenuation of fire hazard intensity follow a normal distribution function, as shown in figure 3.13 (i.e. the initial hazard intensity arising from facility i decreases normally distributed with distance, it impacts value on a potential target j equals to ( $h_{ij}$ ), which is less than  $h_i^0$ ). In fact, figure 3.13 presents the attenuation law that displays the relation between fire hazard intensity and distance.

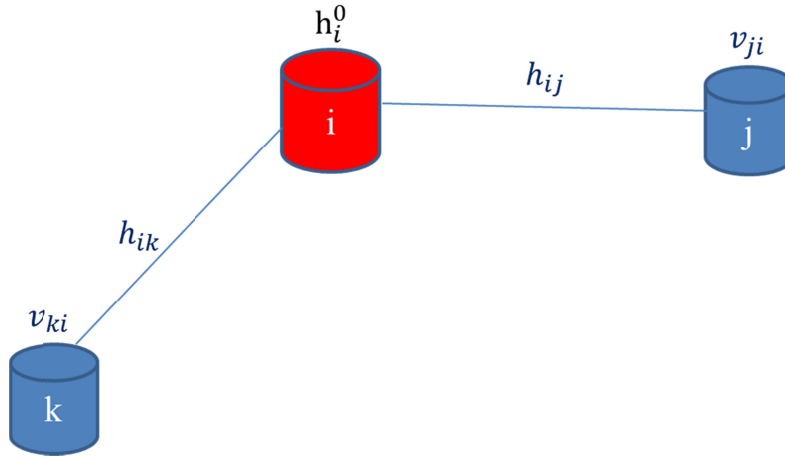


Figure 3.12. Propagation of fire hazard

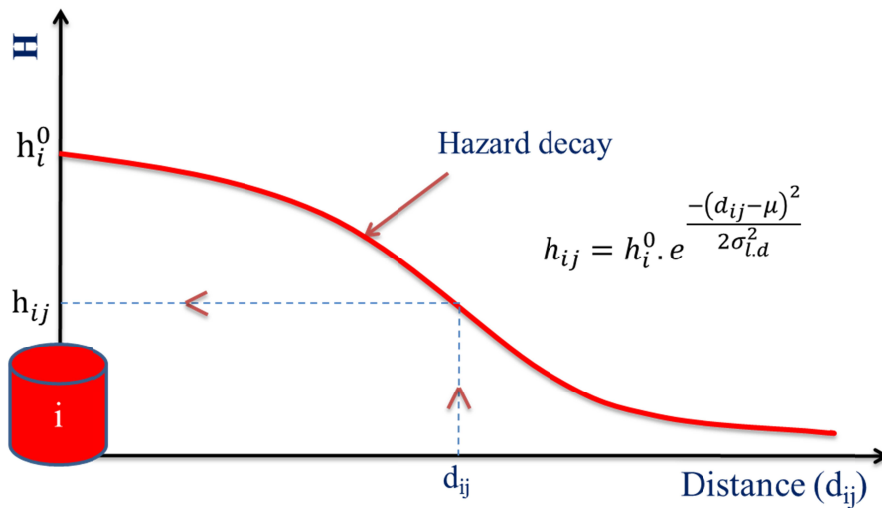


Figure 3.13. Hazard decay as normal distribution function

In general, to construct hazard matrix **H**, suppose there is a total number of facilities that must be set up in a construction site (*n*). Consequently, a matrix of (*n* x *n*) size must be developed. The same equations, utilized in the deterministic model, (3.6 – 3.9) must be established to display the impact of each facility on itself as well as on other existing facilities. The diagonal values of this matrix represent the fire hazard intensity for each facility at itself. It has been selected randomly from a uniform probability distribution based on the hazard level specified for each facility. In fact, these fire hazard intensity values are the highest at the source itself and decline as it becomes far away from the hazard source due to attenuation law. This can be seen in equations (3.31–3.33)

$$h_{ij} = h_i^0 \cdot e^{\frac{-(d_{ij}-\mu)^2}{2\sigma_{i,d}^2}} \tag{3.31}$$

$$h_{ij}^* = P(H_i^0 = h_i^0) \cdot P(H_{ij} = h_{ij} |_{d_{ij}}) \quad 3.32$$

$$P(H_i^0 = h_i^0) = \frac{h_i^0}{\max[h_i^0]} \quad 3.33$$

Where:

$h_{ij}$ : is the fire hazard intensity value that facility (i) impact on the potential target (j).

$h_{ij}^*$ : is the normalized fire hazard intensity value that facility (i) influence on facility (j),  $\forall h_{ij}^* \in [0,1]$

$\max[h_i^0]$ : is the maximum value of fire hazard intensity generated from facility i at distance 0 among all hazardous facilities, i.e. the maximum value among all diagonal values in the hazard matrix.

$h_i^0 = h_{ii}$ : is the potential fire hazard intensity value generated from facility (i) at distance (d=0), i.e. the impact of facility on itself.

$d_{ij}$ : is the Euclidean distance between facilities (i) and (j).

$P(H_i^0 = h_i^0)$ : is the probability of accident occurring at facility (i).

$P(H_{ij} = h_{ij} |_{d_{ij}})$ : is the probability of hazard occurring at (i) to influence at target j

$\mu, \sigma_{l,d}$ : The mean and standard deviation of distances respectively. These are the parameters of hazard attenuation model, which is assumed to be normal distribution. They can be obtained from experimental or historical data. Since the maximum hazard intensity occurs at distance zero, and the normal distribution is symmetrical around the mean, subsequently, the value of mean ( $\mu$ ) should be equal zero.

### 3.3.2 Physical vulnerability modeling

The vulnerability can be defined as the susceptibility of exposed element at risk to suffer a loss as a consequence of hazard occurrence. Modeling vulnerability involves a lot of uncertainties such as; identifying the potential targets that may be impacted by the hazard, the status of these targets, and their expected level of damage. The physical vulnerability of each target depends on its ability to resist various hazard values generated by surrounding sources. Usually, all of the erected facilities in construction site are considered to be potential targets that will be impacted by fire hazard. These potential targets are vulnerable to damage with different damage levels

ranging from 0 (no damage) to 1 (completely collapsed). This damage level depends on impacting hazard intensity, the ability of facilities to resist the hazard, and the remoteness of the facilities from fire hazard sources. Thus the damage level or conditional vulnerability is defined as the probability that the limit state value (the difference between resistance ( $R$ ) of the object and the impacting hazard intensity ( $h$ ) on the object) is less than or equal to zero, given the hazard intensity is ( $h_0$ ), i.e.  $P((R - h)|_{h_0})$ .

Generally, in order to estimate the vulnerability for a specific type of element at risk to specific kind of hazard, there are vulnerability curves, which are developed based on historical or experimental data. These curves are mathematical functions that show the relation between the degree of damage and the hazard intensity. In fact, for earthquake and flood hazard, it is easy to find in literature, vulnerability curves to evaluate the risk for masonry or reinforced structures for these kinds of hazards. In contrast for fire hazard, these curves are not available for permanent facilities and for the temporary facilities located in a construction site. Therefore the vulnerability assessment in this research has been done using the semi-quantitative method proposed by [Mebarki et al. \(2012b\)](#). In this method, [Mebarki et al. \(2012b\)](#) expressed the vulnerability as damage functions, which are considered as a function of hazard intensity. They stated that typical damage curves are in an elliptic shape. Figure 3.14 displays the elliptic shape of the curves and the maximum damage level value for each damage state.

In general, for vulnerability assessment, experts are requested to classify each temporary facility into one of four classes (very safe, safe, dangerous, and very dangerous). For each class, a maximum conditional vulnerability is assigned. Afterward, an ellipse continuous function is utilized to estimate the conditional vulnerability for each facility as displayed in equation 3.34. This equation shows how conditional vulnerability evolved concerning hazard intensity. Based on this equation, the vulnerability interaction matrix  $\mathbf{V}$  with size ( $n \times n$ ) is established as shown in equation 3.35.

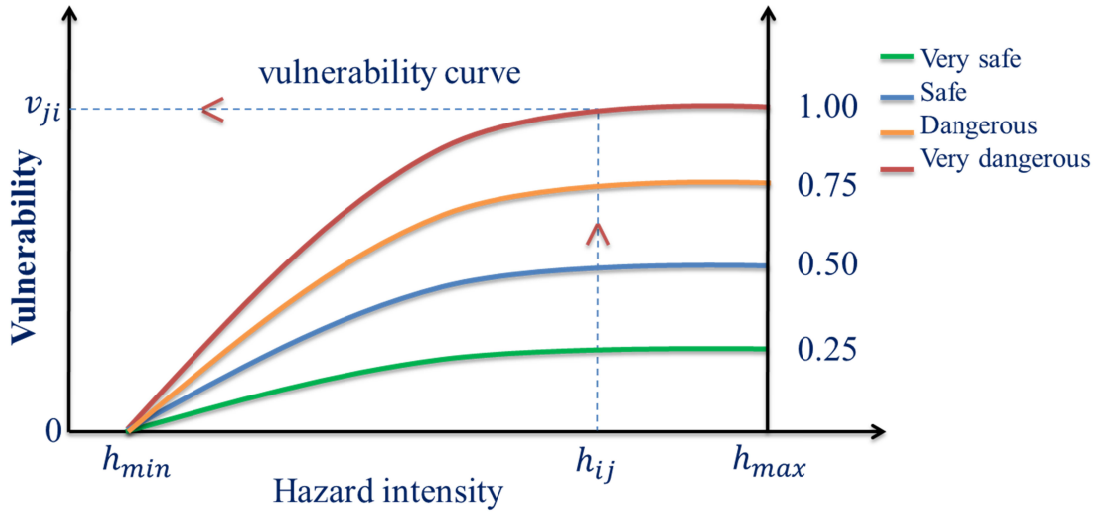


Figure 3.14. Damage curve functions

$$\left(\frac{P(v_{ji}|h=h_{ij})}{P(v_{max})}\right)^2 + \left(\frac{h_{max}-h_{ij}}{h_{max}}\right)^2 = 1 \quad 3.34$$

$$\mathbf{V} = \begin{bmatrix} P(v_{11}|h=h_{11}) & \dots & P(v_{1n}|h=h_{n1}) \\ \vdots & P(v_{ji}|h=h_{ij}) & \vdots \\ P(v_{n1}|h=h_{1n}) & \dots & P(v_{nn}|h=h_{nn}) \end{bmatrix} \quad 3.35$$

Where:

$\mathbf{V}$ : is the vulnerability interaction matrix

$v_{ji}$ : is the vulnerability of target (j) to the hazard generated by source (i)

$P(v_{ji}|h=h_{ij})$ : is corresponding conditional probability of damage for facility (j) as a result of hazard generated by facility (i), given hazard intensity at j equal to  $h_{ij}$  and it is range between 0 (no damage) to 1 (completely collapse).

$P(v_{max})$ : is the maximum expected damage for the facility based on its classification.

$h_{max}$ : is the maximum hazard intensity within the validity domain values of hazard.

$h_{ij}$ : is the fire hazard intensity value that facility (i) impact on the potential target (j).

### 3.3.3 Risk modeling

The risk is a likelihood of damage or loss in elements at risk as a result of hazard occurrence. It is computed as a convolution between hazard and vulnerability as presented in equation 3.13. Due to lack of historical data, it is assumed that the risk failure of each facility is independent of all other facilities and the risk failure of the whole site is a combined of the individual failure of each facility. The workflow of the risk of failure of each facility as well as for whole site derivation is shown in equations (3.36-3.43):

Suppose the risk failure of the whole site is ( $E_{site}$ ), the risk failure of each facility is ( $E_i$ ). Since the risk of failure for the whole site is combined of individual failure of each facility, then:

$$E_{site} = \bigcup_{i=1}^n E_i \quad 3.36$$

If the probability of failure for the whole site is given by  $P(E)$ , then according to probability and Demorgan laws, the safety of the site is the complement of site failure, therefore:

$$\bar{E}_{all\ site} = \bigcap_{i=1}^n \bar{E}_i \quad 3.37$$

$$P(E) = 1 - \prod_{i=1}^n (1 - P(E_i)) \quad 3.38$$

To estimate the probability of failure for each facility  $P(E_i)$ , it is assumed that the failure of each facility (i) is combined of the individual impact of all other facilities on the facility (i), therefore:

$$E_i = \bigcup_{j=1}^n E_{ij} \quad 3.39$$

According to probability and Demorgan laws, the safety of the facility is the complement of the facility failure, therefore:

$$\bar{E}_i = \bigcap_{j=1}^n \bar{E}_{ij} \quad 3.40$$



$$P(E_i) = 1 - \prod_{j=1}^n (1 - P(E_{ij})) \quad 3.41$$

$$P(E_{ij}) = P(h_j) \cdot P(v_{ij}|h_{ji}) \quad 3.42$$

By the Substitution of equations (3.41 and 3.42) in equation 3.38, the probability of failure for the whole site becomes:

$$P(E) = 1 - \prod_{i=1}^n \left( \prod_{j=1}^n \left( 1 - P(h_j) \cdot P(v_{ij}|h_{ji}) \right) \right) \quad 3.43$$

Where:

$P(E)$ : is the probability of risk failure of the whole construction site.

$P(E_i)$ : is the probability of risk failure of facility (i)

$P(E_{ij})$ : is the probability risk failure of facility (i) due to impact of facility (j) on (i).

$P(h_j)$ : is the probability of hazard occurrence in facility (j)

### 3.3.4 Probabilistic model utility function

The objective function aims to minimize the risk due to potential fire hazard. Therefore, it is required to minimize the probability of failure of the whole site. This is achieved by identifying the best position for each facility since the failure of the site is a combined of the individual failure of each existing facility. As shown in equation 3.43 the probability of failure for the whole site can be minimized by maximizing the negative part of the equation that represents the complement of the site failure (i.e. safety of the whole site). If the optimization process achieves the objective function requirements considering both the boundary and overlapping constraints specified in equations (3.17 – 3.22), then the final construction site layout will be developed. The objective function is shown in equation 3.44.

$$\text{maximize} \left( \prod_{i=1}^n \left( \prod_{j=1}^n \left( 1 - P(h_j) \cdot P(v_{ij}|h_{ji}) \right) \right) \right) \quad 3.44$$

### 3.4 Spatial methods for model validation

Once the optimal site layout has been imported into GIS platform, several spatial analysis techniques have been applied to validate the research method.

Foremost, two spatial methods are adopted in order to represent the data, i.e. vector and raster. On one hand, the vector can be divided into three types: points, lines, and polygons. On the other hand, raster is defined by a cell grid, and each cell has one attribute value. The construction site, herein, is represented as a polygon, while the edges of each facility are represented as lines. Each line has attribute value equal to the potential global risk of the concerned facility.

Particularly, as the optimal spatial risk map of a construction site is investigated, understanding the effect of the potential global risk of each facility on the surrounding spaces is highly significant. Thus, the implementation of interpolation technique is a suitable option, since it is assumed that the distributed elements are spatially correlated. In the present study, the interpolation spatial analysis technique called inverse distance weighting (IDW) is adopted. Basically, to carry out this interpolation technique, it is required to convert a line of each facility into multiple points, where each point has attribute value equal to the potential global risk of the concerned facility. This conversion has been performed following two steps; first: convert the line into a raster, where each cell has an attribute value equal to the potential global risk; second: convert the raster into points. Once, all the lines of facilities have been converted to points, the IDW can be implemented.

IDW estimates cell values by averaging the values of sample data points in the vicinity of each cell. Furthermore, IDW assumes that each interpolation sample point has a local influence that decreases with distance, i.e. the closer a sampled point is to the center of a cell, the more influence or weight it has in the averaging process. However, the more input points and the greater their distribution, the more reliable the results will be. In general, the number of nodes used for interpolation depends on the required accuracy and the size of the construction site.

Furthermore, the local function represented by arithmetic operations is used to multiply the results of the interpolation technique with the results of visibility analysis (represented by mean depth value) in order to produce the risk amplification map. The local function processes a raster

on a cell-by-cell basis, where each cell is processed alone based solely on its own values without any reference to the values of other cells.

Finally, Map distance spatial method has been applied in the present study. It is useful to find the shortest or the least-cost path from one location to another based on cost factor specified by the user. Generally, two distance functions are considered (1) straight distance which measures the straight distance from each cell to the closest sources according to Euclidean, or straight line distance, i.e. the source identifies the elements of interest, such as exit gate of a construction site. The distance is measured from center to center of the cell; (2) and cost weighted distance that finds the least accumulative cost from each cell to the nearest source, based on the cell's distance from each source and the cost to travel through it. Cost can be money, time, risk or any other factor identified by the user.

The cost-weighted distance is useful to find the least risk paths in order to accelerate the evacuation of a construction site in case of hazard occurrence. Two datasets are highly important to find the least risk paths: (1) Accumulated least risk dataset that displays the least accumulative cost from each cell to the nearest exit gate; (2) and the back-link dataset that shows the direction from each cell to the nearest exit gate. Thus, starting from a current cell, follow the direction to get to the next cell and so on until arriving to the nearest exit gate. However, the obstacles that might exist in the site will extremely impact on the path selection. Therefore, the cells representing obstacles are assigned "NO DATA" value, in order to stay away from them for any path identification.

### **3.5 Résumé du chapitre 3**

Ce chapitre développe la méthodologie adoptée pour atteindre les objectifs de la thèse et pour élaborer des modèles d'optimisation pour le plan d'aménagement de site. Il comprend : la modélisation de l'aléa, la modélisation de la vulnérabilité, la modélisation du risque, l'importance de l'analyse de syntaxe spatiale et son impact sur le risque global dans un chantier de construction, le rôle des SIG dans la génération de la carte de risque spatiale et la recherche des chemins optimaux. Deux modèles d'optimisation ont été développés : (1) modèle déterministe générique et (2) modèle probabiliste pour les risques d'incendie. Les modèles

mathématiques utilisés pour développer ces deux modèles sont également présentés dans ce chapitre.

## **CHAPTER 4**

### **Model Implementation and Results Discussion**

This chapter presents the implementation of the proposed developed models in order to examine their ability and efficiency in generating optimal site layout. It shows the nature of input data required carrying out the proposed models, the optimization process and, displays discussion about the obtained results. The models have been implemented utilizing python language platform.

#### **4.1 Implementation of deterministic model**

A case study is implemented in order to validate the deterministic proposed model by minimizing and visualizing the risk of a construction site and finding the safest paths from any position on the construction site to the external exit gate.

##### **4.1.1 Case study description**

A case study used to implement a deterministic model is obtained from the project that is still under construction in Palestine. The dimensions of the construction site are 55 x 55 m. The dimensions and nature of the required facilities are shown in table 4.1. It contains nine facilities ( $F_1$  to  $F_9$ ); such that facilities electric generator ( $F_1$ ), fuel storage ( $F_7$ ) and tower crane ( $F_8$ ) represent the highest sources of hazard and threat within the construction site. Furthermore, the objects within the construction site are categorized as either fixed or movable. The term “fixed” means that the coordinates of the object are known in advance and cannot be changed, whereas

“movable” means that the object coordinates are not known. The purpose is to find the best coordinates for these objects in order to minimize the potential hazard consequences. Actually, the locations of building under construction, and sometimes the tower crane, are fixed prior to the construction launch. Thus, they are considered as fixed objects. Other facilities like, for example, job offices (F<sub>4</sub> and F<sub>5</sub>) and storage areas (F<sub>6</sub> and F<sub>7</sub>) can be erected at their optimal position within the construction site (i.e. minimize a total risk). Hence, they are considered as movable.

The proposed model requests that the manager identifies several inputs: (1) the nature of the hazard, which is considered, in this illustration, as thermal flux; (2) the potential hazards and threats from each facility (maximum hazard intensity) in order to fill the diagonal values in the hazard interaction matrix as shown in table 4.2. It is clear from this table that the highest potential hazard refers to the electrical generator, fuel storage, and tower crane facilities; and (3) finally, the hazard attenuation (hazard decay) value, which is assigned as 0.01. This can be changed based on the kind of the hazard or to conduct a sensitivity analysis of the hazard (Mebarki et al., 2012a, 2012b, 2014a; Mebarki and Barroca, 2014). In this implementation, all previous requisition data are utilized to conduct an optimization technique using a differential evolution algorithm and to generate an actual risk map. Therefore, the optimal coordinates for movable facilities and the potential global impact of each facility can be determined within a construction site. The actual risk map visualizes how risk varies from one position to another and identifies the most at-risk locations within a site.

Table 4.1. Facility dimensions, description, and categorization (fixed or movable),

Facility	Length "ℓ" (m)	Width "w" (m)	Description	Location attribute: Fixed or movable
F <sub>1</sub>	2	1	Electric generator	Movable
F <sub>2</sub>	7	3	Labor services	Movable
F <sub>3</sub>	10	6	Concrete plant	Movable
F <sub>4</sub>	12	5	Job office 1	Movable
F <sub>5</sub>	5	12	Job office 2	Movable
F <sub>6</sub>	8	20	Steel storage	Movable
F <sub>7</sub>	2	1	Fuel storage	Movable
F <sub>8</sub>	8	8	Tower crane	Fixed (32,30)*
F <sub>9</sub>	26	50	Building under construction	Fixed (14,28)*

\* The coordinates of predefined (fixed) objects.

Table 4.2. Maximum hazard intensity from each facility

Facility	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	F <sub>4</sub>	F <sub>5</sub>	F <sub>6</sub>	F <sub>7</sub>	F <sub>8</sub>	F <sub>9</sub>
F <sub>1</sub>	4								
F <sub>2</sub>		1							
F <sub>3</sub>			3						
F <sub>4</sub>				2					
F <sub>5</sub>					2				
F <sub>6</sub>						2			
F <sub>7</sub>							4		
F <sub>8</sub>								4	
F <sub>9</sub>									2

#### 4.1.2 Optimization process and discussion of results

The Python language platform was utilized to execute the optimization process. A personal computer with 2.4 GHz Intel(R) core(TM) i7-5500U CPU and 16GB of Ram was utilized. The optimization algorithm is run with an initial population consisting of 100 chromosomes.

The mutation and crossover operators are implemented to create the next generations with better fitness, until finding the optimal solution. Several runs were performed in order to get the optimal location of facilities and determine the potential global impact that each facility has within a construction site.

##### 4.1.2.1 Optimal layout result

The relative disposal between the facilities is found as the optimization solution. The absolute location, therefore, will be defined once any one of the facilities is chosen. For instance, one possible absolute location and the results for this solution are displayed in the figure 4.1. It shows the optimal disposal location of facilities. In addition, tables (4.3 – 4.6) present the optimized coordinates of the facilities, the normalized potential global impact for each facility, the distance between facilities and the optimal interaction risk matrix, respectively.

For the case study, it appears that facility (F<sub>8</sub>) has the highest potential global impact within the site with a value equal to 18.0%, followed by facilities (F<sub>7</sub>) and (F<sub>1</sub>), respectively. Furthermore, it is noticeable that facilities (F<sub>4</sub>), (F<sub>5</sub>), (F<sub>6</sub>) and (F<sub>9</sub>) have approximately the same potential global impact value (about 8.0%). Also, the potential global impact of the facility (F<sub>2</sub>) is the lowest

among all other facilities with a value of 6.1%. Hence, it can be noticed that the electric generator ( $F_1$ ) and fuel storage ( $F_7$ ) are located far away from the other facilities, whereas, the position of the tower crane ( $F_8$ ) cannot be changed, since it is a fixed facility, as shown in figure 4.1.

Table 4.3. Coordinates of each facility center

Facility	Coordinates (x, y) [Units: m]
$F_1$	(1.25,0.5)
$F_2$	(34.1,51.3)
$F_3$	(50,51.1)
$F_4$	(48.4,3.2)
$F_5$	(50.3,13.6)
$F_6$	(51,36.2)
$F_7$	(2.8,54.1)
$F_8$	(32,30)
$F_9$	(14,28)

Table 4.4. Normalized potential global risk of the facilities

Facility	Overall weight	Normalized weight
$F_1$	0.159	0.883
$F_2$	0.061	0.339
$F_3$	0.116	0.644
$F_4$	0.077	0.427
$F_5$	0.080	0.444
$F_6$	0.081	0.450
$F_7$	0.163	0.906
$F_8$	0.180	1.000
$F_9$	0.083	0.461

Table 4.5. Distances [m] between facilities.

Facility	$F_1$	$F_2$	$F_3$	$F_4$	$F_5$	$F_6$	$F_7$	$F_8$	$F_9$
$F_1$	0	60.49	70.22	47.26	50.76	61.13	53.60	42.61	30.47
$F_2$		0	15.88	50.16	41.00	22.58	31.38	21.40	30.64
$F_3$			0	47.85	37.44	14.90	47.23	27.70	42.65
$F_4$				0	10.56	33.05	68.31	31.41	42.52
$F_5$					0	22.57	62.36	24.55	39.10
$F_6$						0	51.26	19.87	37.34
$F_7$							0	37.82	28.23
$F_8$								0	18.09
$F_9$									0



This indicates that the risk consequences from facilities (F<sub>1</sub>), (F<sub>7</sub>) and (F<sub>8</sub>) are the highest. In addition, the risk generated from other facilities are either moderate such as facilities (F<sub>4</sub>), (F<sub>5</sub>), (F<sub>6</sub>) and (F<sub>9</sub>) or low like facility (F<sub>2</sub>) or between moderate and high like facility (F<sub>3</sub>).

Table 4.6. Non-normalized optimal interaction risk matrix.

Facility	F <sub>1</sub>	F <sub>2</sub>	F <sub>3</sub>	F <sub>4</sub>	F <sub>5</sub>	F <sub>6</sub>	F <sub>7</sub>	F <sub>8</sub>	F <sub>9</sub>
F <sub>1</sub>	16.00	11.53	10.88	12.44	12.20	11.48	12.00	12.77	13.66
F <sub>2</sub>	0.16	1.00	0.71	0.25	0.35	0.60	0.47	0.62	0.48
F <sub>3</sub>	5.28	8.07	9.00	6.36	6.89	8.13	6.39	7.41	6.62
F <sub>4</sub>	2.33	2.25	2.31	4.00	3.59	2.79	1.73	2.84	2.48
F <sub>5</sub>	2.23	2.53	2.64	3.59	4.00	3.15	1.89	3.08	2.59
F <sub>6</sub>	1.93	3.15	3.43	2.79	3.15	4.00	2.21	3.24	2.63
F <sub>7</sub>	12.00	13.59	12.44	11.00	11.40	12.16	16.00	13.12	13.82
F <sub>8</sub>	12.77	14.33	13.86	13.59	14.10	14.45	13.12	16.00	14.59
F <sub>9</sub>	2.87	2.87	2.48	2.48	2.59	2.63	2.95	3.31	4.00

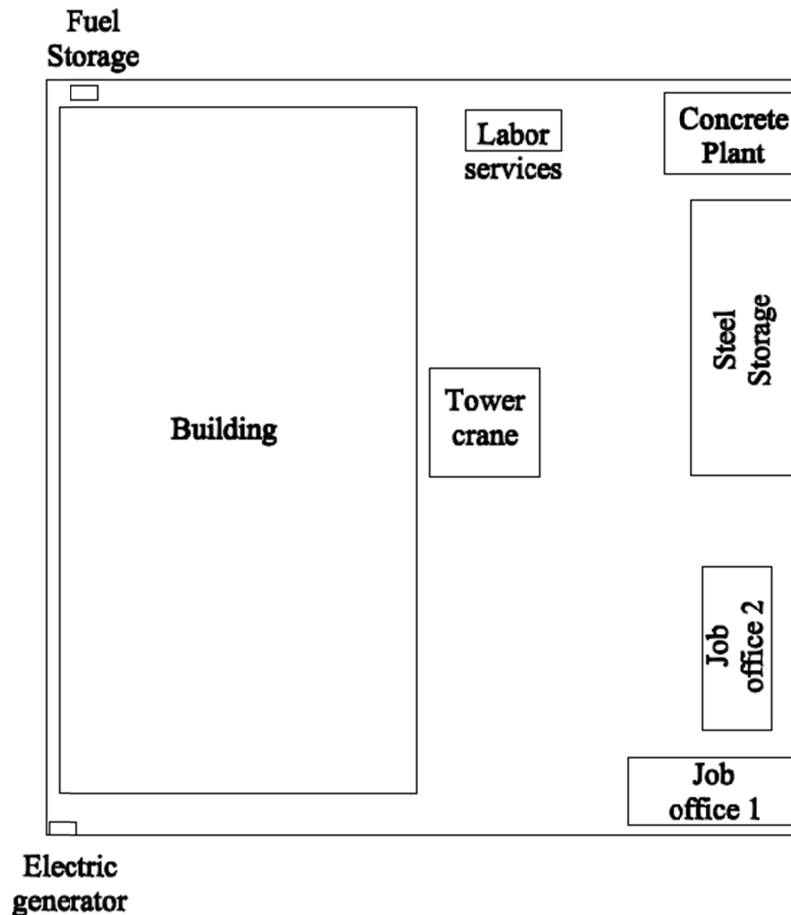


Figure 4.1. Layout of the optimal facility positions

The optimization results (i.e. the potential global impact of the facilities) are imported into the GIS in order to conduct IDW interpolation, which leads to setting up the map of spatial variability of the potential global risk on the construction site as displayed in figure 4.2. It shows the spatial variability of the potential global risk. Figure 4.2 confirms that the nodes closer to the facilities with the highest potential global impact will have a higher value of potential risk compared to those located far away. It is, therefore, obvious from the map that the areas adjacent to facilities (F<sub>8</sub>) at the middle of the site, (F<sub>7</sub>) at the top left of the site and (F<sub>1</sub>) at the bottom left of the site are the most at-risk positions. It also appears that the areas adjacent to the facility (F<sub>2</sub>) have the lowest risk. Finally, all other areas are of intermediate risk due to the proximity to facilities with moderate potential global impact.

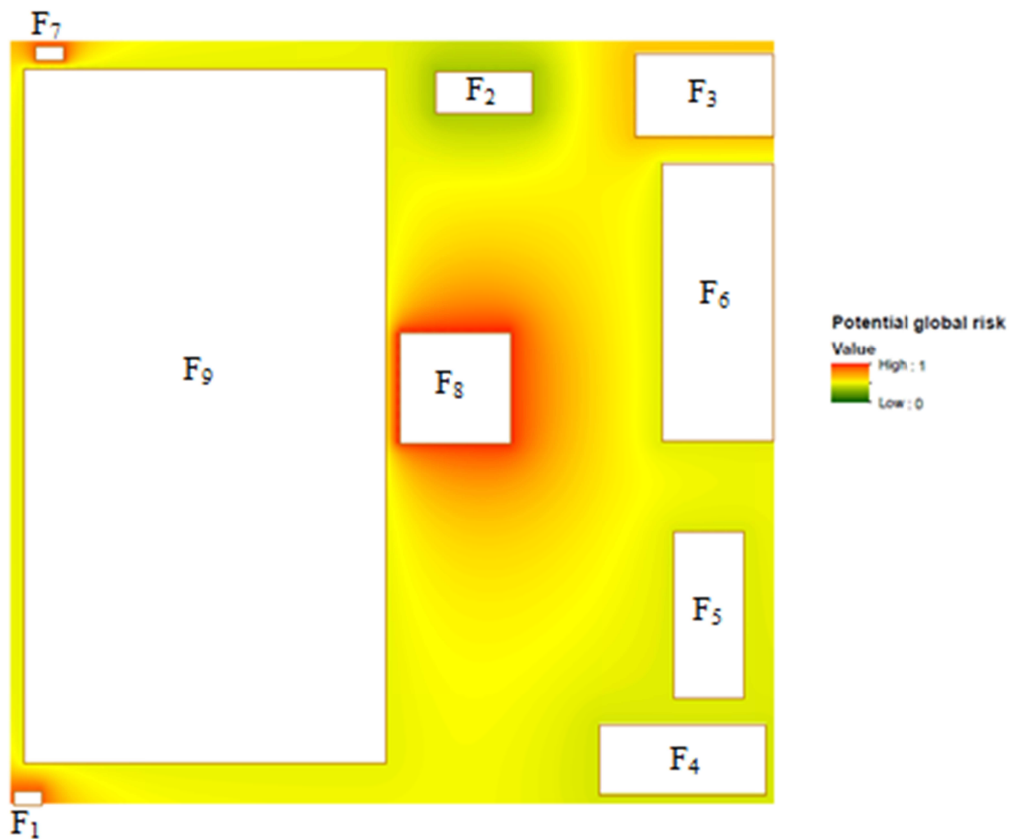


Figure 4.2. Map of site spatial variability of the potential global risk ( $Z_k$ )

Space syntax analysis is performed on the optimal site layout to estimate the mean depth value for each position in a construction site. The mean depth results are displayed in figure 4.3. It can be noticed that the positions with higher integration and low mean depth values have a lower risk. These locations are not segregated and have good visibility to other areas. However, the

positions that have low integration and high mean depth values are at higher risk due to the limited visibility to other locations. These locations can be considered as segregated one. The map shown in figure 4.3 indicates that the following positions are segregated and have a higher risk, compared to others due to limited visibility and connectivity with other locations:

- Along the left side of the site behind the building under construction ( $F_9$ ).
- Bottom left of the site beside electric generator ( $F_1$ ).
- Top left of the site, adjacent to fuel storage facility ( $F_7$ ).
- Bottom right near job offices ( $F_4$ ) and ( $F_5$ ).

Moreover, the mean depth values at the middle of the construction site (figure 4.3) are low due to good visibility and high connectivity. Therefore, evacuation from these areas will be easier than evacuation from other locations, in the case of emergency.

The final map, combining the site potential global risk ( $Z_k$ ) and site mean depth penalty factor ( $\bar{\delta}_k$ ), is shown in figure 4.4. This displays the spatial variability of actual risk within a construction site. The zones that have high values indicate higher risk and are displayed in red and appear at the top left of the site: adjacent to facility ( $F_7$ ), bottom left of the site, near facility ( $F_1$ ) and finally around facility ( $F_8$ ) in the middle of the construction site. This is due to the high potential global impact of these facilities. Moreover, figure 4.4 reveals that the risk behind the building under construction ( $F_9$ ) along the left side of the site, bottom right adjacent to the job offices and areas adjacent to the concrete plant facility ( $F_3$ ) are moderate. This is due to low visibility and connectivity. Finally, the map shows that the remaining zones within the site have lower risk values. These zones are displayed in green and appear almost within the middle of the site. This is due to the fact that their positions are far away from facilities with highest potential global impact. Also, these zones have good visibility, high integration, high connectivity and low mean depth values compared to the most risky ones. The amplification risk map shown in figure 4.4 forms the basis for implementing least-cost path analysis

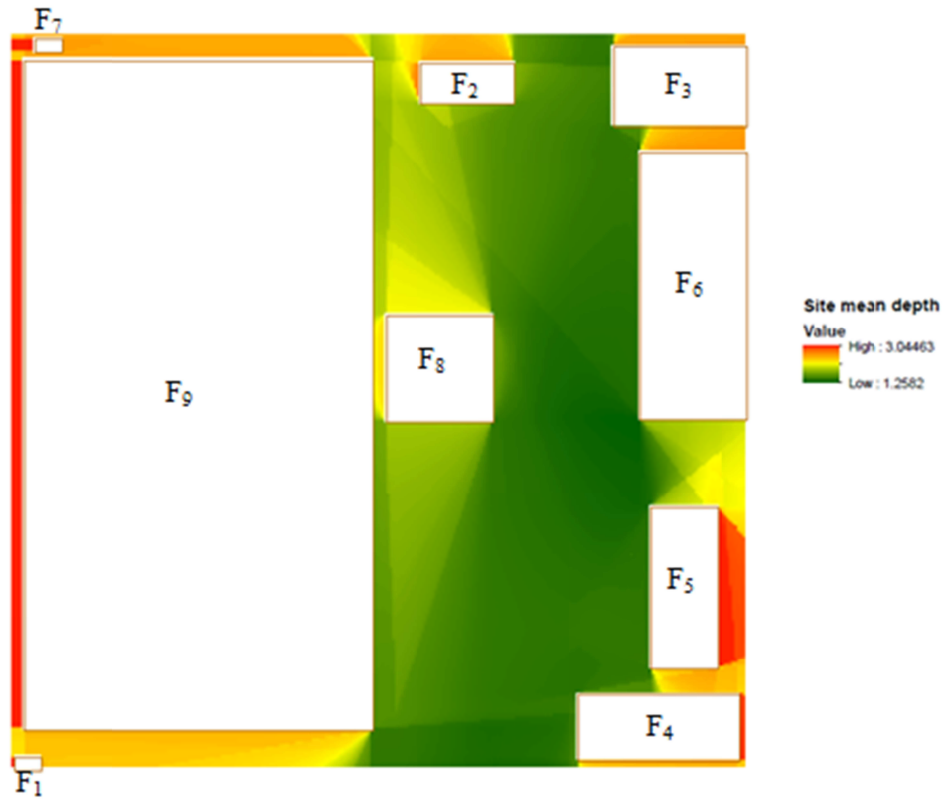


Figure 4.3. Map of site mean depth ( $\bar{\delta}_k$ )

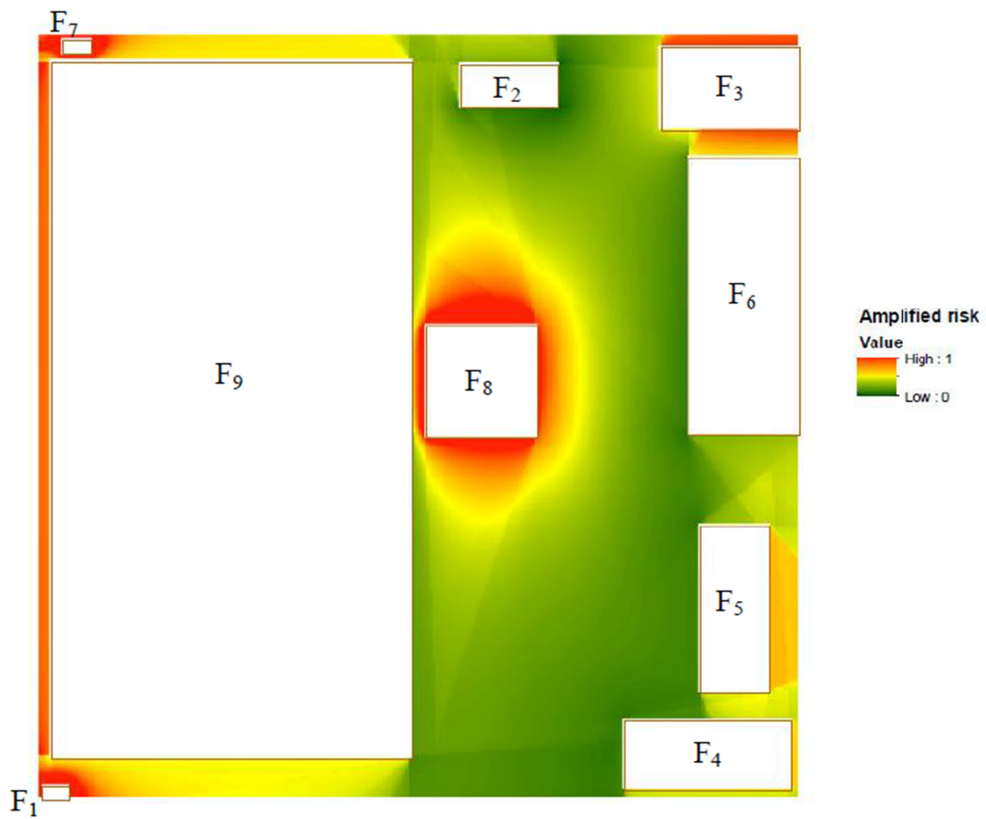


Figure 4.4. Map of spatial variability of risk within a site (risk amplification factor( $\mathcal{R}_{af}$ ))

#### 4.1.2.2 Optimal path result

In the case of the occurrence of the potential hazard, all efforts are directed toward evacuating the site. Therefore it is highly significant to determine a suitable path for the exit gate(s) with the lowest risk. The exit gate will be the destination of everyone on the site during an emergency. Thus the selection of a suitable position for this gate will minimize injuries and fatalities and allow seamless evacuation of the site. Whatever the case, several requirements are significant in performing least-cost path analysis: (1) Source nodes (starting points in calculating the cumulative cost path) must be identified. These nodes define where the least-cost path is going; that is, the source points represent the end of the path. On a construction site, for evacuation purposes, the source represents the exit gate(s) of the site. It is assigned to the safest position, not subjected to high risk, regarding the spatially amplified risk map. (2) A cost dataset must be constructed. It defines the cost of moving through each node. In our case, the spatially amplified risk map of a construction site represents the cost surface dataset. In the example of this case, one exit gate is determined and is allocated at the south of the site near facility F<sub>4</sub>, as shown in figure 4.5. This position is selected because it is the safest zone compared to other zones within a site, where the visibility is high and potential global risk is low.

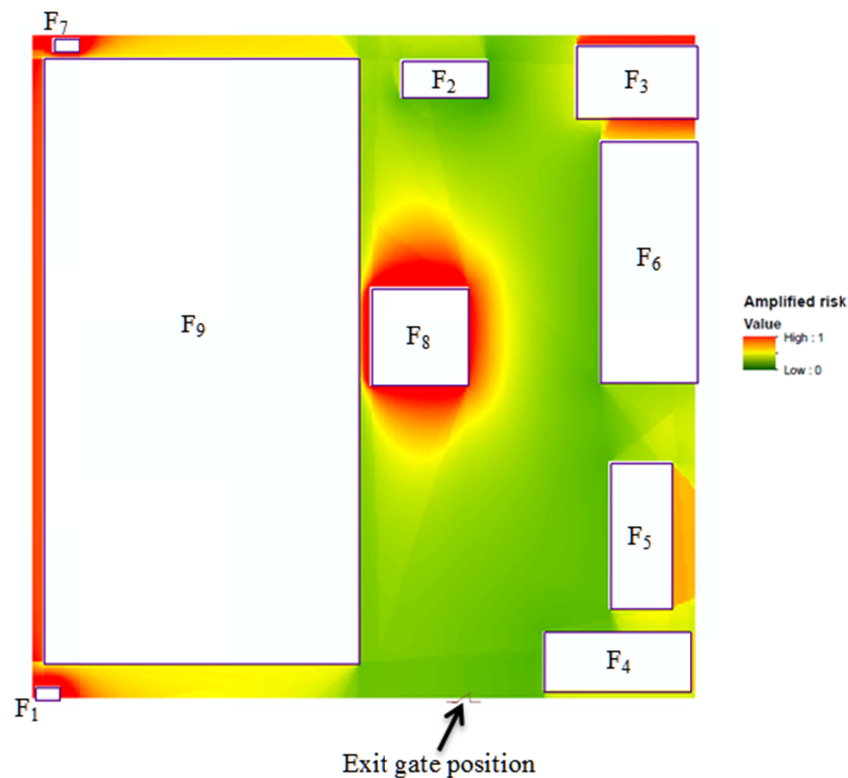


Figure 4.5. Determination of the exit gate position

As mentioned before, the amplification risk map (cost surface map) plays a primary role in finding the safest path from any position on the site to the exit gate. Therefore, the least cumulative cost distance is calculated for each cell with respect to the exit gate (figure 4.6). Furthermore, the direction of movement from each cell to the exit gate is also determined (figure 4.7).

The optimal least risk path from any position on the construction site can then be easily found. As shown in figure 4.6, two positions (A and B) are identified to find the safest path from each of them to the exit gate. Position A represents the exit/entrance of the building under construction ( $F_9$ ), whereas position B is located near the tower crane ( $F_8$ ), which is the most at-risk position within the construction site. However, in any case, the length of the path depends on the existence of obstacles and the amount of accumulated risk along the path. The results in table 4.7 show that even though the length of the safest path is higher than the length of the shortest one, the total associated accumulated risk is less than that of the shortest path.

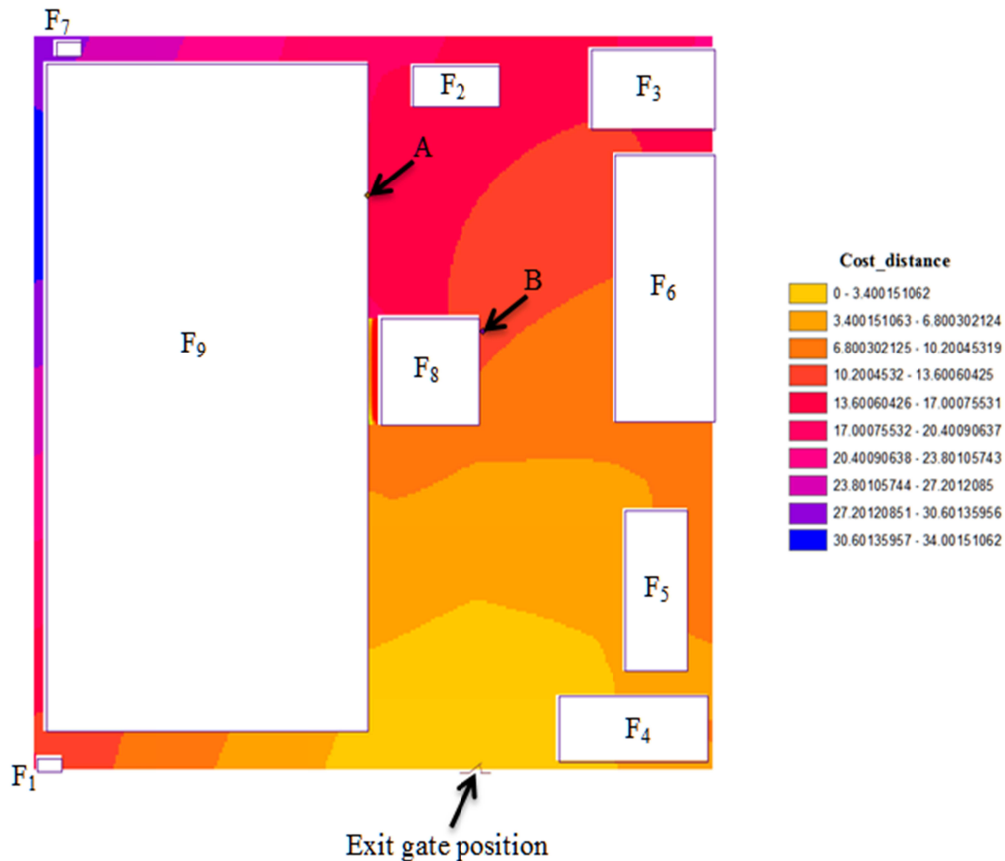


Figure 4.6. Accumulated least risk dataset

The length of the least-risk route from position A is approximately 20% greater than the shortest path length. Moreover, the total accumulated risk along the least-risk route from A is 28% lower than that along the shortest path route. For the route from position B, it is obvious that the length of the safest path is 12% higher than that for the shortest path. In addition, the total accumulated risk associated with the least risk path is 8% lower than that for the shortest path. As evidenced in figure 4.8, the two generated paths tend to travel through locations with the least risk and to avoid, as much as possible, passing through the highest risk zones. This will enhance the evacuation process and allow losses, injuries, and fatalities to be minimized.

Table 4.7. Comparison between least-cost path and straight shortest path

Path from	Length of least-risk path [units: m]	Length of the shortest path [units: m]	Accumulated risk of least-risk path	Accumulated risk of shortest path
Position A	57.02	46.58	16.66	21.34
Position B	36.86	32.93	11.28	12.20

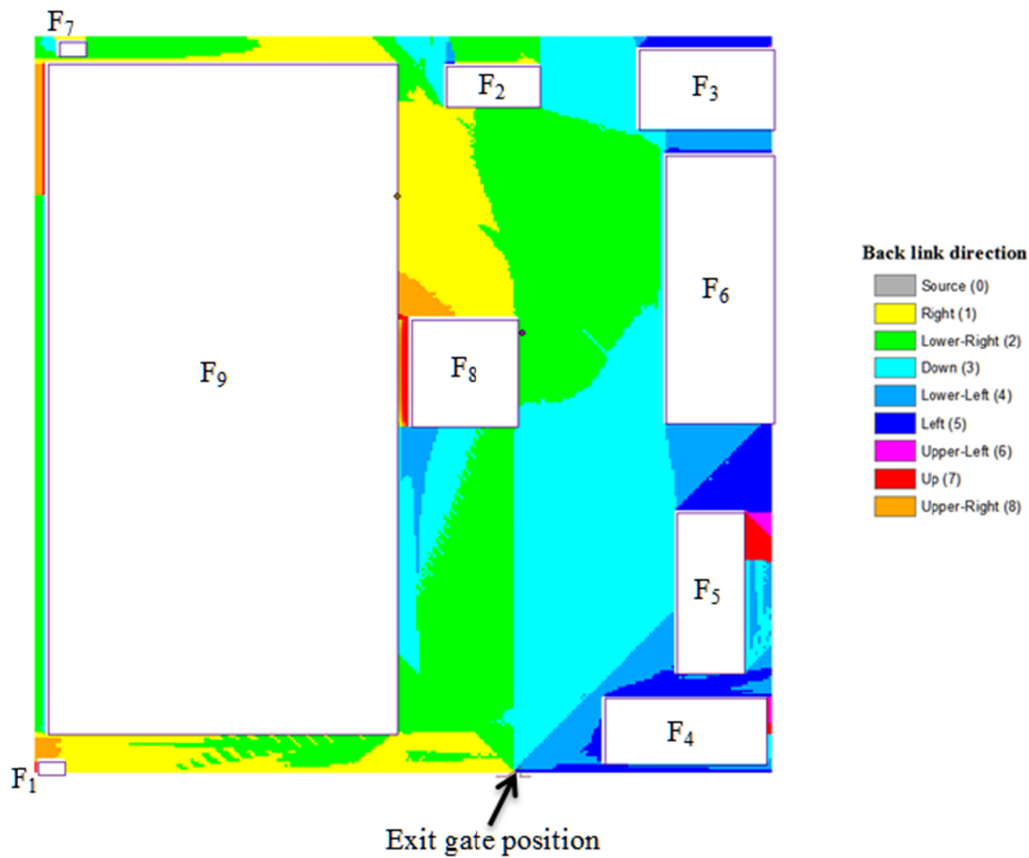


Figure 4.7. Backlink risk dataset

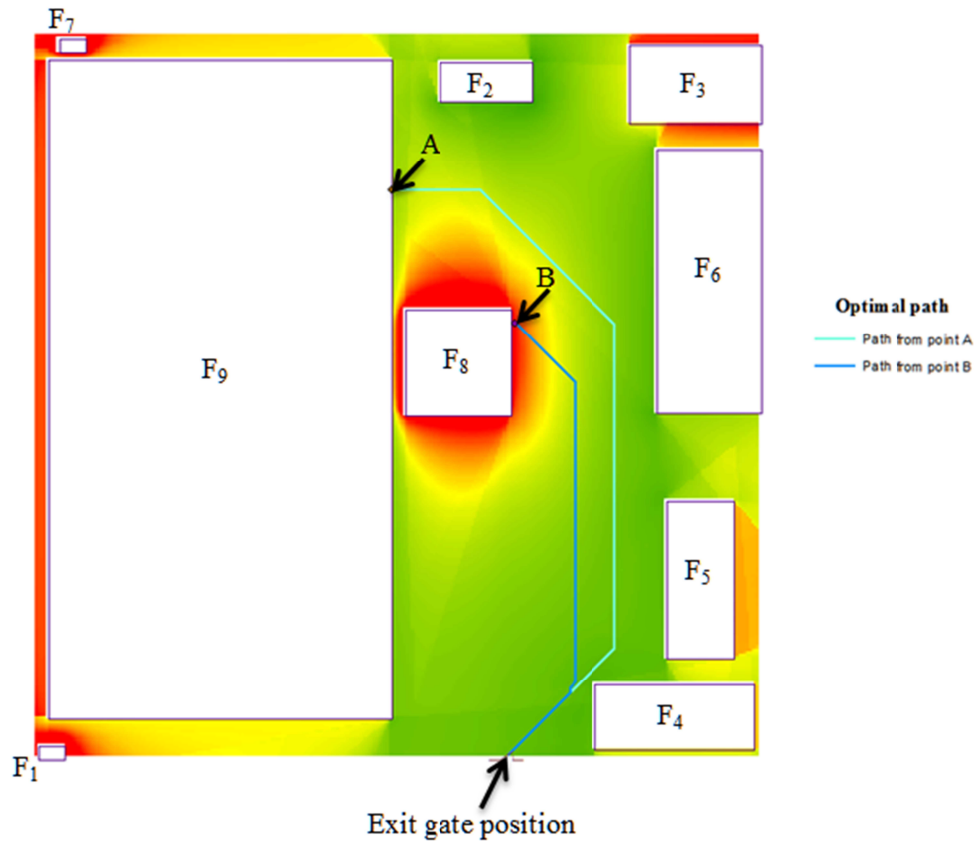


Figure 4.8. Safest paths from positions A and B

## 4.2 Implementation of a probabilistic model

Generally, the same case study utilized in a deterministic model is also adopted in the implementation of a probabilistic model, but with working some amendments fitting the model requirements. The purpose of this implementation is to examine the ability of a proposed probabilistic model for developing site layout aims to minimize the probability of risk failure of the whole site. The case study components' characteristics, dimensions, and the required input data are shown in table 4.8. It is obvious from this table that, the project consists of nine facilities classified to be either fixed or movable. It is required to allocate these facilities in a proper position in a construction site taking into account the boundary and the overlapping constraints. The optimal location of these facilities can be determined by applying the optimization search algorithm technique that aims to achieve the desired utility function (i.e. minimize the probability of failure of the whole site).



Table 4.8. Facilities' description and characteristics

Facility	Nature of facility	Length "ℓ" (m)	Width "w" (m)	Movable or fixed	Hazard source	Hazard level	Vulnerability class
F <sub>1</sub>	Electric generator	2	1	Movable	Yes	High	Safe
F <sub>2</sub>	Labor services	7	3	Movable	No	---	Very dangerous
F <sub>3</sub>	Concrete plant	10	6	Movable	No	---	Dangerous
F <sub>4</sub>	Job office 1	12	5	Movable	No	---	Very dangerous
F <sub>5</sub>	Job office 2	5	12	Movable	No	---	Very dangerous
F <sub>6</sub>	Steel storage	8	20	Movable	No	---	Safe
F <sub>7</sub>	Fuel storage	2	1	Movable	Yes	High	Safe
F <sub>8</sub>	Tower crane	8	8	Fixed (32,30)*	No	---	Safe
F <sub>9</sub>	Construction Building	26	50	Fixed (14,28)*	Yes	Medium	Safe

\* The coordinates of fixed facilities.

The proposed model needs, from project planners and managers, identifying: (1) facilities that may be a potential source of hazard; (2) the hazard level for each of these sources; (3) and the vulnerability class for each facility needed to be erected on a construction site. It is obvious from table 4.8 that, in this case, the electrical generator (F<sub>1</sub>), fuel storage (F<sub>7</sub>), and the building under construction (F<sub>9</sub>) are considered the potential sources of fire hazard occurrence. Moreover, the hazard level for the facilities (F<sub>1</sub> and F<sub>7</sub>) are high, whereas for the facility (F<sub>9</sub>) is medium. In addition, it is assumed that all facilities are a potential target to fire hazard. According to vulnerability classification, it is clear that job offices (F<sub>4</sub> and F<sub>5</sub>), and labor services (F<sub>2</sub>) are classified to be very dangerous. The remaining facilities are classified to be safe, except concrete plant facility (F<sub>3</sub>), which is classified to be dangerous.

As mentioned previously, in the present study, the characteristic parameter of normal distribution (i.e. standard deviation " $\sigma_{l,d}$ ") must be derived from historical data. According to **Butler and Cohen (1998)** the radius of the safety area from the hazard sources should not be less than four times the maximum fire flame height. As the historical data is not available and according to **Butter and Cohen (1998)**, we assumed that the radius of safety area forms 95% confidence interval of impacted zone. This means that there is 95% chance that, all facilities located within a circle radius less than the radius of the safety area will be impacted by the hazard. In addition,

there is only 5% chance that all facilities located within circle radius greater than the radius of the safety zone will be impacted by the hazard. In order to determine standard deviation (" $\sigma_{l,d}$ "), we assume that the average flame height is approximately equal to 4.0 m, so that the safety radius zone should not be less than 16 m. Therefore, according to normal distribution characteristics, 95% confidence interval falls within ( $\mu \pm 1.96 \sigma_{l,d}$ ), since ( $\mu = 0$ ) then the value of  $\sigma_{l,d}$  will be equal to 8.2 m.

In general, all of the input data are utilized to run an optimization algorithm to generate an optimal site layout with minimum probability of failure of the whole site. The Python language platform was used to implement the optimization algorithm. The initial population, to run optimization algorithm (differential evolution algorithm) contains 100 chromosomes. A personal computer with 2.4 GHz Intel(R) core(TM) i7-5500U CPU and 16GB of Ram was used.

The optimization process was run several times to develop the optimal coordinates and probability of failure for each facility as well as the probability of failure for the whole site. The optimization solution provides a relative position between facilities. Figure 4.9 displays one possible layout and the results associated with it. It shows the location and optimized coordinates of each facility on a construction site. It is obvious from this figure that, the hazardous facilities ( $F_1$  and  $F_7$ ) were allocated far away from all other facilities. Furthermore, this state is not applicable for facility  $F_9$ , since it is a fixed facility and its location is defined in advance. Moreover, the facilities were classified to be a high vulnerability ( $F_2$ ,  $F_4$ , and  $F_5$ ) are piled up far away from the facilities representing fire hazard sources. They are located at the top right of a construction site. This result coincides with the logic. Since the failure of each facility is a convolution of hazard and vulnerability and the risk is a combined of individual failure of each facility. Therefore, this requires accommodating the potential hazard sources facilities far away from the high vulnerable ones in order to minimize the total risk.

On another hand, figure 4.10 shows the numerical results for the probability of failure for the whole site. It confirms that, with 95% confidence level, the probability of failure of the whole site will not exceed 0.686. Also, it displays that the expected probability of failure of the whole site is 0.648. Moreover, the probability of failure of the whole site is skewed to the left (negative skewness) and the suitable probability distribution function for it is Weibull distribution function. On the other hand, table 4.9 presents the expected probability of failure for each facility as well as for the whole site. It shows that the expected probability of failure for facilities ( $F_1$  and

F<sub>7</sub>) is the highest, whereas the probability of failure for the facility (F<sub>4</sub>) is the lowest due to its distance from all hazard sources. In general, the probability of failure for hazard sources facilities is the highest. This can be attributed to the highest fire hazard intensity values at these facilities, so that, these facilities greatly govern the probability of failure for the whole site. The project managers must give them more attention during the execution phase of the construction project.

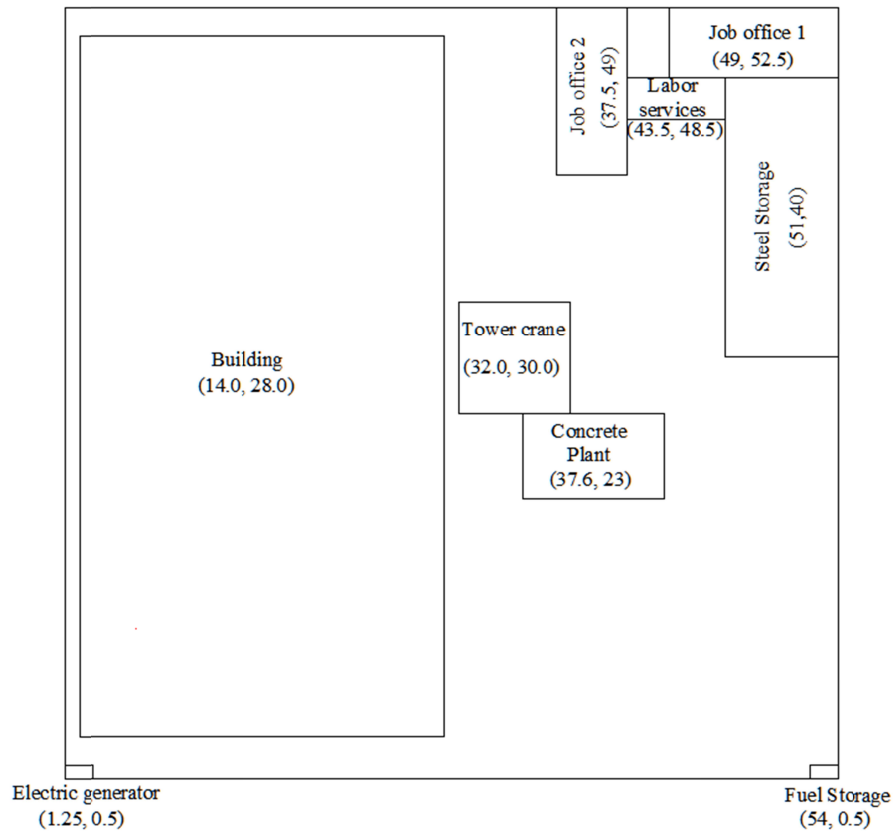


Figure 4.9. Optimal facilities layout and their optimized coordinates [unit: meter]

Table 4.9. Expected probability of failure for each facility and for the whole construction site

Object	Expected Probability of failure
F <sub>1</sub>	0.36561
F <sub>2</sub>	0.00099
F <sub>3</sub>	0.03728
F <sub>4</sub>	0.00013
F <sub>5</sub>	0.00304
F <sub>6</sub>	0.00139
F <sub>7</sub>	0.36311
F <sub>8</sub>	0.04295
F <sub>9</sub>	0.14375
Whole site	0.64811

The expected probability of failure of each facility is imported to GIS in order to do interpolation technique and generate spatial fire risk map. Figure 4.11 confirms that the positions adjacent to facilities with a high probability of failure are more dangerous than those located far away. It is clear that the top right of the construction site near facilities (F<sub>2</sub>, F<sub>4</sub>, F<sub>5</sub>, and F<sub>6</sub>) are the safest places on a construction site, whereas, the most dangerous positions (at most risk) are existing near facilities (F<sub>1</sub> and F<sub>7</sub>) at the bottom right and bottom left of construction site. On the other hand, there is a moderate risk in the zones around the building under construction (F<sub>9</sub>), which can be attributed to the moderate probability of failure of (F<sub>9</sub>).

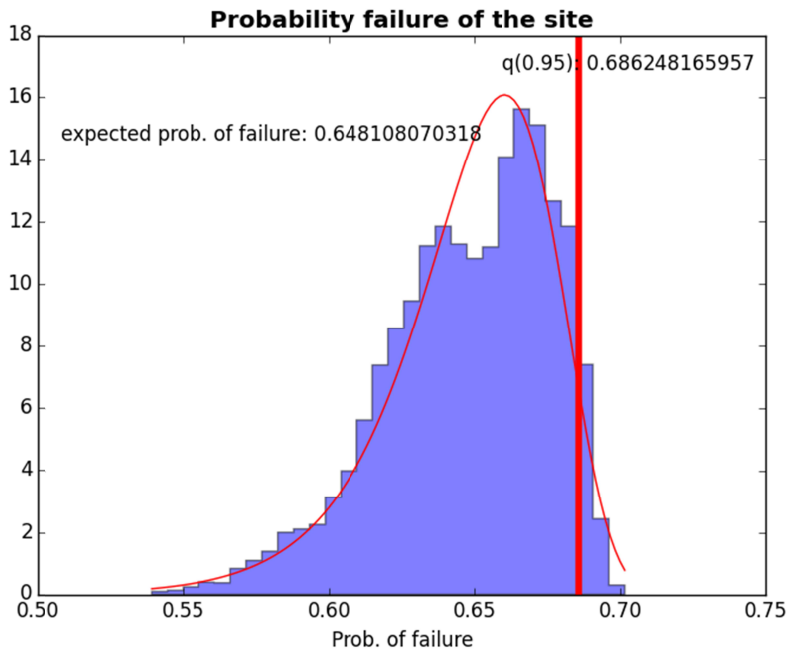


Figure 4.10. Weibull distribution function and numerical results of probability failure of the site

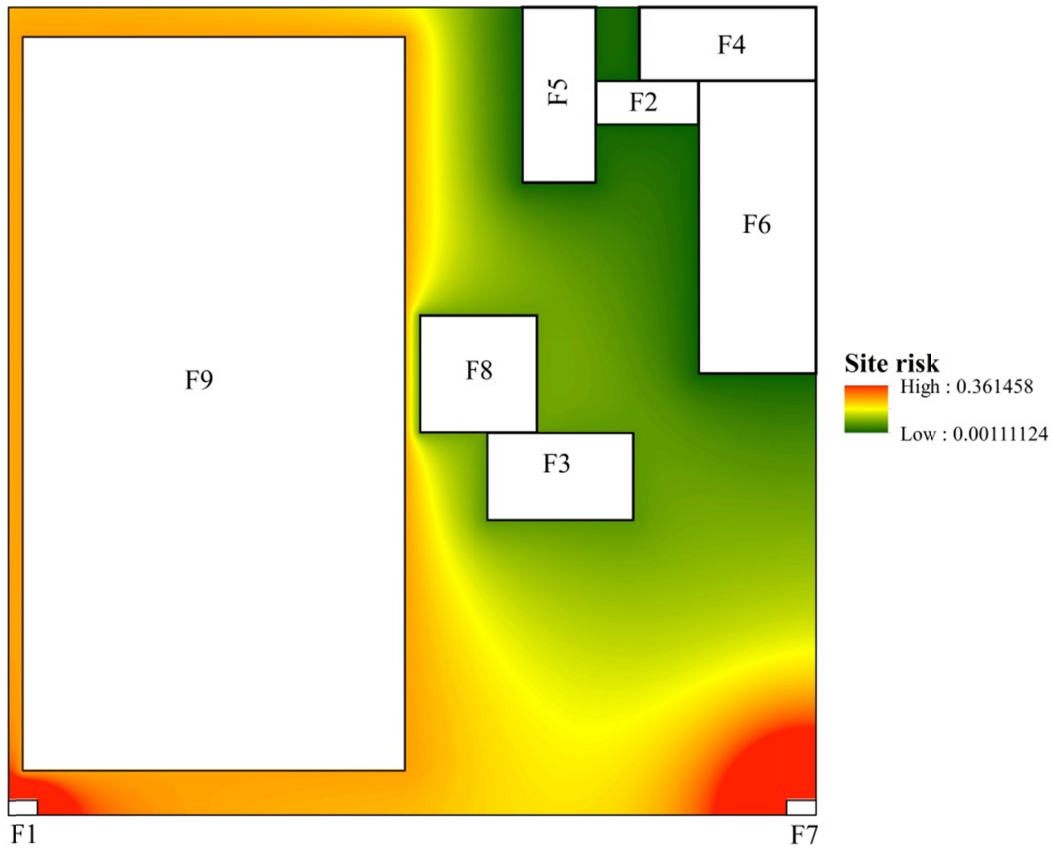


Figure 4.11. Spatial fire risk map

### 4.3 Résumé du chapitre 4

Ce chapitre présente la mise en œuvre des modèles développés afin d'examiner leur capacité et leur efficacité à générer un plan d'aménagement du site optimal. Il montre la nature des données d'entrée requises pour mener à bien les modèles proposés, le processus d'optimisation et les discussions autour des résultats obtenus. Les modèles ont été mis en place en utilisant le langage python.

## **CHAPTER 5**

### **Conclusion and Perspectives**

The current chapter presents a brief summary of the whole study, the conclusions attained from the study, and finally the future developments of the research to enhance site layout planning.

#### **5.1 Summary of the research and findings**

Foremost, one main feature of the construction industry is the frequent occurrence of uncertain extreme events, such as fire, explosion, blast waves, and thermal flux. They may lead to failure and/or adverse effect on the labors' productivity, labors' lives, the project schedule, the project budget, and the project quality. Furthermore, they may lead to catastrophic consequences if they propagate from one area to another within a construction site. In fact, construction site contains several supporting temporary facilities that are necessary to execute and complete construction activities. These facilities must be accommodated in a proper position within a site to be helpful in minimizing consequences of the potential hazard and achieve project intents.

However, the construction site layout planning is one of the complicated tasks that must be conducted by project planners and construction managers. The current attitudes in site layout planning are directed toward minimizing the travel cost distance between facilities only. They disregarded the risk resulted from the occurrence of natural or technological hazards that may lead to non-effectual site layout, which, in turn, may lead to the occurrence of fatal accidents. In addition, some of the construction site managers and planners still give less attention to site space management which still relies on the concept "first come first serve". Furthermore, another important issue that is often ignored during site planning is the identification of the shortest and

safest paths to facilitate the evacuation of the construction site in case of the occurrence of uncertain events. Hence, this research aims to develop a new framework able to generate optimal site layout ables of avoiding or at least reducing the risk of natural or technological hazards. Moreover, it aims to visualize the spatial variability of risk in a construction site, and finally finding the optimal safest paths from any position on the site to the external exit safe gate to evacuate site easily, without fear and chaotic.

This study comprises of five chapters, the followings are a brief summary of each one of them:

- Chapter one (general introduction): involves general introduction to the study, the objectives of the research, the importance of conducted this study, and justifications for doing it.
- Chapter two (related work): contains information about the current attitude of site layout planning, literature review on the previous proposed model for site layout planning, general data about hazard, vulnerability, risk, interaction matrix, the capabilities of GIS, the implementation of Dijkstra's and least cost path algorithm, the impact of space configuration on the risk and how space syntax spatial analysis technique is suitable for that, the working mechanism of the optimization evolutionary algorithm, and finally the principle of uncertainty analysis.
- Chapter three (research methodology and model development): it covers the methodology adopted to achieve the study objectives. It illustrates the steps required to develop two site layout models (deterministic and probabilistic model). It shows the mathematical formulas utilized to conduct hazard, vulnerability and risk modeling that are necessary to develop site layout models. It demonstrates the procedure adopted to generate spatial risk map and determine the optimal paths from any position on a construction site to the external safe exit gate.
- Chapter four (model implementation and result discussion): it involves a description of the case study adopted to implement the proposed models. It contains comments and discussion on the results attained from the implementation of the both proposed developed models.
- Chapter five (conclusion and perspective) includes a summary of the research, presents the conclusion of the study and finally provides suggested orientations for future developments of the current research.

The methodology adopted to develop an optimization model able to minimize the consequences of potential hazards and display the spatial variability of risk within a construction site comprises

of five major steps: (1) hazard modeling; (2) vulnerability modeling; (3) risk modeling; (4) optimization technique; and (5) GIS utilization to generate results in a map format.

The hazard modeling involves the identification kind of hazard, identifying the hazard sources, the hazard intensity at each origin potential source, and the hazard attenuation with distance. On the other hand, vulnerability modeling consists of identifying the potential targets that may be impacted by the hazard and estimating the conditional vulnerability value utilizing the vulnerability curves or vulnerability damage functions which express the vulnerability as a function of fire hazard intensity. The vulnerability of each target depends on its ability to resist various hazard values generated by surrounding sources.

Risk modeling is defined in this research to measure the expected probability of losses or harmful consequences in the erected facilities at a construction site. The risk is a result of interactions between natural or human-induced hazard with vulnerable circumstances. In the current study, the risk is a result of the exposure of facilities accommodated on a construction site to threats, and the vulnerability of these facilities. Once the modeling of hazard, vulnerability, and risk are established, the next step is to run optimization process using a differential evolution algorithm to find the optimal layout that achieves the desired objective function (i.e. minimize the risk that is represented by the failure of the whole site due to potential natural or technological hazards). In the optimization process, the best position for each facility is identified where the overall risk on a construction site is at the minimum level. Afterward, the spatial analyst tools available in ArcGIS were utilized to generate spatial risk map within a construction site. In addition, when the optimal layout generated, it is able to analyze and evaluate the influence of space configuration on the risk within a construction site by utilizing space syntax analysis technique, and it is also possible to find the optimal safest path (least risk paths) for evacuation from any position within a construction site to the exit gate of the site utilizing Dijkstra's algorithm and least cost path analysis.

## **5.2 Conclusion**

This research presented two models for optimizing construction site layout and visualizing of construction site risk due to natural or technological hazards: (1) deterministic; and (2) probabilistic. The models generate an optimized layout of construction facilities based on hazard



produced by the potential sources and the vulnerability of the surrounding potential targets. Moreover, they are capable of visualizing spatial variability of a risk due to potential hazards (natural or technological), within a construction site by utilizing the GIS. The generated spatial risk map is crucial to conduct Dijkstra's algorithm and the least-cost path analysis to identify the accumulated cost (risk) for each cell in the site, in accordance with the nearness to the exit gate, and for creating the safest path that has the lowest risk, which will facilitate evacuation from construction sites during emergencies.

For illustrative purposes, a case study consisting of various facilities was implemented. The most significant conclusions of carrying out proposed models on the case study can be summed up as follows:

- The risk on a construction site is too high at the positions that are relatively too close to the facilities with high potential global impact or high probability of failure compared to those positions located far away from them.
- The positions characterized with good visibility on construction site have low mean depth values, high integration, and have a lower risk compared to those positions with bad visibility.
- As the risk is a convolution of hazard and vulnerability, it is obvious from the results that the objects having high vulnerability are located far away from the objects generating high hazard.
- In the case where two facilities classified to follow the same vulnerability class, the probability of failure of the facility that is considered as hazard sources are higher than the probability of failure of non-hazard sources facility (considered as surrounding potential target). This can be attributed to the attenuation of hazard with distance. Therefore, the hazard intensity at hazard source facility is greater than the hazard intensity at the potential target one. In addition, as the vulnerability is a conditional value of hazard, then, the conditional vulnerability value and the probability of failure for the hazard source facility is higher than the conditional vulnerability value and the probability of failure for potential target facility.
- Generally, the facilities which are considered to be hazard sources governs the probability of failure of the whole construction site.

- Even though the length of the safest optimal path is higher than the length of the shortest one (straight Euclidian distance), the total associated accumulated risk is less than that for the shortest path. In particular, optimal safest paths are usually longer but safer.
- In general, the proposed models are powerful and useful due to their ability to generate optimal layout, visualize construction site risks due to potential hazard, display the most at risk position in a construction site, show the impact of potential global impact of facilities and space configurations on the risk within a construction site, and generate paths travel through the least risky zones. This will facilitate the evacuation process and minimize losses in case of emergencies, and assist construction managers during the construction process, to avoid or at least minimize the consequences of risk's domino effects.

### **5.3 Directions of future research**

The proposed models create an optimal layout based on Euclidian distances between facilities. Utilizing the actual distance between them by considering potential barriers and obstacles will provide more accurate data. Furthermore, the facility optimal location can be enhanced by providing additional decision variables like facility rotation. In addition, the proposed models deal with regular construction sites and facilities, therefore developing models deal with irregular facilities as well as irregular construction sites is another future endeavor of this research. Also, performing specific studies based on the type of hazard and its characteristic provides more realistic hazard model. Moreover, physical and mechanical sophisticated models can assist identifying and developing adequate vulnerability curves of temporary facilities instead of utilizing assumption conditional values, which will provide more accurate risk variability within a site. Additional future development is developing dynamic site layout that takes into account changes over time. Moreover, it is advisable to develop a model that integrates both the risk and the travel cost distance and carry out trade-off analysis between them. Additionally generating an optimal layout based on the amplified risk is another future development of this research. Finally, studying how the identification of safest paths can minimize the total evacuation time and also how site topography can impact on the variability of risk in a construction site are other directions for further research.

## 5.4 Résumé du chapitre 5

Ce chapitre présente deux modèles pour optimiser l'aménagement d'un chantier de construction et pour visualiser le risque lié aux aléas naturels/technologiques : (1) déterministe et (2) probabiliste. Ces modèles génèrent un plan d'aménagement optimisé pour les installations basé sur l'aléa produit par la vulnérabilité des cibles potentielles environnantes. En outre, ils sont capables de visualiser la variabilité spatiale d'un risque dans un chantier en utilisant le SIG. La carte de risque spatiale générée est cruciale pour mener l'algorithme de Dijkstra et pour faire l'analyse de chemin de moindre coût afin de trouver les chemins les plus sûrs, ce qui facilitera l'évacuation du chantier en cas d'urgence. A titre d'illustration, un cas d'étude pratique consistant en diverses installations a été mis en œuvre. Les conclusions les plus importantes peuvent être résumées comme suit :

- Le risque sur un chantier de construction est très élevé dans les positions qui sont relativement proches des installations, ayant un impact global à fort potentiel ou une forte probabilité d'échec, par rapport aux positions situées loin de ces installations.
- Etant donné que le risque est une convolution d'aléa et de vulnérabilité, les résultats montrent clairement que les objets ayant une vulnérabilité élevée sont situés loin des objets générant un aléa élevé.
- Généralement, les installations qui sont considérées comme des sources d'aléas régissent la probabilité d'échec de l'ensemble de chantier.
- Bien que la longueur du chemin optimal le plus sûr soit supérieure à la longueur du chemin le plus court (distance Euclidienne), le risque accumulé est inférieur à celui du chemin le plus court.
- En général, les modèles proposés sont puissants et utiles en raison de leur capacité à générer une disposition optimale, à visualiser les risques liés au chantier en raison d'un aléa potentiel, à afficher la position la plus à risque dans un chantier, à montrer l'impact de l'impact global potentiel des installations et des configurations spatiales sur le risque dans un chantier, et à générer des chemins parcourus dans les zones les moins risquées. Cela facilitera le processus d'évacuation et minimisera les pertes en cas d'urgence.

## **Author's publication and contribution list**

### **Journals**

- 1) Abunemeh, M., El meouche, R., Hijaze, I., Mebarki, A. and Shahrour, I., 2017. Hazards, vulnerability and interactions at construction sites: spatial risk mapping. *Journal of Information Technology in Construction (ITcon)*, 22(4), pp.63-79.
- 2) Abune'meh, M., El Meouche, R., Hijaze, I., Mebarki, A. and Shahrour, I., 2016. Optimal construction site layout based on risk spatial variability. *Automation in Construction*, 70, pp.167-177.
- 3) Xu, M., Hijazi, I., Mebarki, A., Meouche, R.E. and Abune'meh, M., 2016. Indoor guided evacuation: TIN for graph generation and crowd evacuation. *Geomatics, Natural Hazards and Risk*, 7(sup1), pp.47-56.
- 4) EL MEOUCHE, R., ABUNEMEH, M., HIJAZE, I., MEBARKI, A., Shahrour, I., 2017. Developing optimal paths for evacuating risky construction site. Under review. *Journal of Construction Engineering and Management*

### **International conference papers**

- 1) El Meouche, R., I. Hijazi, P. A. Poncet, M. Abunemeh, and M. Rezoug. "UAV PHOTOGRAMMETRY IMPLEMENTATION TO ENHANCE LAND SURVEYING, COMPARISONS AND POSSIBILITIES." ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences (2016): 107-114.
- 2) Xu, M., Hijazi, I., Mebarki, A., Meouche, R.E. and Abune'meh, M., 2016. Indoor guided evacuation: TIN for graph generation and crowd evacuation. *4<sup>th</sup> International Conference on Civil Engineering and Urban Planning*, Oct. 20<sup>th</sup>-23<sup>rd</sup>, 2015 Beijing, China

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